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Effects of Off-Road Tires on Flexible & Granular Pavements

Study SD1999-15
Final Report

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DISCLAIMER

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16. Abstract

The impact of off-road equipment on flexible and granular pavements was evaluated through a combination of field testing program and theoretical modeling. The pavement damage caused by Terragators, grain carts, scrapers, and tracked tractors was evaluated relative to the damage caused by 18,000-lb single axle truck. Field test sections were constructed and instrumented to measure strain, pressure, and deflection caused by the loading of off-road equipment on thin and thick flexible pavements, gravel, and blotter roads. The pavement responses were measured during the fall, spring, and summer seasons. The field collected data were used to assess the impact of the various off-road equipment and to validate the 3D-MOVE theoretical model. The validated model was then used to expand the study over the range of typical pavement structures and soil types in South Dakota.

Both the field testing program and the theoretical analyses showed that loaded Terragators and loaded grain carts are more damaging than the 18,000-lb single axle truck and the legal limit of 20,000-lb single axle, the empty scraper is significantly more damaging than the 18,000-lb single axle truck and the legal limit of 20,000-lb single axle, while the tracked tractor is less damaging than the 18,000-lb single axle truck. Based on the findings of this research, it was recommended that the loaded Terragators and grain carts should be regulated while the empty scraper should be prohibited from driving over highway pavements.

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GLOSSARY OF TERMS

3D-MOVE	computer model for dynamic pavement analysis
8103E	Terragator 8103 empty
8103L	Terragator 8103 loaded
8144E	Terragator 8144 empty
8144L	Terragator 8144 loaded
CAB	crushed aggregate base
ELSYM5	computer model for static pavement analysis
ESAL	equivalent single axle load
FWD	falling weight deflectometer
GCL	grain cart at legal load
GCL+60%	grain cart at 60% over legal load
GCL+150%	grain cart at 150% over legal load
HMA	hot mixed asphalt
LEF	Load Equivalency Factor
M_r	resilient modulus
N_f	number of load repetitions to fatigue failure
PCC	Portland cement concrete
Pulled Trailer	a trailer with two single-tired single axles
RD	rut depth
Tandem	a two-axle group
Tridem	a three-axle group
TT	tracked tractor

EXECUTIVE SUMMARY

The South Dakota Department of Transportation (SDDOT) is responsible for the design and management of several thousands of road miles. The state road network includes high- and low-volume paved roads as well as unpaved roads. The design of pavements includes the determination of the appropriate traffic volumes and the selection of the required structural section to carry such traffic. Managing a pavement network requires the identification of the appropriate maintenance and rehabilitation actions to be applied. In both cases, the agency must be able to predict the damage caused by the various equipment using the road over the life of the pavement. In the case of normal highway traffic, numerous procedures exist to predict its damage to paved roads under various environmental and material conditions. In the case non-standard highway traffic, such as agricultural and heavy construction equipment, there are not any procedures that can predict the damage caused by such equipment on paved and unpaved roads.

The lack of reliable procedures to determine the damage caused by off-road equipment to highway pavements has led the SDDOT to initiate a research program to study the impact of such equipment. The overall objective of this research effort was to evaluate the impact of off-road equipment tires on flexible and granular pavements. The research used a combination of field testing and theoretical modeling of the pavement structure to evaluate its response to tires and tracks used on off-road equipment at normal speed and axle load levels. The field testing of typical pavement sections instrumented with sensors to measure critical pavement responses was used to validate the theoretical model, which was then used to cover other pavement, environmental, and materials conditions. A total of thirteen tasks— including: literature review, field testing, data analysis, theoretical modeling, damage prediction, and economic analysis—were completed in order to achieve the objectives of the research.

Literature Review

This task identified all previous and current studies that dealt with the impact of off-road equipment on paved and unpaved roads. The review indicated that previous and current data on this topic are very limited. A recent research study conducted by the Iowa DOT evaluated the impact of agricultural equipment on flexible and rigid pavements. The Iowa study concluded that agricultural vehicles can be allowed 5,000-7,000 lb per single axle over the 20,000 lb/axle load limit. However, the study's applicability to the SDDOT effort is limited due to the testing of very thick flexible and rigid pavements (8"-9" surface layers) and the exclusion of unpaved roads.

Field Testing

The measurement of in-situ pavement responses under actual off-road equipment presented a major portion of this study. A total of six instrumented pavement test sections were constructed during Summer 2000. The sections were designed to cover both clayey and silty soils and a range of pavement structures. Sections over clayey soils were constructed on US212 near Gettysburg, SD and the sections over silty soil were constructed on SD26 near Polo, SD. Each location had three sections: thin (3" hot mix asphalt—3" HMA), thick (4" HMA) and unpaved. The unpaved section on clayey soil had a gravel surface while the unpaved section on silty soil had a blotter surface.

The instrumentation included strain gauges, pressure cells, deflection sensors and temperature sensors. The strain gauges were installed in the longitudinal direction at the bottom of the HMA layer to measure the tensile strains caused by the passage of a vehicle-load level combination. The pressure cells were installed within the crushed aggregate base and the subgrade layers to measure vertical stresses caused by the vehicles' loading. The deflection sensors were installed to measure the deflection of the pavement surface. The temperature sensors were installed throughout the HMA layer to monitor the temperature of the pavement during field testing. All of the instrumentation was installed in the outer wheel path.

The field testing program collected pavement response data under the following vehicle-load level combinations:

- Terragator Model 8103, empty and loaded
- Terragator Model 8144, empty and loaded
- Grain Cart, legally loaded and over loaded
- Scraper, empty
- Tracked Tractor

In addition to the off-road equipment, a 18,000-lb single axle truck was tested and used as a reference load. Pavement responses measured under the various vehicle-load level combinations were all compared to pavement responses measured under the 18,000-lb single axle truck. Field tests were conducted on September 14-15, 2000, April 4-5, 2001, and August 28-29, 2001, representing the fall, spring, and summer seasons, respectively.

Each vehicle-load level combination was driven at its normal operating speed for a minimum of five replicate runs. The same equipment was tested on all flexible, blotter, and gravel surface sections following the same field testing plan. The South Dakota Highway Patrol measured the axle loads and tire pressures during the field testing programs.

Data Analysis

The analysis of field data consisted of reviewing the pavement response curves collected under each passage of a vehicle-load level combination and select the critical responses. This was done by plotting each curve and identifying the maximum strain, stress, or deflection caused by each vehicle passage. In the case of pressure and deflection measurements, the replicate data were examined for repeatability and the average of the most repeatable set of measurements was calculated and reported. The repeatability of the pressure and deflection measurements was excellent (coefficient of variations less than 5%). In the case of strains, the responses from all four strain gauges were examined under each run and the maximum of all replicates was reported.

The field data were used to assess the impact of off-road equipment relative to the 18,000-lb single axle truck. The pavement response under each combination of vehicle-load level was divided by the pavement response under the 18,000-lb single axle truck to generate “pavement response ratios”. Since the expected variability of field measured pavement responses can be around 30%, it was considered that any vehicle-load level combination creating a ratio above 1.3 would be more damaging than the 18,000-lb single axle truck. Based on this criterion, it was concluded that the loaded Terragators and loaded Grain Cart are more damaging than the 18,000-lb single axle truck, the empty scraper is significantly more damaging than the 18,000-lb single axle truck, and the tracked tractor is not more damaging than the 18,000-lb single axle truck.

Theoretical Modeling

The expanded phase of the research required the use of theoretical modeling to extend the findings of the field testing efforts over the range of materials and pavement conditions that exist in South Dakota. This task necessitated the identification of a theoretical model that can reliably predict pavement responses under the loading conditions of off-road equipment. Off-road equipment has unique characteristics—including the use of large lugged tires, dynamic loads, and nonuniform pressure distribution at the tire-pavement interface—that must be handled by the selected model. These requirements led to the selection of the 3D-MOVE pavement model, which can accommodate irregularly loaded areas with nonuniform pressure distributions while incorporating the dynamic nature of traffic loads and pavement responses.

The 3D-MOVE model was verified against previous field testing data from Penn State University and Minnesota road tests. Because off-road equipment present unique and non-standard loading conditions, the field data generated in this research were also used to validate the 3D-MOVE model. The validation effort showed that the 3D-MOVE model’s capability to simultaneously predict multiple measured pavement responses was very good.

The 3D-MOVE model was then used to predict the response of pavement sections typical of South Dakota’s highways. Modeled pavements structures included HMA layers 0", 1.5", 3", 5", and 7" thick over crushed aggregate base layers 6" and 12" thick. These 10 pavement combinations were evaluated over 4 soil classes and 4 seasons, giving an expanded pavement data base of 160 pavement sections.

Damage Prediction

This analysis used the pavement responses generated by the 3D-MOVE model to predict the pavement damage caused by the off-road equipment relative to the 18,000-lb single axle truck. The damage analysis considered fatigue and rutting performance of flexible pavements and the rutting performance of unpaved roads. The concept of load equivalency factors (LEF) was used in this analysis and defined as follows: a load equivalency factor represents the number of repetitions of the 18,000-lb single axle load necessary to cause the same damage as one repetition of the specific vehicle-load level combination. For example, a vehicle-load level combination with LEF of 10 indicates that it takes 10 passes of the 18,000-lb single axle load to cause the same damage as one pass of the vehicle-load level combination. In other words, one pass of the vehicle-load level combination is equivalent to 10 passes of the 18,000-lb single axle load.

The fatigue damage caused by each vehicle-load level combination was estimated using a fatigue performance model that relates the number of loads to fatigue failure with the magnitude of the tensile strain at the bottom of the HMA layer. The rutting damage caused by each vehicle-load level combination was estimated using a rutting performance model that relates the number of loads to rutting failure to the magnitude of the compressive strains within each of the pavement layers. Using this analogy, LEFs were produced for all 160 pavement sections. A close evaluation of the damage analysis led to the following conclusions:

- Significant fatigue damage was caused on ultra-thin flexible pavements of 1.5" HMA over 6" and 12" CAB by all vehicle-load combinations during the summer season. The following observations were made:

    - One trip of the empty Terragator is equivalent to 51-150 trips of the 18,000-lb single axle truck.
    - One trip of the loaded Terragator is equivalent to 230-605 trips of the 18,000-lb single axle truck.
    - One trip of the legally loaded grain cart is equivalent to 77-240 trips of the 18,000-lb single axle truck.
    - One trip of the grain cart over legal is equivalent to 264-799 trips of the 18,000-lb single axle truck.
    - The empty scraper is detrimental to ultra-thin flexible pavements.

- On unpaved roads and flexible pavements that are not ultra-thin (HMA = 3"-7"), the following observations were made:

    - One trip of the empty Terragator is equivalent to 1-3 trips of the 18,000-lb single axle truck.
    - One trip of the loaded Terragator is equivalent to 2-20 trips of the 18,000-lb single axle truck.
    - One trip of the legally loaded grain cart is equivalent to 1-5 trips of the 18,000-lb single axle truck.
    - One trip of the grain cart over legal is equivalent to 1-20 trips of the 18,000-lb single axle truck.
    - One trip of the empty scraper is equivalent to 20-2900 trips of the 18,000-lb single axle truck.

These observations express the relative damage in terms of a range of equivalent trips. The lower end of each range represents the number of trips expected on thick pavements over strong subgrade soils , while the upper end of the range represents the number of trips expected on thin pavements over weak subgrade soils.

The above observations led to the same conclusions derived from the field testing program, which recommended that the movement of loaded Terragators, grain cart over legal, and the empty scraper over gravel and flexible pavements be regulated. In addition, these observations point out the extreme vulnerability of ultra-thin flexible pavements to fatigue damage as they are subjected to loadings from off-road agricultural and construction equipment.

Damage•Cost Analysis

A Damage•Cost analysis was conducted to identify alternatives for the transportation of commodities carried by Terragators (i.e. chemicals) and grain carts (i.e. grain) that would cause less pavement damage and would not impose high costs on off-road equipment operators. The best balance of acceptable pavement damage and cost was defined as the minimum product of load equivalency factor and operating cost per mile. The tridem axle single unit truck was identified as the optimum transporting method for both agricultural chemicals and grain.

Implementation Recommendations

The analysis conducted in this study compared the damage caused by agricultural and construction equipment relative to the 18,000-lb single axle truck. This approach was selected to stay consistent with current pavement design, analysis, and management technologies which use the 18,000-lb Equivalent Single Axle Load (ESAL) concept. However, it should be noted that the single axle legal load limit in South Dakota is 20,000-lb, with a load equivalency factor of 1.5. Therefore, any recommendation concerning the damage caused by agricultural and construction equipment considers both the 18,000-lb single axle truck and the 20,000-lb legal load limit.

Using the combined data from field testing and theoretical modeling, this research project supports implementation recommendations that are both vehicle-specific and generalized to any lugged tires under a certain load level. The following represent the recommendations resulting from this research.

Vehicle Specific Recommendations

- Scrapers as heavy or heavier than those tested in this study should not be allowed to travel over unpaved roads and flexible pavements throughout the state of South Dakota. Transporting scrapers to the project site with multi-axle trucks meeting the legal load limits creates far less pavement damage. This is supported by the extremely high damage caused by the empty scraper on all pavement sections and during all seasons. Both the front and rear axles of a scraper were significantly more damaging than the standard 18,000-lb single axle truck and the legal 20,000-lb single axle.

- Terragators should only be allowed to travel empty on unpaved roads and flexible pavements. Loaded Terragators caused more damage than the 18,000-lb single axle trucks and the legal 20,000-lb single axle when operated during the summer, fall, and spring seasons. Transporting chemicals to the field using legally loaded axles and loading them onto Terragators at the job site creates far less pavement damage. For jobs requiring single or multiple Terragator loads, a tridem axle truck would be the most effective method of transporting chemicals.

- Grain carts traveling on unpaved roads and flexible pavements should only be allowed to transport the legal load limit. This study found that grain carts loaded over the legal load limit impose more damage than the 18,000-lb single axle truck and the legal 20,000-lb single axle during the summer, fall, and spring seasons. Transporting grain with legally-loaded tridem axle trucks create far less pavement damage.

General Recommendations

- Tires designed with rectangular lugs should not be allowed to carry more than 20,000 lb/axle. This is supported by the high load equivalency factors that were computed for lugged tires on loaded vehicles as compared to the lugged tires on empty vehicles over the entire range of pavements and environmental conditions.

- The load per unit width of tire regulation should not be applied to the entire area of lugged tires due to the high ratio of gross to net contact areas of such tires. If such a regulation is desired it should only apply to the net area of the lugged tires.

- The low inflation pressure of lugged tires, 30 psi as compared to 100 psi for standard tires, should not be considered to offset heavier axle loads. This is supported by the fact that the low tire inflation pressure of 30 psi results in contact stresses at the lug-pavement interface in excess of 150 psi. Therefore, special allowances for lugged tires on the basis of low tire inflation pressure are not warranted.

- Special load restrictions should be posted on flexible pavements having HMA layer equal or less than 1.5" thick (including blotter) to prevent severe fatigue damages caused by all types of off-road equipment during the summer season. The data from this study showed that the ultra-thin flexible pavements can suffer severe fatigue damage when loaded with empty and loaded off-road equipment due to their extremely low resistance to bending stresses.

- The high pressure concentrations at the lugged tire-pavement interface (more than150 psi) could be highly damaging to unpaved roads during extremely wet seasons and to flexible pavements in areas where sharp turning movements are anticipated. Therefore, it is recommended that the movement of vehicles equipped with lugged tires on extremely wet unpaved roads should be regulated. Also such vehicles should not be allowed to maneuver on flexible pavements during the hot summer season.

PROBLEM DESCRIPTION

The conditions of the road system in South Dakota are similar to the road systems in the rest of the states around the country. A high percentage of it is in need of continuous rehabilitation and maintenance in order to accommodate current traffic and economic growth. In spite of these pressing needs, the state highway agencies (SHA) are continuously facing budget cuts and reductions in revenues which force them to optimize the use of the available funds and get as much coverage as possible without jeopardizing the level of service being achieved by the current road system. Another way of coping with such conditions is to lengthen the useful life of pavement sections by imposing certain restrictions on the characteristics of the vehicles using the road system. Typical restrictions have included: seasonal load limits, limits on tire inflation pressure, and limits on the number of tires per axle (dual vs single tires). In the case of normal highway traffic conditions, these criteria and procedures have been well established based on full scale pavement testing facilities such as the AASHO and WASHO road tests during the 50's and 60's and WesTrack, Minnesota road test (Mn/ROAD) and the Long Term Pavement Performance (LTPP) program during the 90's. However, when road pavements are loaded with non-standard highway traffic loads such as off-road agricultural and heavy construction equipment, the applicability of these criteria becomes highly questionable.

The operation of off-road agricultural and heavy construction equipment on highway pavements presents new challenges to the pavement engineering and management community. Equipment such as chemical applicators, grain carts, and heavy construction machinery has become larger and heavier, and is often supported by unconventional tire configurations, including low-pressure floatation tires, lugged tires, or rubber tracks. All such characteristics are unique to the off-road equipment and do not distribute the loads to the pavement surface as normal highway traffic vehicles would. Some of their characteristics could in fact cause less damage than normal highway traffic while other characteristics could cause more damage. It is usually not the individual characteristic but the combination of characteristics of a given vehicle that leads to more or less damage as compared to normal highway traffic. For example, the low tire inflation pressure of off-road equipment should be less damaging than the high tire pressure of normal highway traffic. But when the low tire pressure is coupled with heavier loads, certain tire designs, and low vehicle speed, it may become more damaging than higher tire inflation pressures.

The lack of information concerning the relative impact of off-road equipment as compared to normal highway traffic puts any SHA in an awkward position when it comes to implementing restrictions which are intended to lengthen the useful life of the pavement. Without knowledge of the effects of off-road equipment on typical state and local pavements, it is impossible to assess the financial impacts of its use, or to determine whether present regulations are too strict, too loose, or appropriate. Without the appropriate background analyses and justifications, the goodwill actions of a SHA to preserve the road system could be interpreted as an unjustifiable action toward a single group of road users who believe they are doing their fair share toward maintaining the road system.

OBJECTIVES

The overall objective of this research project was to evaluate the impact of off-road equipment tires on flexible and granular pavements. The research used a combination of field testing and theoretical modeling of the pavement structure to evaluate its response to tires and tracks used on off-road equipment under their respective speed and axle load levels. Field testing of typical pavement sections instrumented with sensors to measure critical pavement responses was used to validate the theoretical model, which was then used to cover other pavement, environmental, and material conditions. The project started on December 1, 1999 and was completed on January 30, 2002.

The specific objectives of this research study were:

- *To model pavement damage caused by tires and tracks on off-road equipment.* This objective was achieved through measuring in-situ pavement responses under selected off-road equipment. Using the field data, a theoretical model was verified and then used to expand the evaluation over a wide range of pavements and environmental conditions typical of South Dakota.

- *To assess the economic benefits and costs associated with the use of off-road tires and tracks under present regulations.* This objective was accomplished through converting pavement damages into reductions in pavement life and assessing the equivalent costs of using off-road equipment on pavements as compared to transporting the products with normal highway vehicles.

- *To recommend policies for regulating transportation of off-road equipment over state and local highways.* Using the pavement damage and life reduction data, recommendations were made to regulate the transportation of off-road equipment.

TASK DESCRIPTION

Task 1: Meet with the Project Panel

Meet with the project panel to review the project's scope and work plan.

The first meeting with the project panel was held on December 17, 1999, in Pierre, SD. The principal investigator presented the work plan for all thirteen tasks of the project. All tasks were discussed and several recommendations were made. Some of the major recommendations included the following:

- Test as many types of off-road equipment as practical.
- Use the actual combinations of tire type, tire pressure, speed and axle load that are typically used on the various equipment.
- Test thin and thick flexible pavements, a gravel road and a blotter road.
- Use the tire manufacturers' supplied data on the pressure distribution at the tire-pavement interface.
- Measure the surface deflection only using the single layer deflectometer.
- Plan on testing during the summer and fall of 2000 and spring and summer of 2001.
- Provide access to the finished base course for one day to install the instrumentation.

Task 2: Review Literature

Thoroughly review literature pertaining to the effects of off-road equipment tires on flexible and granular pavements.

An extensive search was carried out to identify any previous studies that evaluated the effects of off-road equipment tires on flexible and granular pavements. The following data bases were searched electronically for information:

Transportation Research Information System
National Technical Information Services
Transportation Research Board
ASCE Journal of Transportation Engineering
American Society of Testing and Materials
National Cooperative Highway Research Program
American Association of State Highway and Transportation Officials
National Transportation Library
Transport

Also a request was sent through the Internet to all Local Technical Assistance Program Centers (57 Technology Transfer Centers throughout the country) asking them for information related to the impact of off-road equipment on pavements. As a result of all these efforts the following references were identified:

- Heavy Agricultural Loads on Pavements and Bridges (1)
- Vehicle Travel Costs on Paved, Granular and Earth Surfaced County Roads (2)
- Stressing our Future (3)
- Response of Iowa Pavements to Heavy Agricultural Loads (4)

The first two items were not directly related to the issues being investigated in this research. The first study assessed the structural performance of concrete and timber bridges under severe loads. The report mentioned that there is a possibility of over-stressing pavements without providing any supporting data. The second study described the variable cost per mile of vehicle types traveling on rural county roads. The study looked at 14 types of road vehicles and 34 types of farm vehicles. However, the study did not address the effects of these vehicles on pavements.

The third and fourth references were both issued by the Iowa Department of Transportation. The third study came out as a pamphlet entitled “Stressing our Future.” The pamphlet discussed the equipment used by agricultural operations in Iowa and its estimated impact on the maintenance of the road system. It showed that many farming vehicles exceed the weight limits imposed on highway vehicles. The pamphlet listed the effects of farm vehicles on rigid pavements and noted that similar effects would be realized on flexible pavements.

The fourth study represented the only significant study that evaluated the impact of off-road equipment on the response of rigid and flexible pavements. The following represent the key findings of the Iowa study.

Response of Iowa Pavements to Heavy Agricultural Loads

This research study was conducted by the Center for Transportation Research and Education (CTRE) at the Iowa State University and funded by the Iowa Department of Transportation. The overall objective of the study was to evaluate the impact of agricultural equipment on Iowa’s paved county roads. In order to achieve this objective, the research evaluated the response of rigid and flexible pavements under agricultural equipment using a combination of field instrumented pavement sections and theoretical analyses.

One rigid pavement section and one flexible pavement section were instrumented and tested during the period of August through September 1999. The instrumentation included strain gauges and temperature sensors. The rigid pavement section had a 7.75" Portland cement concrete (PCC) slab while the flexible pavement had a 9" hot mixed asphalt (HMA) layer. The strain gauges in the rigid pavement were placed near the bottom of the slab at the corner and near the top of the slab at the edge. The strain gauges in the flexible pavement were placed at the mid-depth of the HMA layer.

Tables 1 and 2 summarize the recommendations/findings of the rigid and flexible pavement studies, respectively. The study evaluated the impact of agricultural equipment as compared to a standard semitrailer truck loaded with 20,000 lb/axle. In the case of the rigid pavement, the comparison was based on developing the same stress magnitude. In other words, how much axle load can a grain wagon carry in order to keep the same stress level as the semitrailer with 20,000 lb/axle. In the case of the flexible pavement, the fatigue and rutting lives were used to establish the axle equivalencies.

The report did not provide any specific conclusions or recommendations. However, if the data provided in Table 2 are evaluated, it can be seen that for single axles on flexible pavements, the agricultural vehicles can be allowed up to 5,000-7,000 lb per single axle over the 20,000 lb/axle load limit of the semitrailer. In the case of dual-axle grain carts, the allowable load for the two axles ranges from 33,200 during spring to 44,500 during fall as compared to 20,000 lb/single axle on a semitrailer.

Table 1: Load Capacity of Different Implements Resulting in Equivalent Stress in Rigid Pavements to a 20-Kip Single Axle on Semitrailer as Determined by the Iowa Study

		Axle Load (Kips)	
Vehicle/Axle Type	Load Configuration	Spring	Fall
Semitrailer	Single axle dual tires	20	20
	Tandem axle dual tires	41	42
Grain Wagon	Single axle single tire	24.4	25
	Tandem axle single tire	36	37.5
Honey Wagon	Single axle single tire	24	25
	Single axle dual tires	38	39
Tracked Wagon	108 in by 24 in track	110	110

Table 2: Effect of Seasonal Conditions on Flexible Pavements Capacity under Different Implements as Determined by the Iowa Study

Season	Reference Axle	Single Grain Wagon	Dual Single Grain Wagon	All Honey Wagons
Spring	20,000	25,200	33,200	25,200
Fall	20,000	27,800	44,500	27,800

In addition to the fact that the report on the Iowa study did not provide any specific recommendations on the issues of pavement damage caused by agricultural equipment, the study had some issues which limits its applicability to the current study.

- The study evaluated flexible pavements having 8" and 9" HMA layers (9" in the field study and 8"in the theoretical study). Such pavements are very thick relative to what are considered county roads.

- The field instrumentation plan located the strain gauges near mid-depth of the newly constructed HMA layer, which is not an appropriate location for measuring strains that cause fatigue cracking of new flexible pavements.

- It was not clear from the report how the field measurements were used to meet the objective of the research.

- No testing nor theoretical analyses were conducted on unpaved county roads.

Task 3: Identify Factors That Affect Pavement Response

Identify primary factors relating to equipment, granular and flexible pavements, and environment, that affect pavement response to load.

In order to devise an effective field testing program, it was necessary to identify the primary factors that affect pavement response to load. The primary factors were divided into three groups: vehicle factors, pavement factors, and environmental factors.

The primary factors of the off-road equipment commonly used in South Dakota were identified by the project panel, and included axle type, spacing, load, tire type, size, inflation pressure, and vehicle operating speed. The following equipment was selected:

- Terragator Model 8103 (three wheels) (Figure1)
- Terragator Model 8144 (four wheels) (Figure 2)
- Grain Cart (single axle) (Figure 3)
- Tracked Tractor (Figure 4)
- Scraper (Figure 5)

Terragators are used to apply agricultural chemicals in the field. Grain carts are used to transport grain in the field from combines to trucks. Tractors are used to pull grain carts and other equipment. Scrapers are used for earth movement during roadway construction.

The primary pavement factors included structure, materials behavior, and in-situ conditions. The pavement structure was handled by constructing thin and thick pavement sections at each location. Materials behavior was handled by selecting locations with different soil deposits (clay and silt). The in-situ conditions were measured using the falling weight deflectometer (FWD) test to evaluate the in-situ properties during field testing.

Figure 1: Terragator 8103

Figure 2: Terragator 8144

Figure 3: Grain Cart Pulled by a Tractor

Figure 4: Tracked Tractor

Figure 5: Scraper

The environmental primary factors included temperature and moisture. The impact of temperature and moisture were handled by testing during three seasons of fall, spring, and summer. The temperature of the pavement during testing was measured using sensors embedded in the pavement structure at various depths. The moisture content of the supporting layers was reflected in the back-calculated moduli of the pavement layers.

<u>Task 4: Propose and Test a Theoretical Pavement Response Model</u>

Propose and test a theoretical model of pavement response under load applied by off-road equipment tires and tracks.

Selecting a theoretical model to evaluate pavement response under loads applied by off-road equipment tires and tracks is not a simple task. The following represents a discussion of the issues that must be considered while searching for the appropriate model.

The pavement structure represents a complex system relative to analyzing its response to traffic loading. Several factors must be handled correctly in order to accurately predict pavement response to traffic loading. These factors include:

- *Dynamic Nature of Traffic Loads*—The dynamic nature of traffic loads is influenced by axle load, gross vehicle weight, wheel path location and speed, and axle suspension, with axle load having the greatest impact on pavement deterioration. Speed and road roughness interact to increase the dynamic wheel loadings. Axle suspension is effectively a filter for attenuating the road induced dynamic loads. Various axle and suspension configurations filter the road inputs differently, and therefore, each configuration has a different potential for attenuating the inputs. Additionally, wheel base filtering affects the low frequency dynamic loads and, based on vehicle speed, changes the bounce and pitch modes of the vehicle response.

- *Nonuniform Pressure Distribution at the Tire-Pavement Interface*—The tire-pavement interaction mechanism controls the way in which traffic loads are transferred to the pavement surface and, therefore, to the entire pavement structure. The tire inflation pressure and the tire structure are the two most important factors that influence the contact area and contact pressure at the tire-pavement interface for a given load magnitude. Most pavement analysis procedures assume a circular contact area with uniformly distributed pressure equal to the tire inflation pressure. However, several field and laboratory studies have contradicted these assumptions. Recent Federal Highway Administration (FHWA) studies and other research on the characteristics of the vehicle loading revealed that the loaded area is non-circular, with nonuniform normal as well as interfacial shear stress components (5,6,7).

- *Dynamic Response of Pavement Structure*—It is common knowledge that the loads generated by the moving traffic are highly dynamic. Several field studies have shown that dynamic loads generate pavement responses which are significantly influenced by vehicle speed. The pavement is a layered system and the HMA surface layer exhibits viscoelastic behavior. It has been hypothesized that the viscoelastic nature of the surface layer is the reason for the dependancy of strain response on the vehicle speed. It has been shown by Harr, Sebaaly and Tabatabaee, and more recently by Dai *et al* (Mn/ROAD) that vehicle speed has a significant effect on pavement strain response (8,9,10). The latter two investigations measured the pavement strain response directly by instrumenting the pavements with strain gauges. Sebaaly and Tabatabaee measured longitudinal pavement strain response and reported that the strain reduced by as much as 50% when the vehicle speed increased from 20 mph to 50 mph.

During the past several years, the research team at the University of Nevada has developed a pavement response model that incorporates all of the identified critical factors in evaluating pavement response to vehicle loads (11). It is a moving-load model, which is capable of predicting pavement response (strains, stresses and deflections) and treats the tire-pavement interaction as a moving loaded area. It also accounts for the dynamic nature of the moving load. It is a continuum-based finite-layer approach that uses the Fourier transform technique; therefore, it can handle complex surface loadings such as multiple loads and nonuniform and non-circular tire-pavement contact stresses (normal and shear). The tire imprint can be of any shape, thus making this model suitable to analyze tires and tracks used on off-road equipment. The method is much more computationally efficient than the moving-load models based on the finite element method. The HMA layer is treated as viscoelastic, in which the properties (complex shear modulus and Poisson's ratio) can vary as a function of frequency while the base course and the subgrade are considered linear elastic. The validity of using linear elastic characterization of the base and subgrade layers has been verified by Thompson and Barenberg and by recent studies at Mn/ROAD (10,12).

A computer program 3D-MOVE has been developed incorporating the above solution technique. This program can handle any number of layers with any type of load distribution at the surface. Based on its excellent characteristics, the 3D-MOVE model was selected to model pavement responses under loads imparted by the off-road equipment evaluated in this research. The applicability of the proposed model has been verified using data generated by the commonly used elastic solutions under simple static loading conditions and two full scale field tests (Penn State test track and Mn/ROAD). The results of these verification efforts are summarized below.

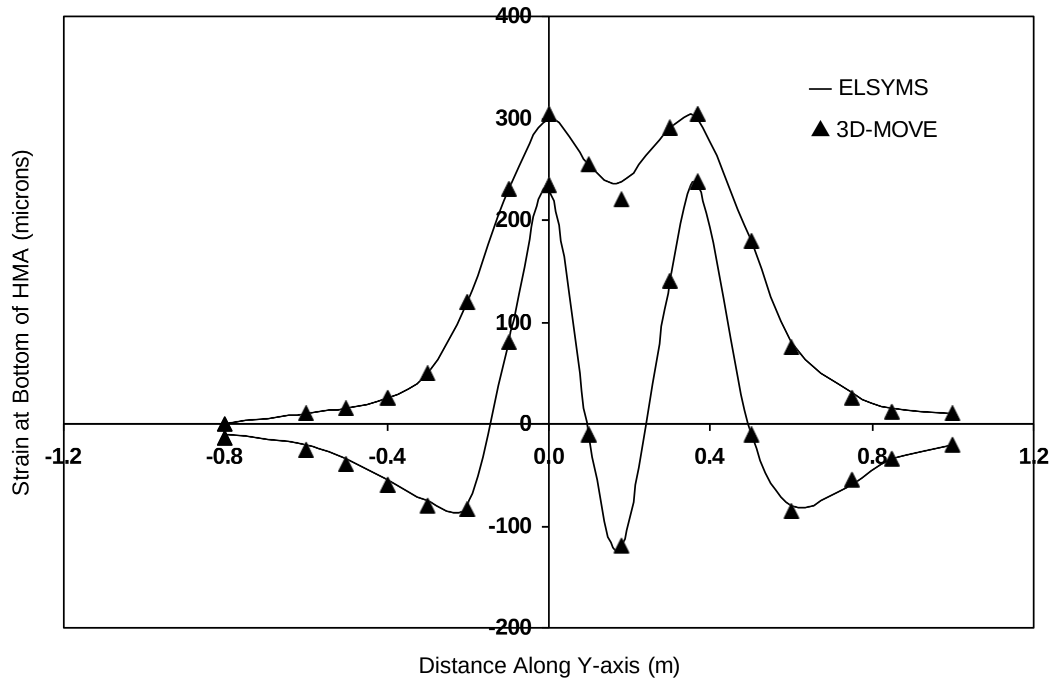


Figure 6: Comparison of Pavement Strains Calculated by 3D-MOVE and Multilayer Elastic Solution

Validation Using Existing Analytical Solutions

There are a number of analytical solutions against which the applicability of the proposed mechanistic model and the ensuing computer program (3D-MOVE) can be verified. Of course, the analytical solutions are available only for many simplified conditions. Since ELSYM5 is one of the widely used programs in pavement studies, it was used to conduct the theoretical verification. The solution technique used in ELSYM5 is based on Burmister's elastic layer theory, while the Fourier transform technique along with finite-layer formulation is used in the 3D-MOVE model. Therefore, validation using ELSYM5 was considered an independent check. Furthermore, this validation using ELSYM5 verified the capability of 3D-MOVE to simulate circular loaded area and its ability to combine layers with different material properties. Figure 6 shows the computed results from ELSYM5 and 3D-MOVE for a typical 3-layer flexible pavement loaded with a single axle equipped with dual tires. The results are within 2%, indicating that the 3D-MOVE is capable of simulating correctly the static circular loads applied to a layered system.

Validation Using Penn State University Test Track Tests

Sebaaly et al. have reported on an extensive full-scale field-testing program sponsored by the Federal Highway Administration (9, 13). The field-testing program included the installation of strain gauges, pressure cells, thermocouples, and displacement gauges to measure the response of in-service pavements under moving truck loads. The gauges were installed at the Pennsylvania State University test track in newly constructed pavement sections. The experimental plan for field testing focused on the longitudinal strain response time history at the bottom of the HMA layer (ϵ_{AC}) as a function of vehicle speed and tire load. A semitrailer-type vehicle with a single drive axle in the front and a tandem axle in the rear was used in the study. The actual field testing occurred during the summer of 1989 over a period of a few months. The material properties for the pavement section were estimated from Falling-Weight Deflectometer (FWD) tests.

The in-situ material properties and the actual axle loads along with the actual pavement structure were used in the 3D-MOVE model to predict the tensile strains at the bottom of the HMA layer under both the single and tandem axles. Figures 7 and 8 show the maximum computed and measured strains for all truck load levels and axles. The diagonal line represents equal computed and measured strain responses. In the vast majority of the cases the computed values are within the range of strains measured in the field tests. There is more disagreement at the higher level of strains. The higher strains are present when the truck is fully loaded and in this case the tire load (dynamic) is expected to be significantly affected by the roughness of the road. This may be the reason for the discrepancy between the computed and measured responses. In light of the variability that can be expected in pavement material properties and tire load generated by the roughness of the road, the comparison can be concluded as excellent.

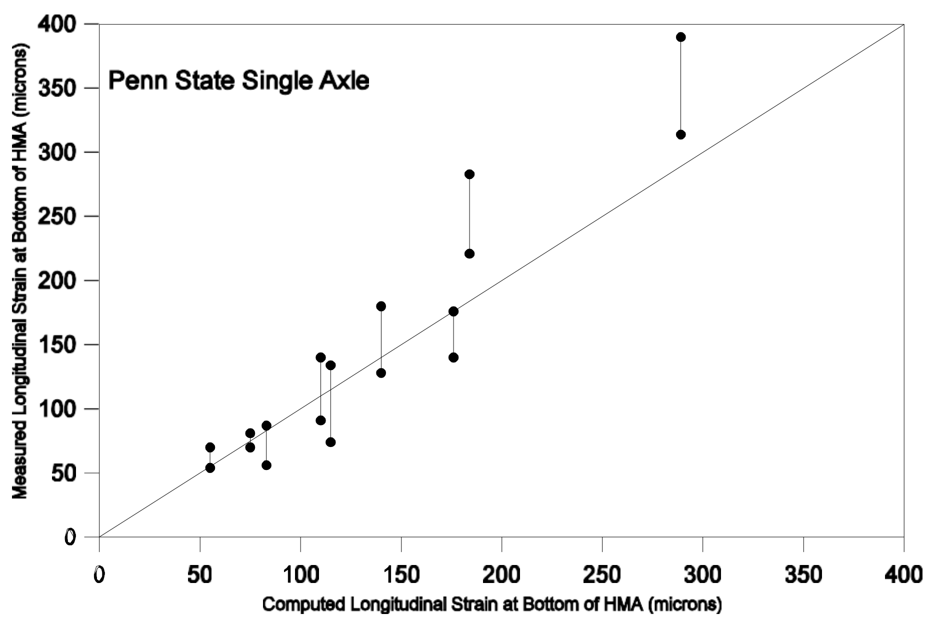


Figure 7: Comparison of Pavement Strains Calculated by 3D-MOVE and Measured at the Penn State Road Test under Single Axle

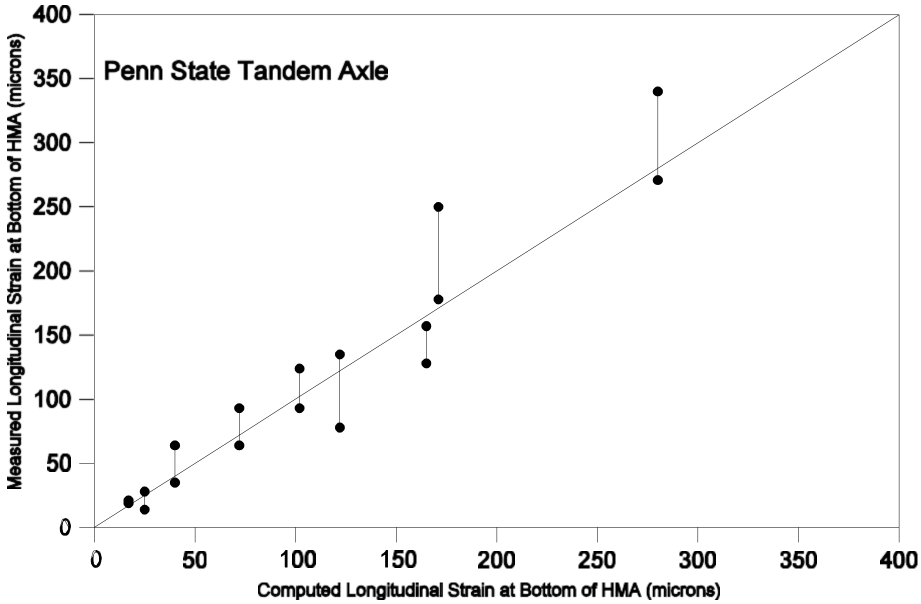


Figure 8: Comparison of Pavement Strains Calculated by 3D-MOVE and Measured at the Penn State Road Test under Tandem Axle

Validation Using Minnesota Road Tests

Dai *et al* have reported on an extensive full-scale field-testing program sponsored by the Minnesota Department of Transportation and Minnesota Road Research Board (10). The field-testing program included the installation of strain gauges, linear variable differential transformers (LVDT), and thermocouples throughout the pavement and subgrade layers to measure pavement strains and deflections due to moving truck loads and environmental conditions such as temperature and moisture content. The gauges were installed at the Minnesota Road Research project test track located about 40 miles northwest of Minneapolis/St. Paul in Ostego, Minnesota on and adjacent to Interstate 94. Pavement layer properties were also assessed using FWD testing at the time of the field tests.

The in-situ material properties and the actual axle loads along with the actual pavement structure were used in the 3D-MOVE model to predict the tensile strains at the bottom of the HMA layer under tandem axles. Figures 9 and 10 compare the maximum pavement strains computed by 3D-MOVE along with those measured for the tandem axle loading. In the vast majority of the cases, the computed values are within the range of field measured strains. The deviation of the computed response relative to the measured range is believed to be due to the variability that can be expected in pavement material properties and the variability in tire load generated by the road roughness.

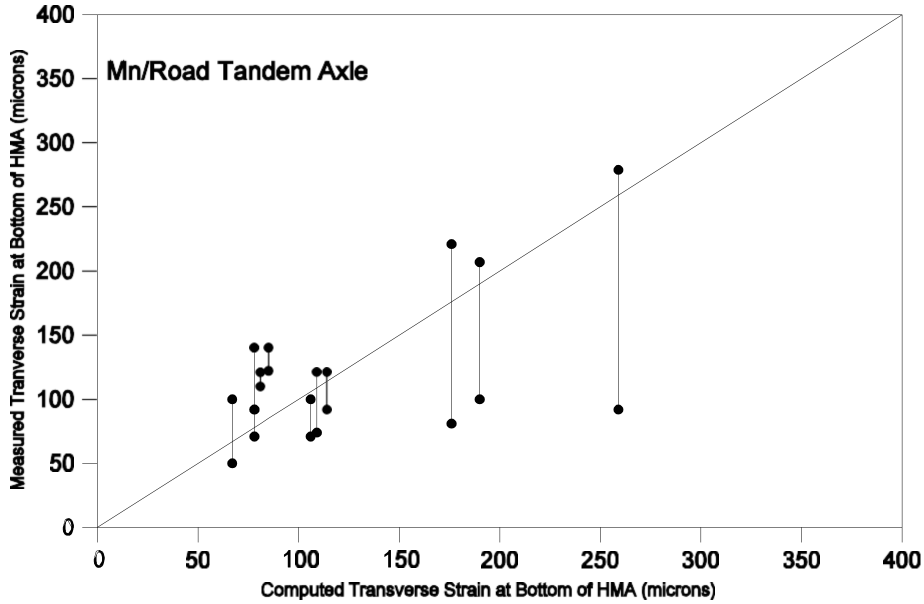


Figure 10: Comparison of Pavement Transverse Strains Calculated by 3D-MOVE and Measured at Mn/Road under Tandem Axle

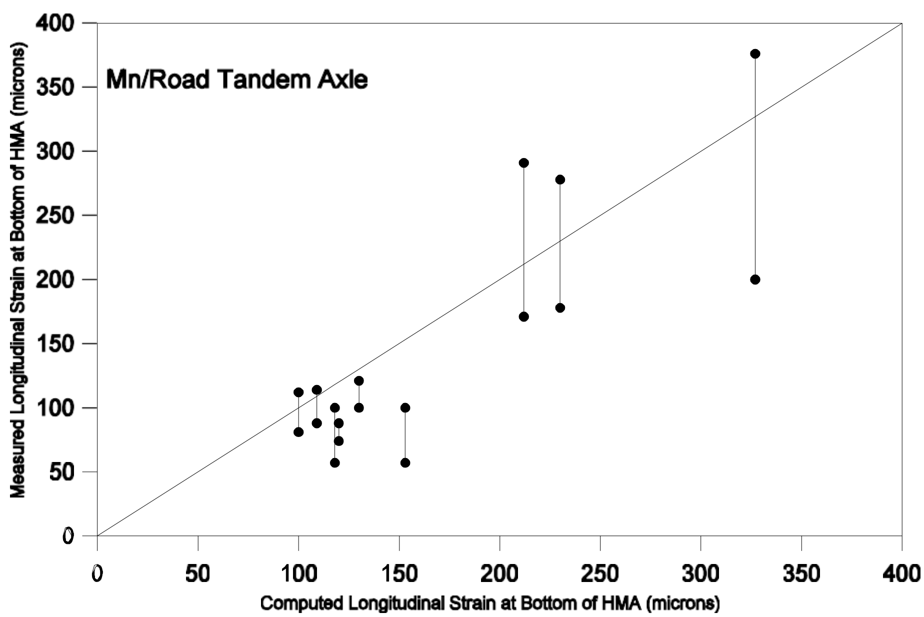


Figure 9: Comparison of Pavement Longitudinal Strains Calculated by 3D-MOVE3 and Measured at Mn/Road under Tandem Axle

Task 5: Review Response Model and Confirm Field Validation Plans

Meet with Technical Panel to review the pavement response model and to confirm plans for its field validation.

The second meeting with the project panel was held on June 7, 2000 in Gettysburg, SD. The principal investigator presented the results of the validation studies conducted on the proposed theoretical model (3D-MOVE) and the field testing plans. Some of the major recommendations included the following.

- Select the 3D-MOVE model to predict pavement responses under off-road equipment.
- The list of equipment to be tested during in the field should include: Terragators, grain carts, scraper, and tracked tractor.
- The field testing program should cover testing the selected equipment at the empty and loaded conditions during the fall, spring and summer seasons.

Task 6: Measure In-Situ Response

Measure the in-situ response of representative granular and flexible pavements under load applied by off-road equipment tires and tracks. Measurements should span seasons during full year, on three pavement types (gravel, thin, and thick asphalt) and two soil types (weathered shale typical of central and western South Dakota and silty soils typical of eastern South Dakota), under representative equipment types.

Construction of Test Sections

In order to achieve the objective of this task, pavement sites were identified on clayey and silty soils. At each site, a thin flexible pavement, a thick flexible pavement, and a gravel or blotter road were identified. A total of six pavement sections were constructed and instrumented during the summer of 2000.

Each flexible pavement section was instrumented with the following:

- Four strain gauges at the bottom of the HMA layer
- One pressure cell at the middle of the CAB layer
- One pressure cell 4" below the top of the subgrade layer
- One single layer deflectometer
- Temperature sensors throughout the pavement depth

The blotter surface section was instrumented with the following:

- One pressure cell at the middle of the CAB layer
- One pressure cell 4" below the top of the subgrade layer
- One single layer deflectometer

The gravel surface section was instrumented with the following:

- One pressure cell 7" below the surface
- One pressure cell 10" below the surface
- One single layer deflectometer

The sections on US212 were new construction, while the sections on SD26 consisted of an HMA overlay over an old flexible pavement. Each section was 100 ft long with 300-ft transition between the sections on US212 and 400-ft transition between the sections on SD26. All instrumentation was installed in the outer wheel path. Figures 11 through 14 show the layout of the instrumentation for the six sections. Figures 15 through 18 show the installation of strain gauges and pressure cells. The strain gauges were first laid on top of the base and then covered with a thin layer of HMA to protect them from sharp aggregates during lay-down and compaction activities. The delivery trucks were guided to avoid running their tires directly over the strain gauges. After the overlay materials were laid over the strain gauges, normal construction operations were followed. The pressure cells were installed over a thin layer of sand to allow for accurate leveling of the gauge. Once the pressure cell was leveled, base materials were compacted using a hand compactor (i.e. whacker) as shown in Figure 18. The single layer deflectometers were installed after the construction was completed.

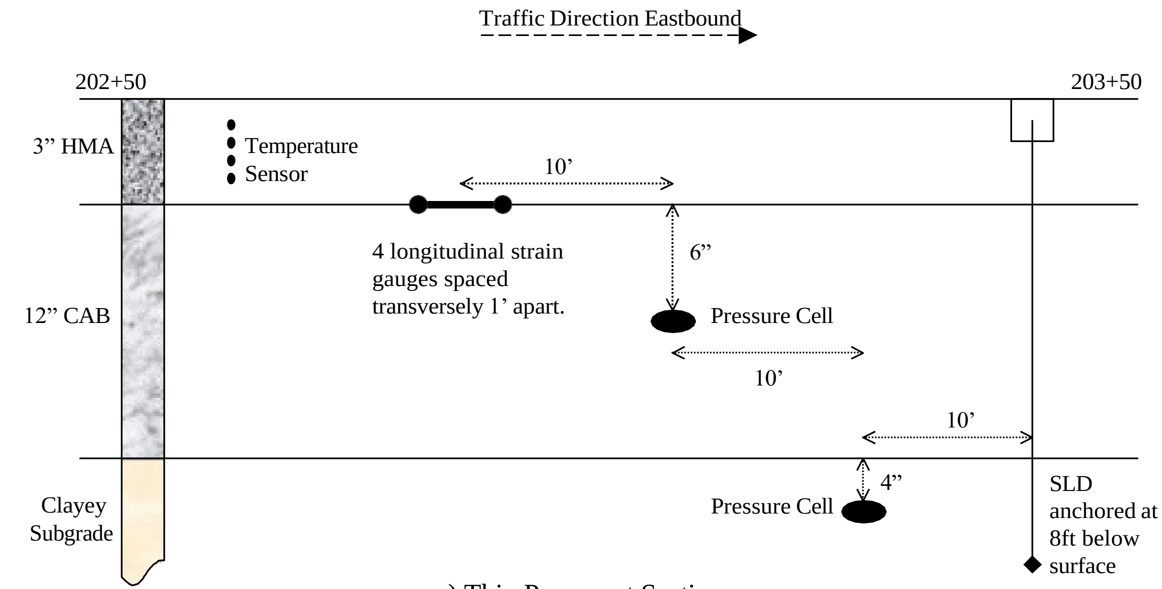
One hundred percent of the pressure cells were operational throughout the entire testing program. The strain gauges experienced 85 percent survival rate throughout the testing program. The single layer deflectometer on the blotter section had to be replaced after the spring season testing due to the failure of the base course materials during the wet season testing

Field Testing Plan

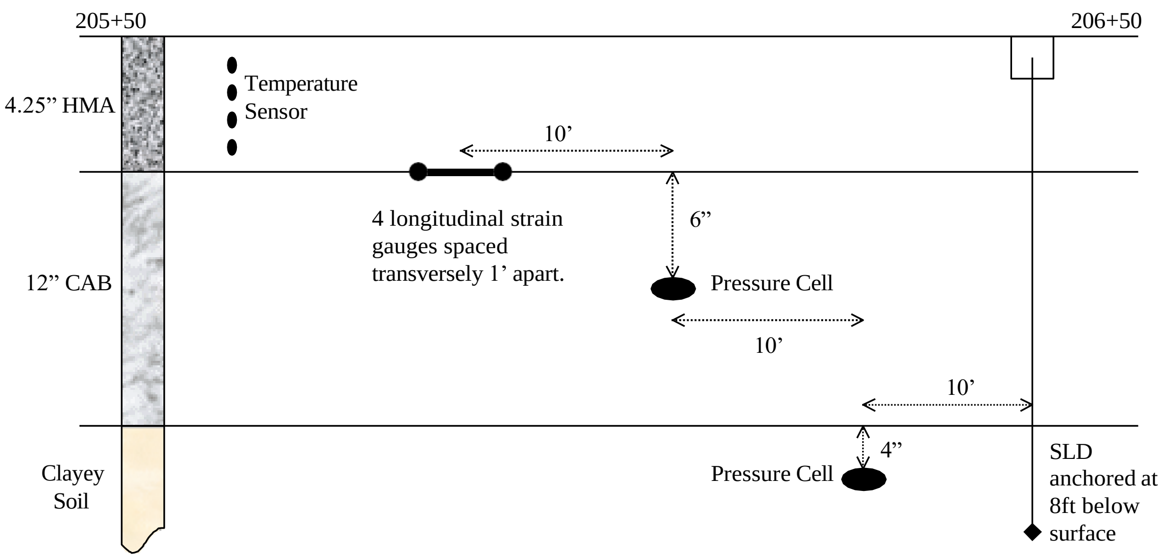
Field testing programs were conducted on September 14-15, 2000, April 4-5, 2001, and August 28-29, 2001. Table 3 summarizes the conditions for the field testing programs. Each vehicle-load combination was driven at its normal operating speed for a minimum of five replicate runs. The single axle truck was tested at various time intervals during the day at speeds consistent with the off-road equipment being tested at the time. The same equipment was tested on all flexible, blotter, and gravel surface sections following the same field testing plan.

Measurement of Axle Loads

The South Dakota Highway Patrol measured the axle loads and tire pressures during the field testing programs. Axle loads were measured using static scales used in load enforcement activities. The axle load data showed that there were some minor differences among the axle loads used on different sections. These differences were caused by the fact that vehicles may not have been loaded exactly to the same level every time.

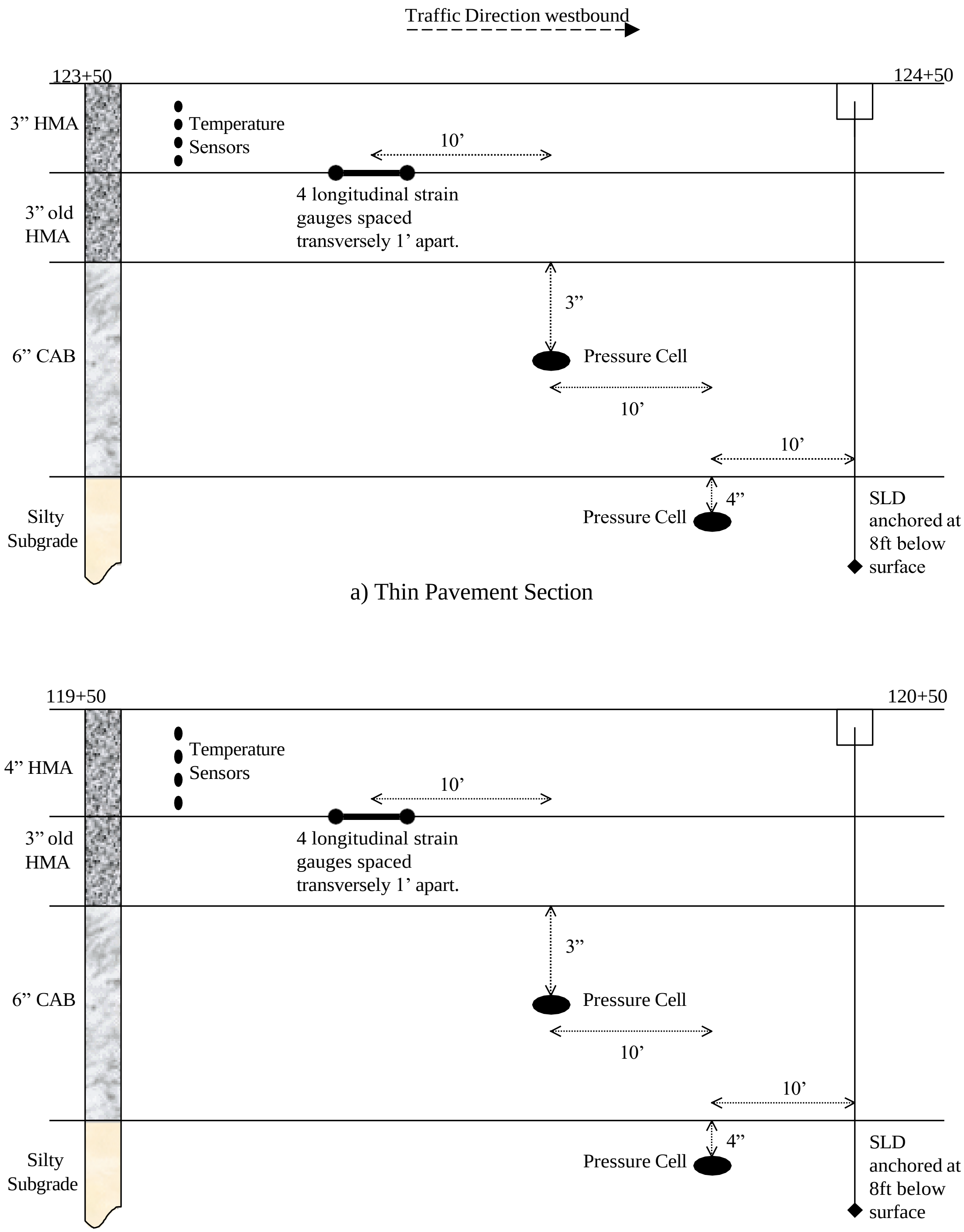


a) Thin Pavement Section



b) Thick Pavement Section

Figure 11: Flexible Pavement Sections on US212



a) Thin Pavement Section

b) Thick Pavement Section

Figure 12: Flexible Pavement Sections on SD26

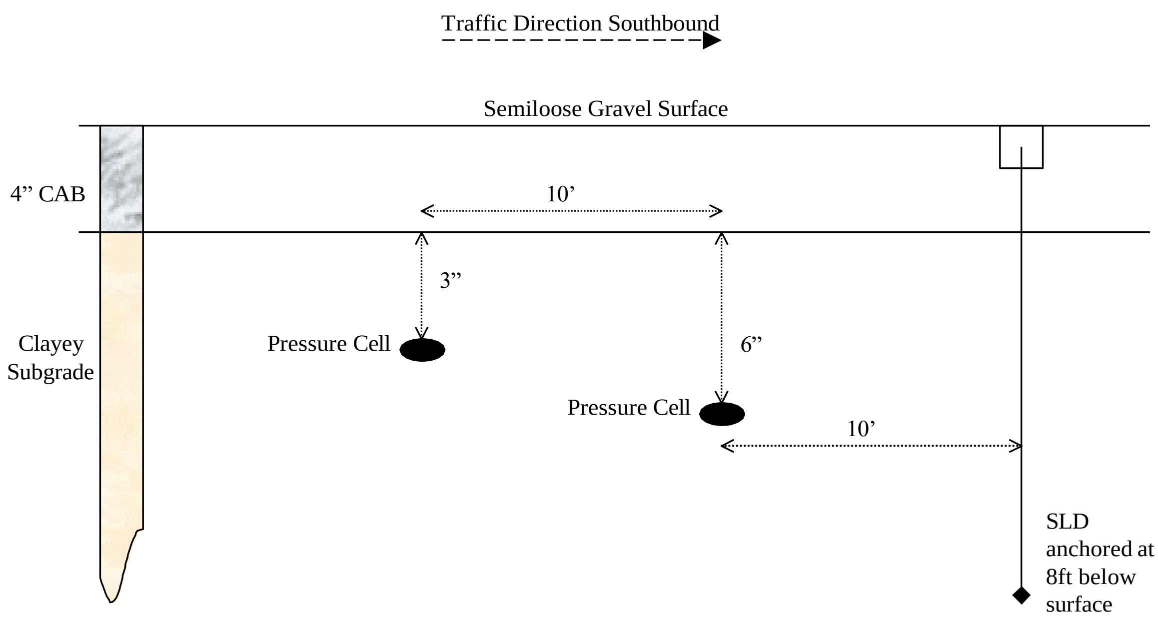


Figure 13: Gravel Pavement Section near US212

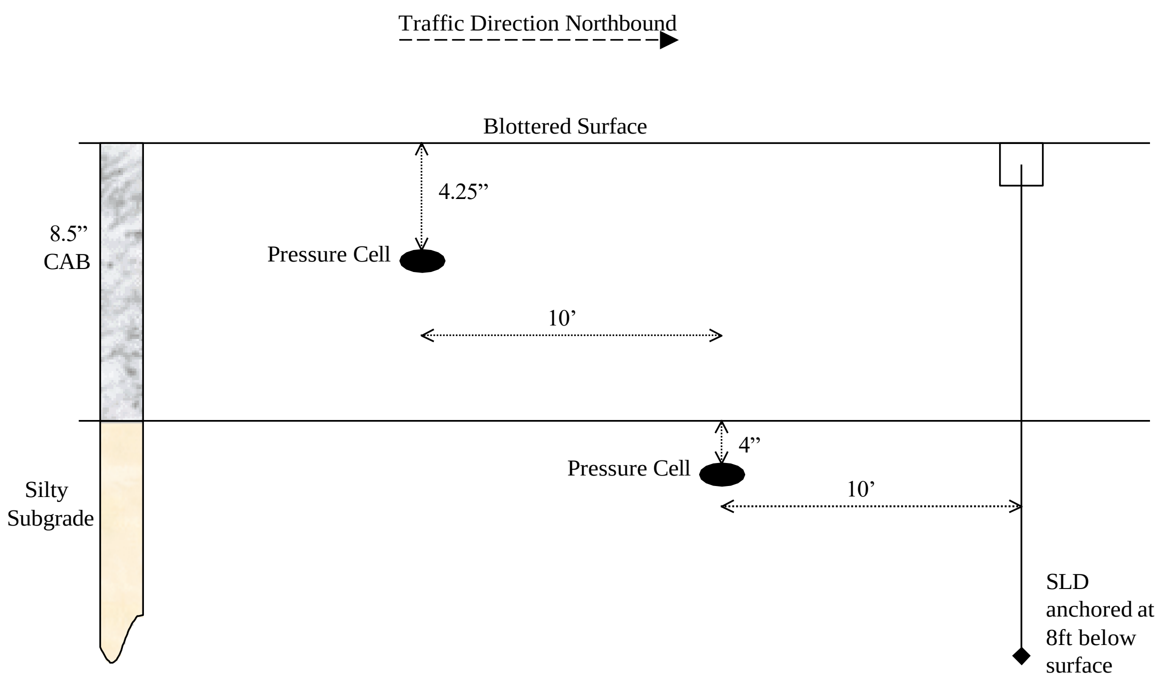


Figure 14: Blotter Pavement Section on 348th Avenue near SD26

Figure 15: Layout of the Strain Gauges on Top of the Base Course

Figure 16: Strain Gauges Covered with HMA Mix and Being Overlaid

Figure 17: Pressure Cell Installed 4" Into Subgrade

Figure 18: Base Materials Being Compacted on Top of the Pressure Cell

Table 3: Vehicle-Load Combinations Tested in the Field

Vehicle	Condition	Speed (mph)	Tire Pressure (psi)	Nominal Axle Load (kips) Fall 2000	Spring 2001	Summer 2001
Single Axle Truck	Loaded	40	100-110	17.9	18.3	17.9
Terragator 8103	Empty	40	30-36	18.7	18.7	17.4
Terragator 8144	Empty	40	30-36	18.1	17.9	14.6
Terragator 8103	Loaded	40	30-36	33.1	33.9	28.5
Terragator 8144	Loaded	40	30-36	31.4	30.6	26.7
Single Axle Truck	Loaded	20	100-110	17.9	18.3	17.9
Scraper Front Axle	Empty	20	55-60	59.7	72.9	not tested
Scraper Rear Axle	Empty	20	55-60	41.4	44.8	not tested
Grain Cart	Legal Load	20	16-30	21	20.8	20.2
Grain Cart	Over Legal	20	16-30	31.1	33.1	49.5
Tracked Tractor	Empty	20	na	25.4	25.4	not tested

Analysis of Field Data

This effort consisted of processing the data from the data acquisition software, which involved identifying the responses of the individual gauges as the pavement was loaded by the various vehicles. Figures 19, 20, and 21 show typical responses of the pressure, deflection, and strain gauges, respectively. The peak responses were identified from each vehicle pass and are summarized in Appendix A.

As indicated in Table 3, the grain cart was tested at the following conditions:

- Grain Cart at legal load: GCL
- Grain Cart at 60% above legal load: GC+60%
- Grain Cart at full load: GC+150%

The GCL condition was tested during the three seasons, the GC+60% was tested during the fall and spring seasons, and the GCL+150% was tested during the summer season only.

The field testing program collected the pavement response under five replicates of each combination of test vehicle and load level. In the case of pressure and deflection measurements, the replicate data were examined for repeatability and the average of the most repeatable set of measurements was calculated and reported. The repeatability of the pressure and deflection measurements was excellent (coefficient of variations less than 5%). In the case of strain, the responses from all four strain gauges were examined under each run and the maximum of all replicates was reported.

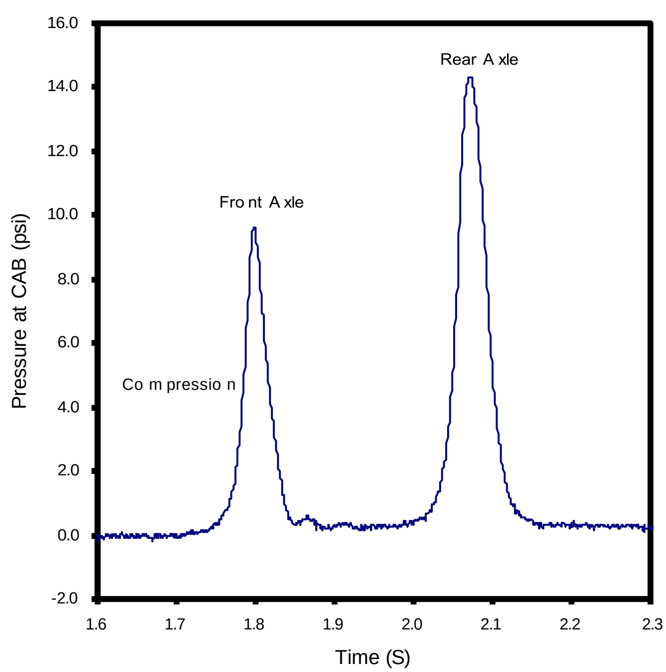


Figure 19: Typical Pressure Response under Terragator 8144 Loaded on US212 Thin Section

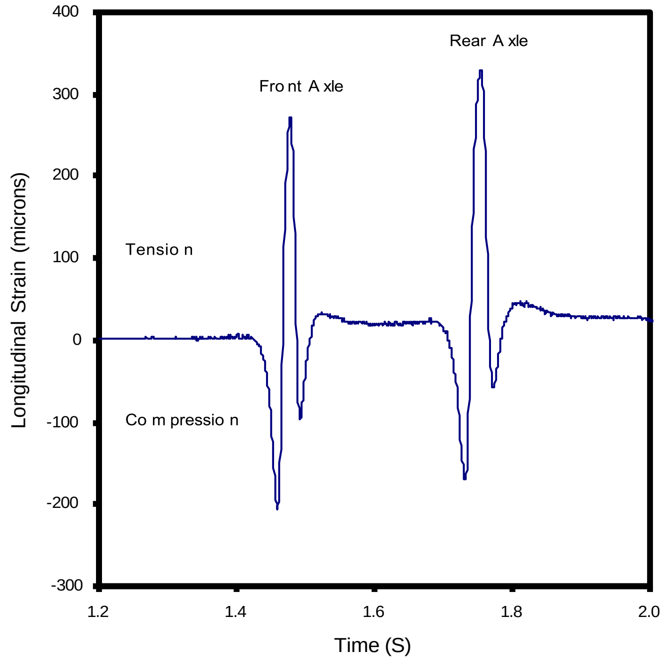


Figure 20: Typical Strain Response Under Loaded Terragator 8144 on US212 Thin Section

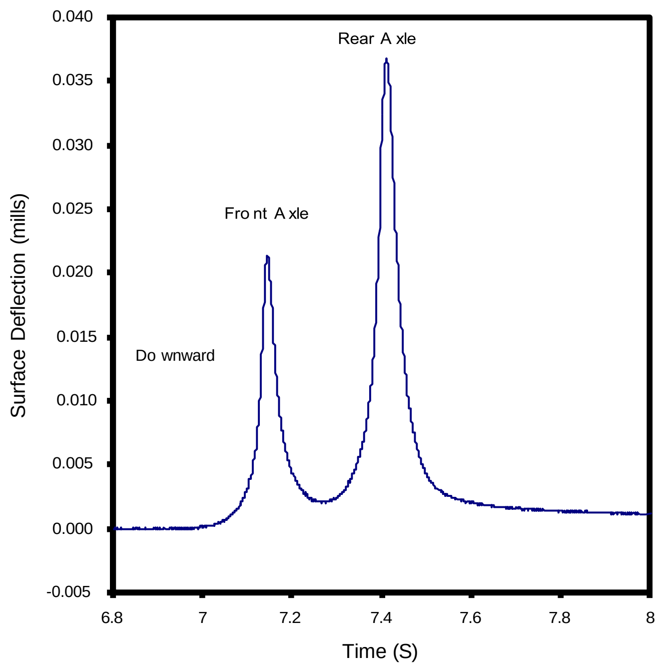


Figure 21: Typical Deflection Response under Loaded Terragator 8144 on US212 Thin Section

The data in Appendix A are missing some entries labeled as NC or NR. The NC symbol indicates that the data were not collected during the field testing program due to the unavailability of the specific test vehicle-load level combination. The NR symbol indicates that the data were collected but not reported as part of the study. This situation occurred when the measured data showed some erratic behavior without any justification. Such data were considered the results of malfunctioning instrumentation or inappropriate conditions of the test such as the vehicle being repeatedly far from the location of the sensors. The NC condition occurred in 0.75 % of the data and the NR condition occurred in 3 % of the data. The low percentages of the NC and NR conditions were considered excellent for such an extensive field testing program.

Since the ultimate objective of the data presented in Appendix A was to assess the relative impact of the various vehicles as compared to the standard 18,000-lb single axle truck (loaded dump truck), these analyses were conducted under the following guidelines:

- A pressure measurement less than 5 psi is below the accuracy of the measuring sensor.
- A pressure measurement less than 5 psi does not impose a significant damage to the pavement.
- A deflection measurement less than $5x10^{-3}$ in (5 mils) is below the accuracy of the measuring sensor.
- A deflection measurement less than $5x10^{-3}$ in (5 mils) does not impose any damage to the pavement.
- A strain measurement less than 25 microns is below the accuracy of the measuring sensor.
- A strain measurement less than 25 microns does not impose any damage to the pavement.

Applying the above criteria to the field data in Appendix A resulted in excluding a larger number of the subgrade responses than the base and surface layer responses.

Impact of Off-Road Equipment Based on Field Measurements

One objective of the field testing program was to assess the impact of off-road equipment on pavements using actual in-situ pavement responses. Field testing was conducted during the fall, spring, and summer seasons. The fall season represents a warm HMA layer (i.e. average pavement temperature of 95^{o}F) and a moist subgrade. The spring season represents a cold HMA layer (i.e. average pavement temperature of 41^{o}F) and a wet subgrade. The summer season represents a hot HMA layer (i.e. average pavement temperature of 108^{o}F) and a dry subgrade. Using the field measurements, the impact of the following factors were evaluated:

- pavement type: paved and unpaved
- pavement thickness: thin and thick
- subgrade type: clay and silt
- season: fall, spring, and summer

This analysis compared the impact of the various equipment relative to the 18,000-lb single axle truck. The pavement response under each combination of vehicle-load level (Appendix A) was divided by the pavement response under the 18,000-lb single axle. This analysis excluded the pavement responses that violated the criteria set forth in the previous section. Appendix B summarizes the ratios of the measured pavement responses. When using the pavement response ratios to assess the relative damage of the various vehicle-load combinations, the following guidelines were followed:

- Field measurements include the impact of dynamic load profiles induced by the interaction between road roughness and vehicle suspension. The interaction between road roughness and vehicle suspension generates a transient dynamic load that changes in magnitude along the travel path of the vehicle. The transient dynamic load profile is not exactly repeatable, introducing variations among the measured pavement responses under replicate test runs.

- Field measurements include the effect of embedding sensors within a homogenous material. Placing solid instruments—such as strain gauges, pressure cells, and single layer deflectometers—within the asphalt concrete, base, and subgrade layers disturbs the internal state of these layers and introduces variations into the measured responses.

- Field measurements include the accuracy and resolution of the measuring sensors, which at best can be at the 5 percent level. For example, a pressure sensor rated up to 100 psi pressure, under ideal conditions, can be repeatable and accurate for measuring pressures in the range of 5 to 95 psi.

- Field measurements include electrical noise which can be transmitted through the wires, the data acquisition system, and the computer. The analysis of the field data showed that the electrical noise levels were very minimal and did not present a problem.

Investigating each of the sources independently, it was decided that their compounded impact could be in the range of ± 30%. This indicates that only the combinations of vehicle-load level producing a response ratio greater than 1.30 should be considered significantly more damaging than the 18,000-lb single axle truck.

Impact of Agricultural Equipment

Table 4 summarizes the agricultural vehicle-load level combinations resulting in ratios higher than 1.30. A "√" entry in the table indicates that the vehicle-load level combination creates significant damage to the pavement as compared to the 18,000-lb single axle truck. Figures 22-27 present a graphical comparison of the various ratios. The data summarized in Table 4 and Figures 22-27 can be used to assess the effects of vehicle type, season, soil type, and pavement structure on the impact of the various vehicle-load level combinations. While evaluating the data in Table 4 and Figures 22-27, it should be noted that: a) the tracked tractor was not tested during August, 2001 (summer); b) the gravel section was not tested during August, 2001; c) the GCL+60% was not tested during August, 2001; and d) the GCL+150% was only tested during August, 2001. Based on the summary of the field testing data presented in Table 4 and comparisons presented in Figures 22 through 27, the following conclusions can be made:

- The Tracked Tractor was not more damaging than the 18,000-lb single axle truck on both unpaved and paved pavements.

- The unloaded Terragators 8103 and 8144 were more damaging than the 18,000-lb single axle truck on gravel and blotter pavements during the Spring and Summer seasons.

- The loaded Terragators 8103 and 8144 were more damaging than the 18,000-lb single axle truck on gravel, blotter, and flexible pavements during all three seasons.

- The Grain Cart loaded at the legal limit was more damaging than the 18,000-lb single axle truck on gravel, blotter, and flexible pavements over silty soil during the Spring and Summer seasons.

- The Grain Cart loaded over the legal limit was more damaging than the 18,000-lb single axle truck on gravel, blotter, and flexible pavements during all three seasons.

- The cold HMA layer during the spring testing significantly reduced the pressure and strain responses while the surface deflection was influenced more by the wet conditions of the subgrade. The strain gauges on the SD26 sections were placed at the bottom of the new HMA layer which located them near the center of a composite HMA layer (i.e. 3 in or 4 in of new HMA and 3 in of old HMA). This location represents the zone where strains are changing from compression to tension making the magnitude of the measured strains highly sensitive to in-situ conditions. Nevertheless, the measured strains on SD26 sections were valuable in assessing the damage imposed by heavy equipment relative to the 18,000-lb single axle truck on overlaid flexible pavements, which represents the condition of a great number of flexible pavements in South Dakota and throughout the nation.

- The strain ratio on US212 identified fewer damaging vehicles than the strain ratios measured on SD26. This behavior was caused by the lower bending strength of the US212 sections as compared to the SD26 sections. The SD26 sections are built over a 3" old HMA layer that contributed to their higher bending strength. With US212 having lower bending strength, the strains generated under the 18,000-lb. single axle truck were high, which made the strain ratios lower than 1.30 except for extreme cases.

- The additional 1" thickness of the HMA layer did not have a significant impact on the damage of the various vehicle-load level combinations as compared to the 18,000-lb single axle truck. However, when absolute values of the pavement responses are compared, the additional 1" of HMA showed some reductions in the measured pressures and deflections.

- The type of subgrade soil (e.g. clay or silt) had an impact on the relative damage of the various vehicles. This is shown by the significant variations in the response ratios between the gravel and blotter sections and between the US212 and SD26 sections.

- The impact of vehicle speed on flexible pavements was evaluated by comparing pavement responses measured under the 18,000-lb single axle truck at speeds of 40 and 20 mph. The analysis of this data showed that reducing the speed from 40 mph to 20 mph increased the measured strains by 30-40%, while the speed impact on the measured pressures and deflections was insignificant.

The preliminary recommendations based solely on the field testing efforts can be summarized as follows:

- The Tracked Tractor weighing less than 25,500 lb per axle should not be subjected to any limitations.

- The Terragators should be subjected to certain limitations depending on their expected load levels (unloaded vs. loaded).

- The Grain Carts should be subjected to certain limitations depending on their expected load levels (legal vs. over legal).

These preliminary recommendations led to the expanded analysis presented in the following sections.

Impact of the Scraper

As can be seen from Table 3, two different scrapers were tested: one during Fall 2000 and one during Spring 2001. Both scrapers used the same tire type and tire inflation pressure, but had different load levels. The scraper tested during the fall season had 59,700 lb on the front axle and 41,400 lb on the rear axle while the scraper tested during the spring season had 72,900 lb on the front axle and 44,750 lb on the rear axle. The variations in the scrapers' axle loads with similar tire type and inflation pressure provided an opportunity to compare the impact of the scraper at four load levels ranging from 41,400 lb/axle to 72,900 lb/axle.

Figures 28 and 29 show the pavement response ratios generated under both the front and rear axles of the scrapers tested during the fall and spring seasons, respectively. It should be noted that the gravel and blotter sections were not instrumented for strain measurement. Inspection of the data in these figures leads to the conclusion that the scraper was significantly more damaging than the 18,000-lb single axle truck at axle load levels ranging from 41,400 to 72,900 lb/axle. Even though the rear axle carried slightly lower load, it still imposed significantly more pavement damage than the 18,000-lb single axle load. Therefore, it is recommended that neither the front nor the rear axle of the scraper be allowed to travel on flexible and unpaved roads in South Dakota.

During the spring testing on SD26, a short experiment was conducted to compare pavement responses generated by the scraper to those generated by an 11-axle semitrailer loaded with the scraper. The comparison of the measured data indicated the following:

- Surface deflection caused by the scraper was 5-21 times the surface deflection caused by the 11-axle semitrailer loaded with the same scraper.

- The pressures in the base and subgrade caused by the scraper were 3-9 times the pressures caused by the 11-axle semitrailer loaded with the same scraper.

- The strains at the bottom of the HMA layer caused by the scraper were 5-21 times the strains caused by the 11-axle semitrailer loaded with the same scraper.

The above ranges represent comparisons of the pavement responses under the scraper with those measured under the various axles of the 11-axle semitrailer. The lower end represents the ratio of the response under the scraper over the response under the heaviest axle of the semitrailer while the higher end represents the ratio of the response under the scraper over the response under the lightest axle of the semitrailer. It should be noted that this comparison was conducted based on a single run without any effort to establish repeatable results.

Table 4: Summary of Vehicle-Load Level Combinations Considered Damaging to Pavements Relative to the 18,000-lb Single Axle Truck

		Base Pressure								Subgrade Pressure							
Section	Season	8103	8144	8103L	8144L	TT	GCL	GCL +60%	GCL +150%	8103	8144	8103L	8144L	TT	GCL	GCL +60%	GCL +150%
Gravel	Fall																
	Spring																
Blotter	Fall																
	Spring																
	Summer																
US212 Thin	Fall																
	Spring																
	Summer																
US212 Thick	Fall																
	Spring																
	Summer																
SD26 Thin	Fall																
	Spring																
	Summer																
SD26 Thick	Fall																
	Spring																
	Summer																

NOTE: Scraper was not tested during the Summer 2001 field testing program.

Table 4: Summary of Vehicle-Load Level Combinations Considered Damaging to Pavements Relative to the 18,000-lb Single Axle Truck (continued)

		Surface Deflection								Tensile Strain							
Section	Season	8103	8144	8103L	8144L	TT	GCL	GCL +60%	GCL +150%	8103	8144	8103L	8144L	TT	GCL	GCL +60%	GCL +150%
Gravel	Fall																
	Spring																
Blotter	Fall																
	Spring																
	Summer																
US212 Thin	Fall																
	Spring																
	Summer																
US212 Thick	Fall																
	Spring																
	Summer																
SD26 Thin	Fall																
	Spring																
	Summer																
SD26 Thick	Fall																
	Spring																
	Summer																

NOTE: Scraper was not tested during the Summer 2001 field testing program.

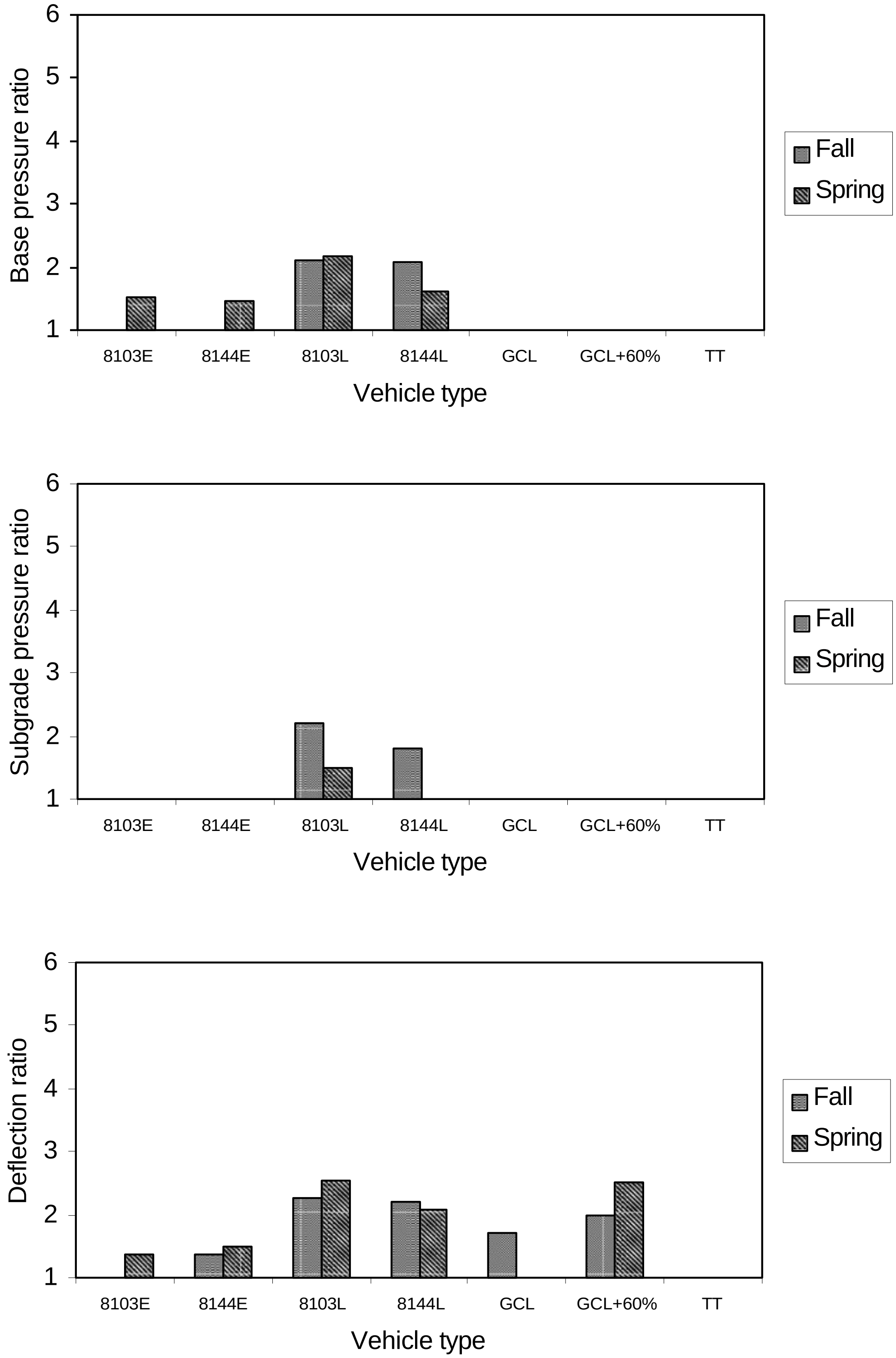


Figure 22: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Responses Caused by 18,000-lb Single Axle Truck, Gravel Section

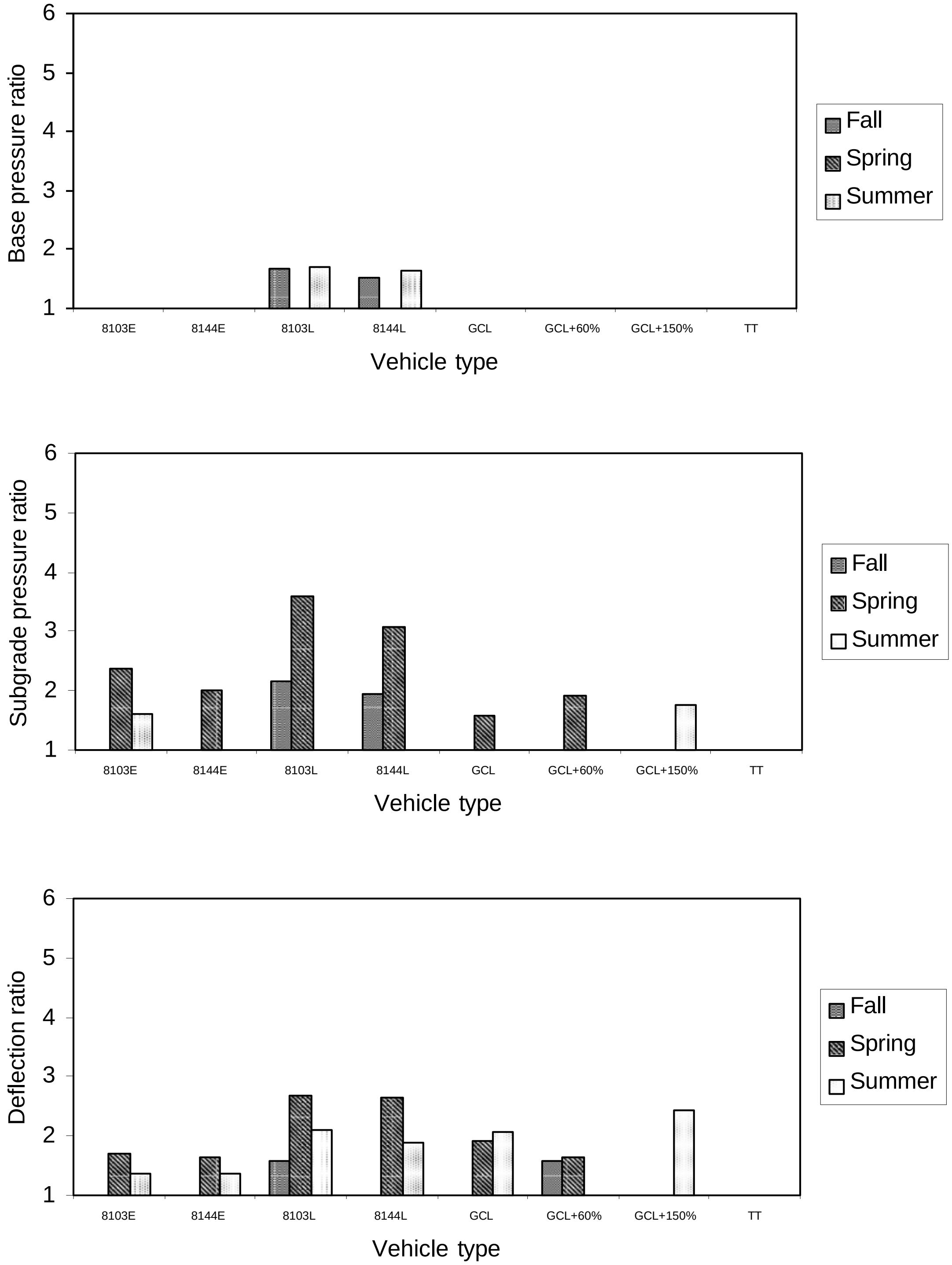


Figure 23: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Responses Caused by 18,000-lb Single Axle Truck, Blotter Section

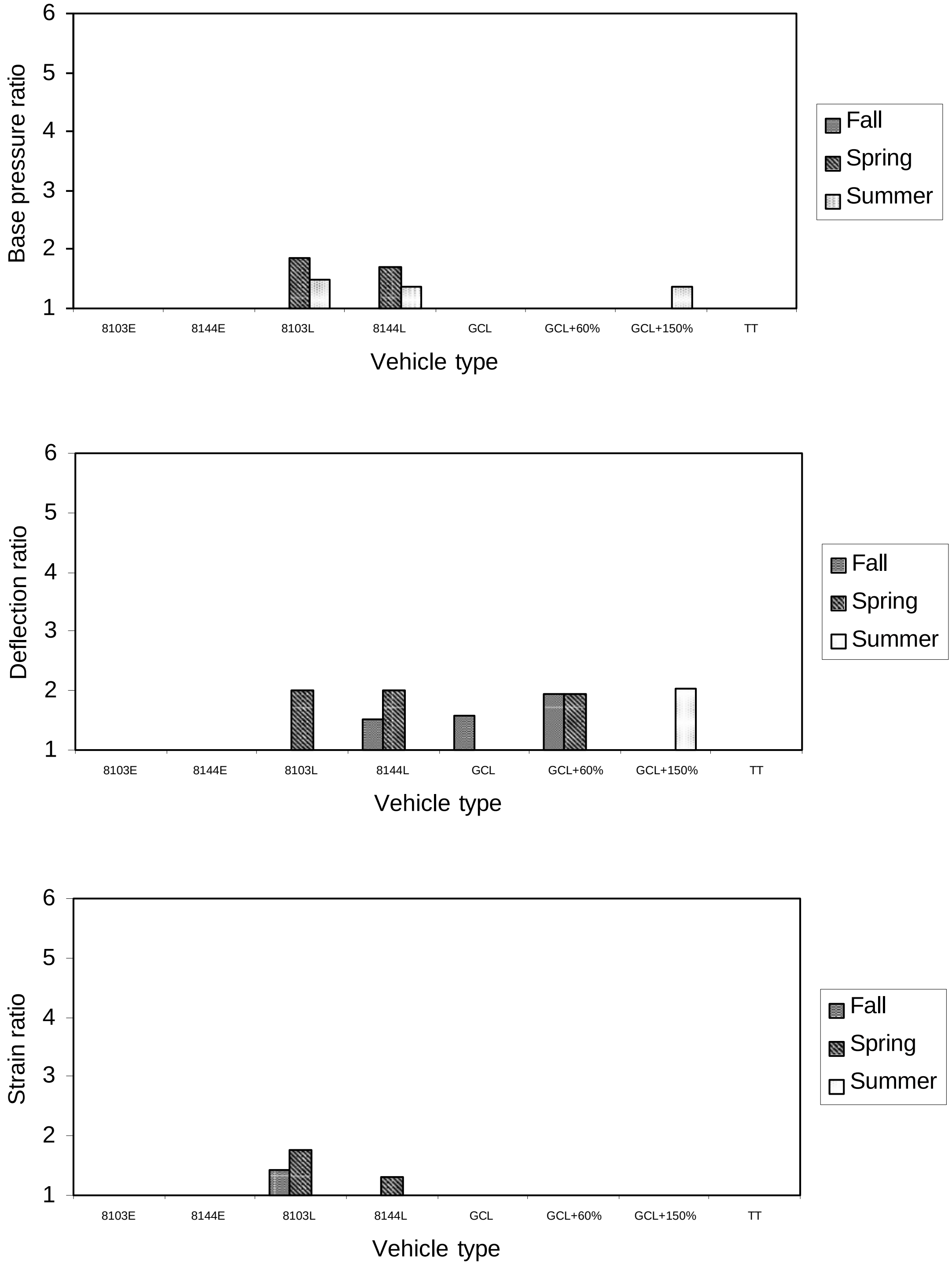


Figure 24: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Responses Caused by 18,000 Lb Single Axle Truck, US212 Thin Section

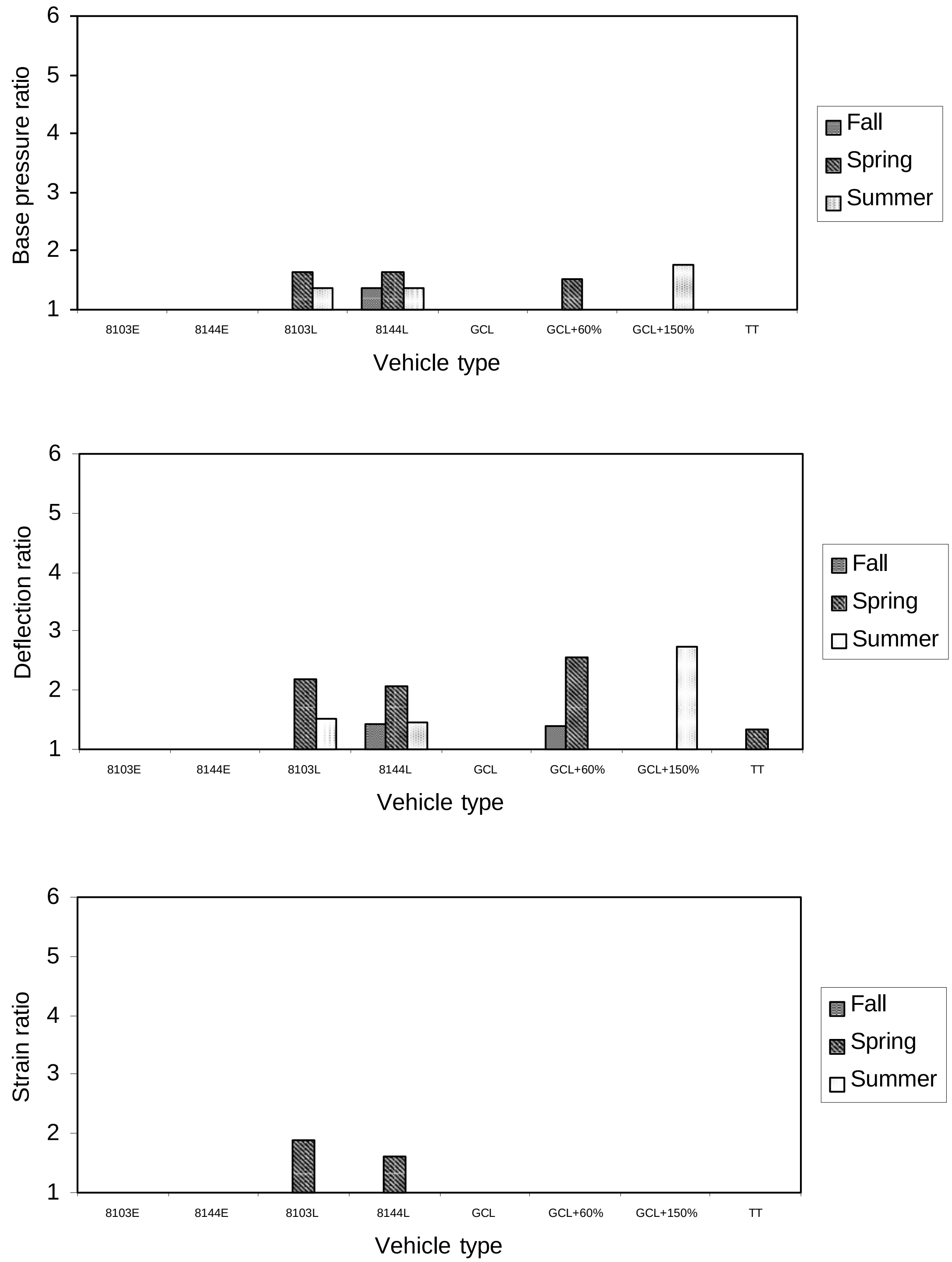


Figure 25: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Responses Caused by 18,000-lb Single Axle Truck, US212 Thick Section

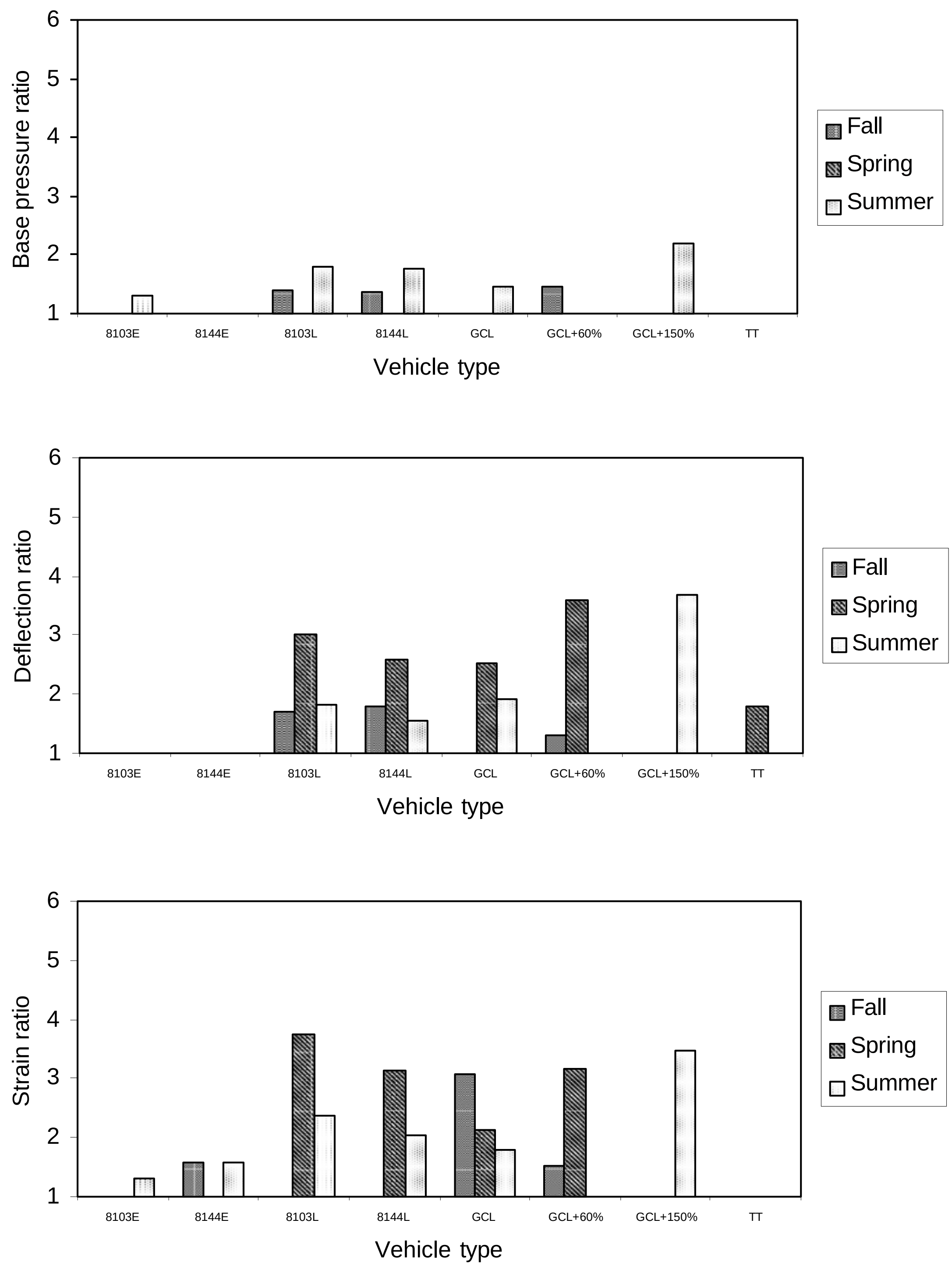


Figure 26: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Responses Caused by 18,000 Lb Single Axle Truck, SD26 Thin Section

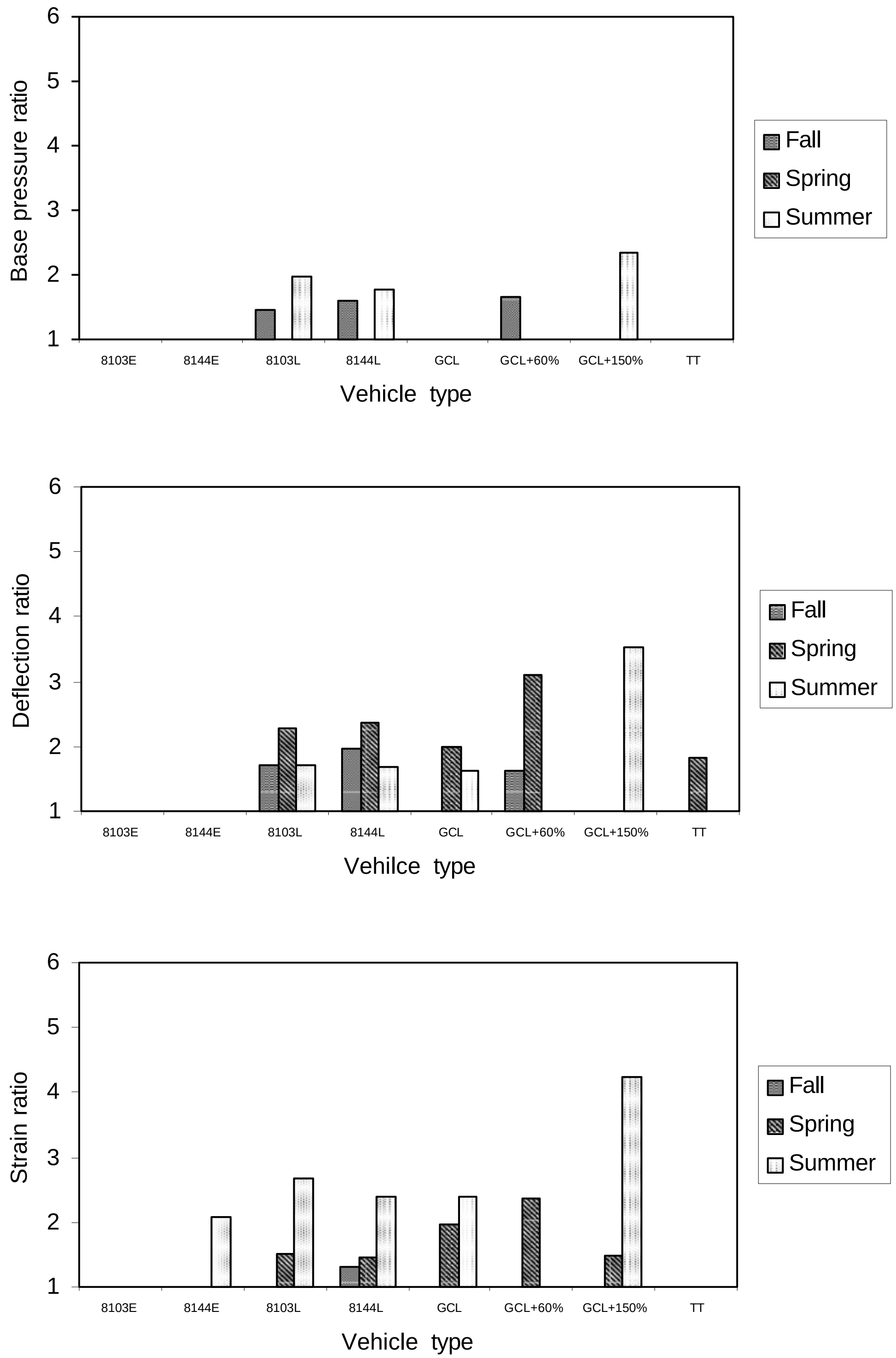


Figure 27: Ratios of Pavement Responses Caused by Off-Road Equipment over Pavement Response Caused by 18,000-lb Single Axle Truck, SD26 Thick Section

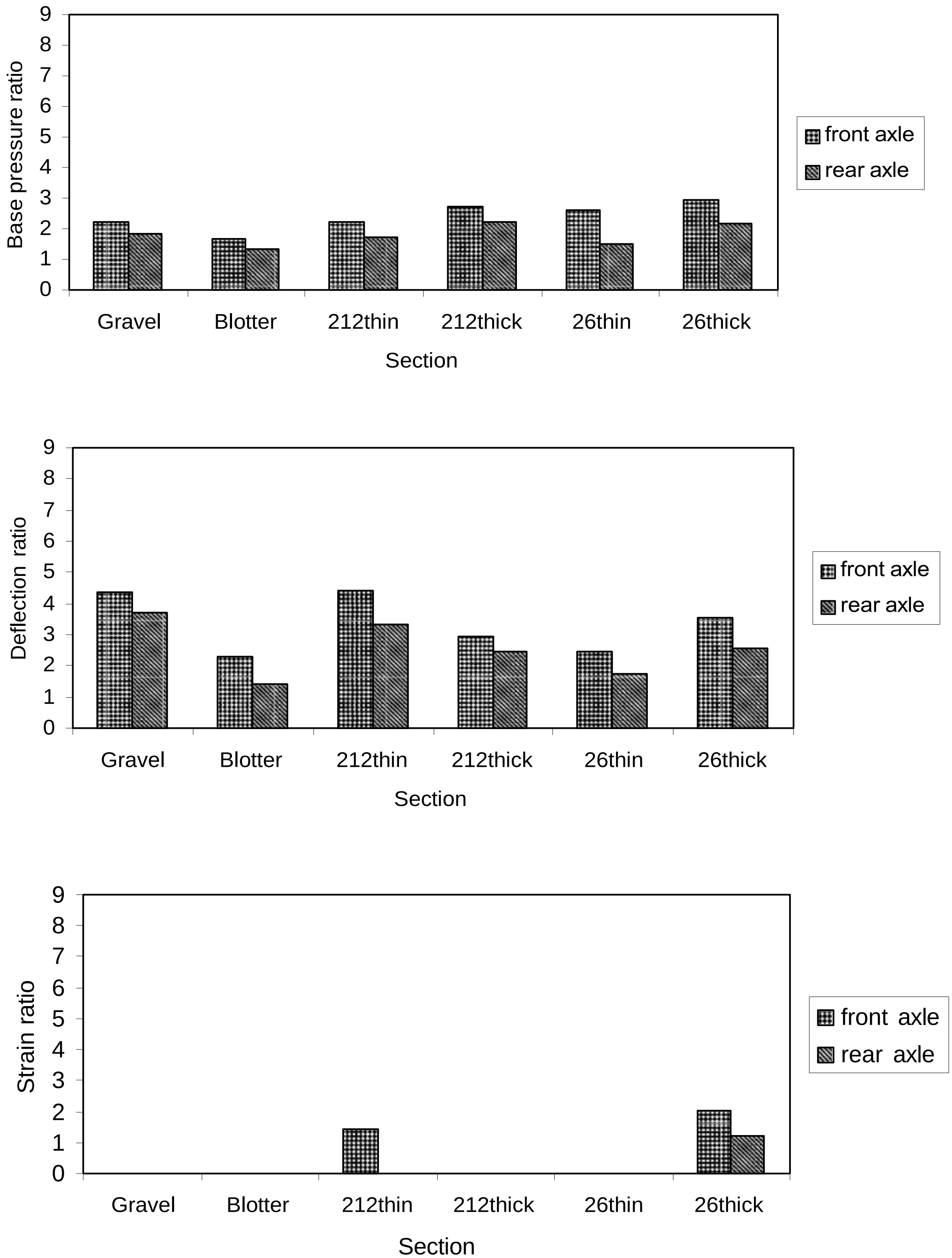


Figure 28: Comparison of the Front and Rear Axles of the Scraper During Fall Season

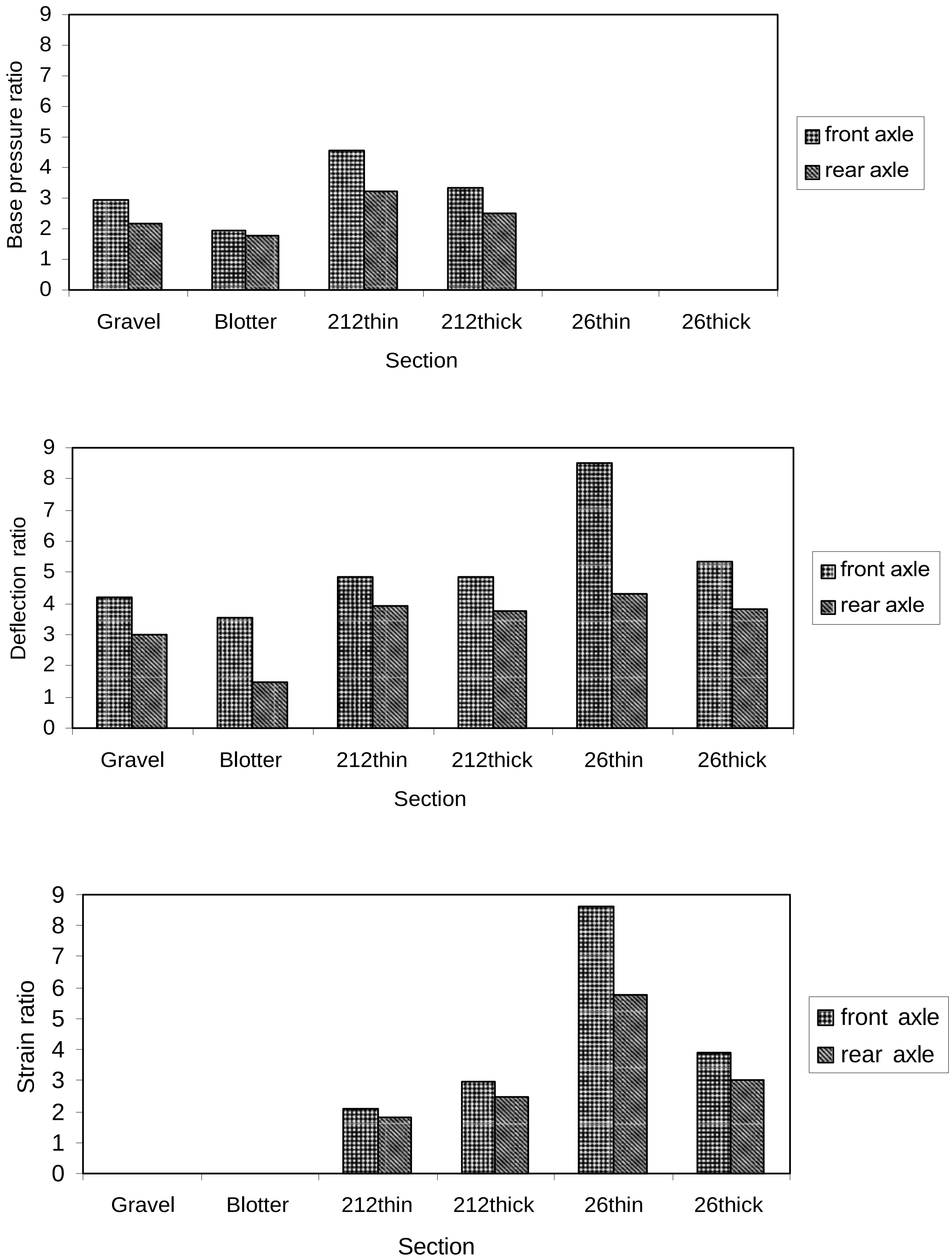


Figure 29: Comparison of the Front and Rear Axles of the Scraper During Spring Season

Task 7: Validate and Refine Pavement Response Model

Validate and refine the pavement response model based on results of the in-situ measurements.

The task of validating and refining the pavement response model requires the conduct of three subtasks dealing with evaluation of materials properties, identification of tires characteristics, and analysis of pavement responses.

Evaluation of Materials Properties

The objective of this subtask was to evaluate the properties of the pavement layers during the conduct of the field testing programs. The required pavement layer properties include the following:

- complex shear modulus of the HMA layer under various loading frequencies and temperatures
- resilient modulus of the crushed aggregate base
- resilient modulus of the subgrade.

A combination of laboratory and field testing were used to evaluate the complex shear modulus of the HMA layer and the resilient modulus of the base and subgrade layers. The complex shear modulus is a property that describes the viscoelastic behavior of the HMA layer under dynamic loading. The complex shear modulus as a function of loading frequency and temperature was measured using the Superpave Shear Tester (SST). The SST testing followed the AASHTO Standard TP7-94: Determining the Permanent Deformation and Fatigue Cracking Characteristics of HMA Using the SST Device. The tests were conducted in the Pavements/Materials Laboratory of the University of Nevada on cores from the sections on US212 and SD26. The loading frequency ranged from 0.01 to 10 Hz.

The resilient modulus of the base and subgrade layers is a property that describes the elastic behavior of these layers under dynamic loading. The FWD is a non-destructive testing device that measures the load-deflection response of pavements. The measured FWD data consist of vertical deflections at various distances from the center of the loaded area referred to as the “deflection basin.” The FWD deflection basins are used in a back-calculation process that determines the resilient modulus of the various pavement layers.

The backcalculation of the resilient modulus from FWD testing was used to evaluate the in-situ properties of the pavement layers. This state-of-the-art technique is currently being used by the great majority of state highway agencies in the United States and throughout the world. The SDDOT Data Inventory Program conducted the FWD evaluations during the field testing and provided the data to the research team, who conducted the back-calculation analyses. Table 5 summarizes the resilient modulus data back-calculated from the FWD testing during the field testing programs.

Table 5: Back-calculated Resilient Modulus Properties During Field Testing

Season	Section	Mr of New HMA (ksi)	Mr of Old HMA Base (ksi)	Mr of CAB (ksi)	Mr of Subgrade (ksi)
Fall 2000	US212 Thin	100	na	25	8
	US212 Thick	100	na	25	8
	US212 Gravel	na	na	25	8
	SD26 Thin	350	300	15	10
	SD26 Thick	350	300	15	10
	Blotter on 348th Avenue	na	na	15	10
Spring 2001	US212 Thin	746	na	25	4.8
	US212 Thick	746	na	25	4.8
	US212 Gravel	na	na	25	4.8
	SD26 Thin	2000	1000	15	10
	SD26 Thick	2000	1000	15	10
	Blotter on 348th Avenue	na	na	15	10

Identification of Tire Characteristics

The type and dimensions of the tire has a significant impact on the stress distribution at the tire-pavement interface. The tire information was obtained through a combination of: a) measuring the actual dimensions of the tires used during the field testing; b) contacting tire manufacturers directly; and c) accessing web pages. Table 6 shows the types of tires that were used on the various vehicles during field testing. The majority of the equipment used lugged tires which generate highly complex stress distributions at the tire-pavement interface. The scraper used during field testing had tires that were extremely worn with a minimal amount of lugs area remaining, unlike the tires shown in Table 6. This is a typical condition for heavy construction equipment like the scraper. Therefore, for the analysis conducted in this study, the scraper tires were assumed to be unlugged. Figures 30, 31 and 32 show the stress distributions at the tire-pavement interface for the Terragator, grain cart, and scraper, respectively.

The stress distributions at the lug-pavement interface were determined using a combination of field measurements and theoretical computations. The tire manufacturers provided the gross contact area as a function of load level for each tire type. During field testing, the researchers measured the actual dimensions and orientations of the lugs. Using the gross area and the measured characteristics of the lugs, the net contact area at the lug-pavement interface was established for every tire-load combination. The stress distribution over each lug area was assumed parabolic based on data reported by Kasahara and Fukuhara (14). Finally, the actual values of the parabolic stress distributions were determined by applying the principle of equilibrium between the applied load and the contact stresses times the contact area.

The stress distributions shown in Figures 30 through 32 were used in the theoretical model to evaluate the response of the pavement sections as they are loaded by the field testing equipment. The complex stress distributions made it very difficult to compare the measured and calculated pavement responses. As the vehicle with lugged tires passed over the instrumentation, the responses of the sensors were significantly influenced by the location of the lugs relative to the sensors. This introduced variability in the measured responses under multiple vehicle passes. Since the strain gauges were located the closest to the pavement surface, they were the most significantly impacted by the relative location of the lugs. The pressure cells and the deflection sensors were located deeper in the pavement structure, and therefore were not significantly impacted. As a result, the strain measurements showed larger overall variability than the pressure and deflection measurements. Due to this problem, it was necessary to calculate the pavement responses under each vehicle along a transverse line across the entire loaded area and to select the peak responses to be compared with the measured values.

Validate and Refine Pavement Model

The objective of this effort was to use the measured materials properties, axle loads, and tire pressures in the theoretical model to predict the responses of the field sections under the various testing equipment. Because of time constraints, it was decided to use the September 2000 and April 2001 measurements to validate and refine the pavement model. Comparison of the measured pavement responses with the calculated ones was accomplished under the guidelines set forth under the section entitled, “Impact of

Off-Road Equipment Based on Field Measurements,” which discussed the anticipated sources of variability in the measured data. The theoretical model computes a “single level response” under each test condition (i.e. vehicle-load level combination) which does not include any of the sources of data variability discussed earlier. Therefore, comparing the measured with the computed values should allow for the anticipated variability in the measured data coming from the previously identified sources. As indicated earlier, the ± 30% range would be considered acceptable. In other words, if the field measured pressure is 50 psi, the computed pressure would be compared to a range of 35 to 65 psi.

Using the measured materials properties, the measured load levels, and the pressure distributions at the tire-pavement interface, the theoretical responses were computed for each vehicle-load level. Figures 33 through 38 in Appendix C show the ratios of the computed responses over the measured responses. If the ratio fit within the expected range of 0.7 to 1.3 (measured response ± 30%), then the theoretical model was considered capable of predicting this specific response. Table 7 summarizes the results of the comparisons. A 79% entry in Table 7 across from the Dump Truck (loaded) indicates that the computed responses for the dump truck fit within the respective ranges in 79% of the cases.

Table 6: Summary of Tire Types Used on Various Equipment

	Tire Type	
Vehicle	Front	Rear
Grain Cart 875-16		 30.5´32 ply12 High traction lug Titan International
Terra Gator 8103	 Flotation 23º Deep Tread 66´43.0-25 10 ply Firestone	 Flotation 23º Deep Tread 66´43.0-25 16 ply
Terra Gator 8144	 Flotation 23º Deep Tread 48´31.0-20 10 ply Firestone	 Flotation 23º Deep Tread 66´43.0-25 16 ply
Scraper	 37.25-35 Firestone	
Tracked Tractor	 Trackman Rubber Track (Type TD) Goodyear	

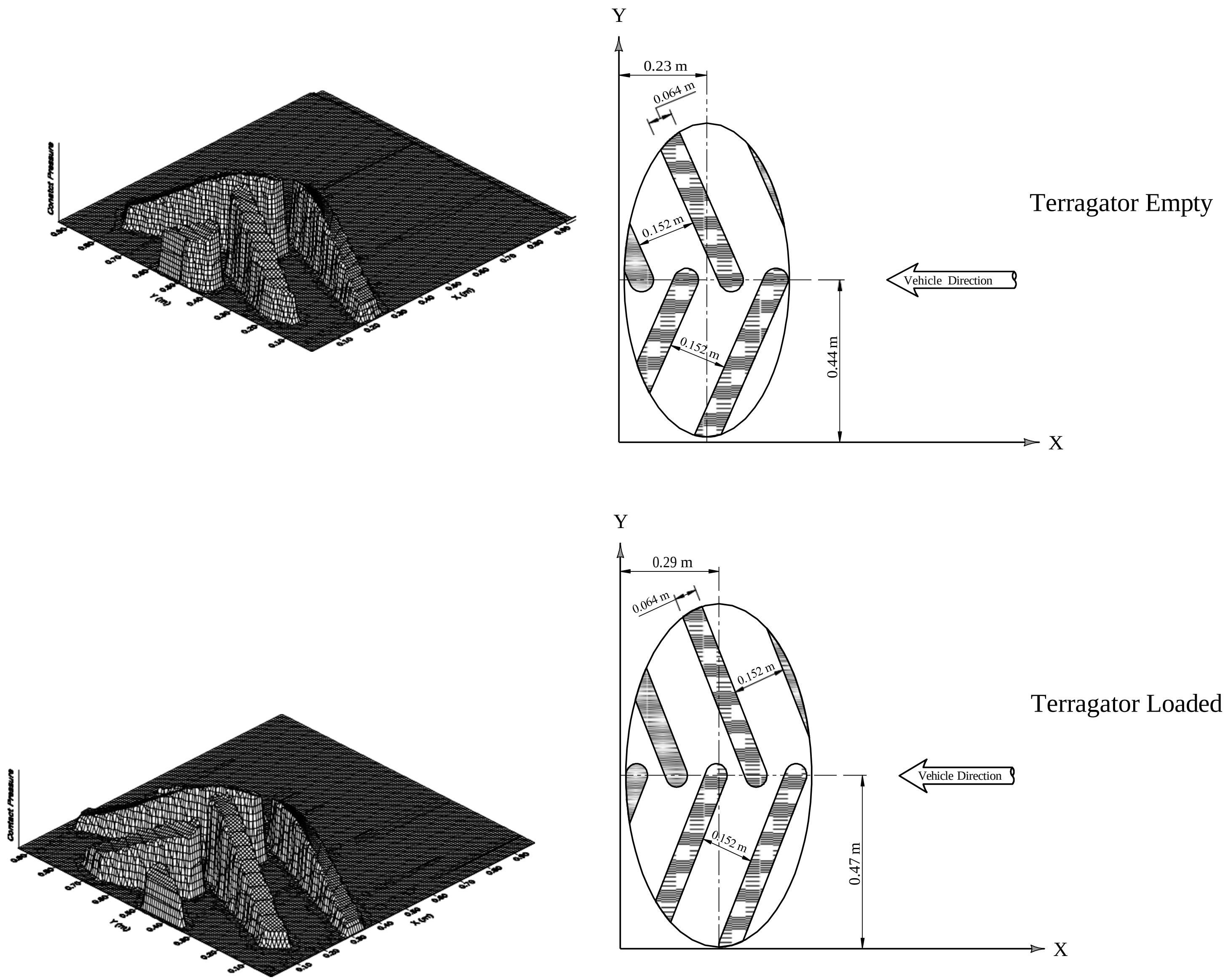
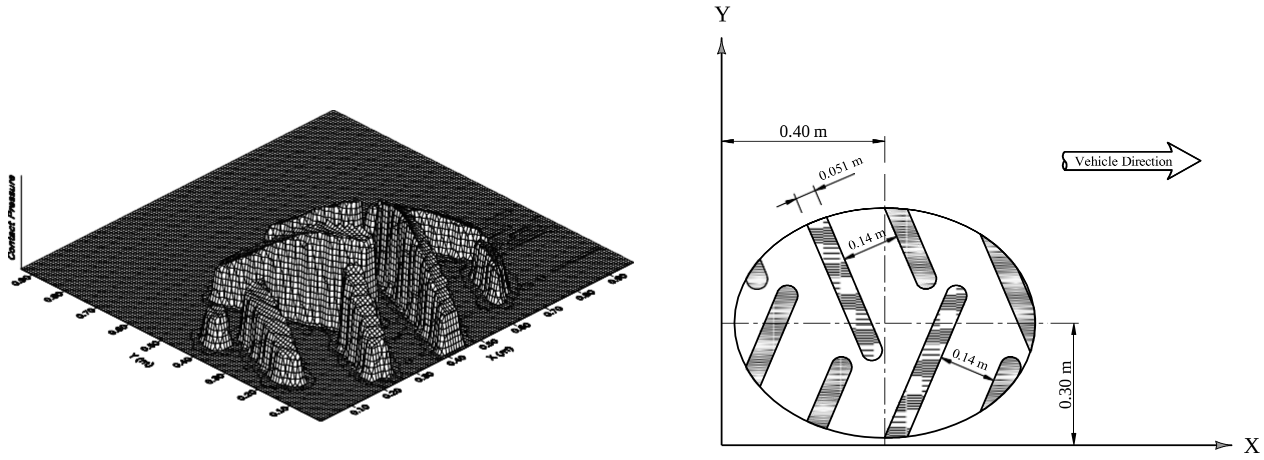
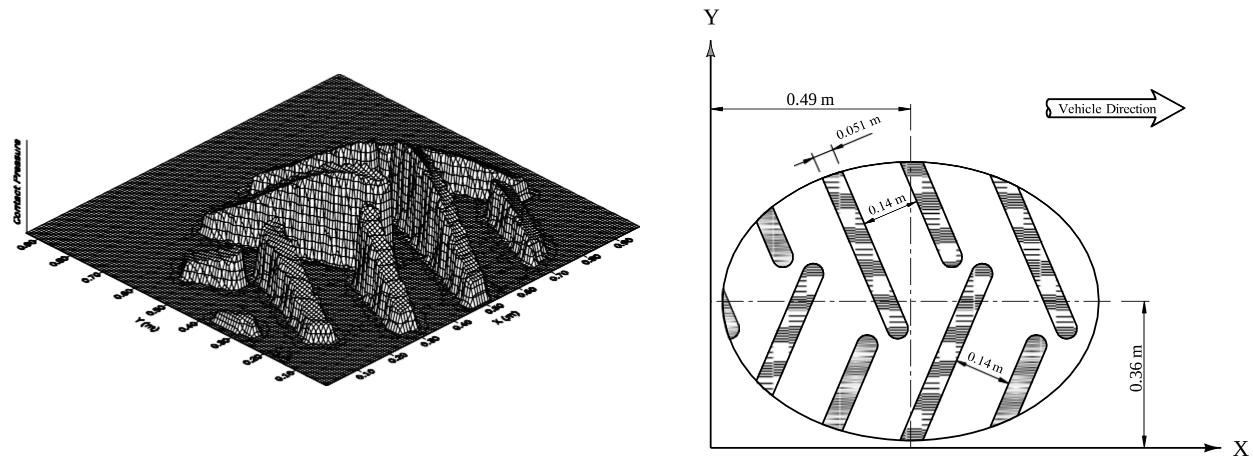


Figure 30: Stress Distribution at the Tire-Pavement Interface for the Terragators



Grain Cart-Legal weight



Grain Cart-Over Legal weight

Figure 31: Stress Distribution at the Tire-Pavement Interface for the Grain Cart

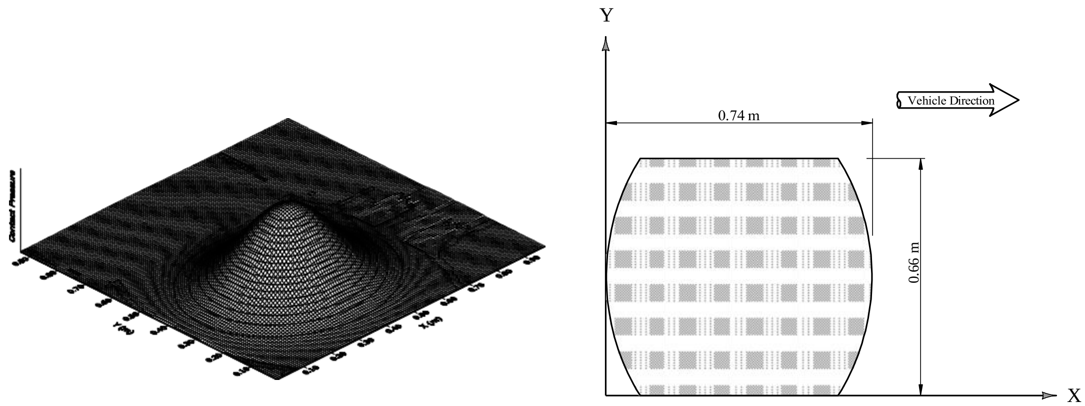


Figure 32: Stress Distribution at the Tire-Pavement Interface for the Scraper

The following scale was used to judge the capability of the theoretical model to predict the measured responses:

Excellent:	75-100 %
Moderate:	50-75 %
Poor:	< 50 %

The data in Table 7 show that the theoretical model's capability to predict the measured responses was excellent for four vehicles and moderate for four vehicles. The capability of the theoretical model in predicting pavement responses under the Terragator 8103 and the Scraper were ranked the lowest. During field testing, the Terragator 8103 experienced extreme bouncing when driven over the instrumented sections generating a highly variable dynamic load profile which can not be accurately handled through theoretical modeling. In the case of the Scraper, the lower percent within range was mainly caused by the pressure data collected during the spring season testing program. The Scraper used during the spring season test was heavier than the Scraper used during the fall (72,900 lb/axle vs. 59,740 lb/axle). Under the extreme wet conditions and heavy axle loads, the theoretical model was unable to simulate the dynamic pore water pressure that existed under these conditions, leading to the lower percent within range. If the pressure data of the spring season are taken out of the comparison, the percent within range for the Scraper becomes 75% (shown in parenthesis in Table 7).

In summary, considering all of the contributing factors and limitations of field instrumentation and testing, and theoretical modeling, it can be concluded that the capability of the theoretical model selected for this research (3D-MOVE) in predicting a wide variety of pavement responses (e.g. stresses, strains, and deflections) under the various combinations of off-road equipment and load levels was excellent.

Table 7: Comparison of the Computed Pavement Responses with Measured Pavement Response

Vehicle	Percent Within Range (%)
Dump Truck (loaded)	79
Terragator 8103 (empty)	65
Terragator 8144 (empty)	83
Terragator 8103 (loaded)	63
Terragator 8144 (loaded)	76
Scraper	62 (75)
Grain Cart (legal load)	69
Grain Cart (over legal load)	79

Task 8: Estimate Pavement Life Consumed by Load Application

Using results obtained from the validated pavement response model, estimate the amount of pavement life consumed by application of loads by representative off-road equipment tires and tracks.

The objective of this effort was to expand the analysis of the impact of off-road equipment to cover the wide range of pavement structures and soil types commonly encountered in South Dakota. Based on the available properties of typical South Dakota soil deposits, it was recommended to group the soil types into four distinct classes as shown in Table 8. In order to cover a range of pavement structures, the following layer thicknesses were recommended:

HMA Layer: 0", 1.5", 3", 5", and 7"
CAB Layer: 6" and 12"

The above combinations result in a total of 10 pavement structures on each of the four soil type classes. Recognizing that the properties of pavement materials change drastically at various seasons, each pavement structure within each soil class will have four sets of seasonal properties. Table 9 summarizes the seasonal resilient modulus of the pavements evaluated in this effort. In summary, this effort analyzed the following number of pavements:

Number of Pavements Analyzed = (5 HMA)x(2 CAB)x(4 soil classes)x(4 seasons) = 160 pavements

The approach used to assess the impact of off-road equipment on the 160 pavements consisted of the following:

- Identify the appropriate performance models for fatigue and rutting of flexible pavements.
- Use the verified/refined theoretical model 3D-MOVE to calculate the response required by the performance models, for each of the 160 pavements under the loading conditions imparted by the Terragators, scraper, and grain cart.
- Evaluate the fatigue and rutting load equivalency factors (LEF) for Terragators, scraper, and grain cart for the 160 pavements.

Table 8: Characteristics of Typical Soil Classes in South Dakota

Soil Type Class	County	Soil Type	Soil Classification	Representative Mr, ksi
1	Stanley and Aurora	Opal and Beadle	A-7-6(20), A-7-6(18)	4.5
2	Day and Brown	Poinsett and Harmony	A-7-6(14), A-7-6(19)	8
3	Potter, Hanson, Meade	Highmore, Clarno, and Parchin	A-6(12), A-6(9), A-6(2)	10.5
4	Bennett	Valentine	A-3(0)	29

Table 9: Seasonal Materials Properties

			Subgrade Mr (ksi)			
Season	HMA Mr (ksi)	CAB Mr (ksi)	Class 1	Class 2	Class 3	Class 4
Winter	750	50	12	16	20	30
Spring	500	15	3	5	7	12
Summer	100	35	5	8	10	30
Fall	300	25	5	8	10	30

Identify Performance Models

Performance models relate pavement responses to number of load repetitions to failure. In the case of flexible highway pavements, performance models have been developed for fatigue and rutting distresses. This research selected the fatigue and rutting performance models that are being included in the AASHTO 2002 Pavement Design Guide (15).

Fatigue Performance Model

$$N_f = \beta \, \varepsilon_t^{-5}$$ **Equation (1)**

where:

N_f = number of load repetitions to fatigue failure
p = material constant, a function of mixtures properties and resilient modulus
$\mathbf{r}_t$ = tensile strain at the bottom of the HMA layer (microns)

The fatigue performance model indicates that the number of load repetitions to fatigue failure of flexible pavements is inversely related to the 5^{th} power of the magnitude of the tensile strain at the bottom of the HMA layer. Therefore, in order to predict the number of repetitions of a given vehicle-load level combination to cause fatigue failure of a flexible pavement, the tensile strain at the bottom of the HMA layer caused by the vehicle must be evaluated.

Rutting Performance Model

Rutting in the HMA Layer:

Rutting in the HMA layer is predicted by the equation:

$$\frac{\varepsilon_p}{\varepsilon_r} = 1.781 \times 10^{-4} N^{0.4262} T^{2.028}$$ **Equation (2)**

where:

$\mathbf{r}_p$ = plastic compressive strain at middle of HMA layer (microns)
$\mathbf{r}_r$ = resilient compressive strain at middle of HMA layer (microns)
N = number of load repetitions
T = average temperature of the HMA layer

Rutting in the Base and Subgrade:

Rutting in the base and subgrade is predicted by the equation:

$$\frac{\varepsilon_p}{\varepsilon_r} = aN^b$$ **Equation (3)**

where:

ε_p = plastic compressive strain at middle of base or on top of subgrade (microns)
ε_r = resilient compressive strain at middle of base or on top of subgrade (microns)
N = number of load repetitions
a and b = constants

The values of the a and b constants depend on the magnitude of the resilient compressive strain, as shown in Tables 10 and 11. The rutting performance models indicate that the accumulated plastic strain in the HMA, CAB, and subgrade layers is related to the number of load repetitions and resilient strain. In order to calculate the amount of rutting in each of the pavement layers, the plastic strains in the various layers must be calculated and then converted into permanent deformations by multiplying the plastic strains times the layer thickness. The total rutting at the pavement surface (i.e. rut depth, RD) is the accumulation of the permanent deformations from the various layers.

$$PD_i = \varepsilon_{pi} \times H_i \quad \textbf{Equation (4)}$$

$$RD = \sum PD_i \quad \textbf{Equation (5)}$$

where:

PD_i = permanent deformation from layer i
ε_{pi} = plastic strain in layer i
H_i = thickness of layer i, inches
RD = total surface rut depth, inches

Therefore, in order to predict the number of repetitions of a given vehicle-load level combination to cause rutting failure of a flexible pavement, the compressive strain at the middle of each of the pavement layers caused by the vehicle must be evaluated. In the case of the subgrade, it was assumed that the top 24 inches would contribute to surface rutting. Therefore, the plastic strain was calculated at 12 inches into the subgrade and multiplied by 24 to estimate the total rutting from the subgrade.

Evaluate Load Equivalency Factors

This analysis requires the transformation of the relative damage into load equivalency factors (LEF). The LEF is defined as follows (16):

> A load equivalency factor represents the number of repetitions of the 18,000-lb single axle load necessary to cause the same damage as one repetition of the specific vehicle-load level combination. For example, a vehicle-load level combination with LEF of 10 indicates that it takes 10 passes of the 18,000-lb single axle load to cause the same damage as one pass of the vehicle-load level combination. In other words, one pass of

the vehicle-load level combination is equivalent to 10 passes of the 18,000-lb single axle load.

Table 10: Rutting Model Coefficients for Base Course Layer

Strain Level (microns)	a	b
50	0	0
200	0.7	0.19
500	1.2	0.28
600	1.33	0.18
700	1.29	0.19
800	1.25	0.2
4800	1.04	0.36
5400	1.48	0.19
21800	1.01	0.61
27700	1.01	0.55

Table 11: Rutting Model Coefficients for Subgrade

Strain Level (microns)	a	b
60	0	0
200	0.8	0.13
400	1.25	0.15
800	1.63	0.13
1700	1.24	0.16
5300	1.32	0.14
9100	2.2	0.14
9900	2.02	0.16
29600	1.01	0.61

Fatigue Load Equivalency Factors

The fatigue LEF is calculated as the ratio of the measured tensile strain at the bottom of the HMA layer under a given vehicle-load level combination to the measured tensile strain under the 18,000-lb single axle truck, raised to the 5th power. Note that the material constant **p** cancels out since the LEF is based on the same pavement section.

For example, the fatigue LEF for the loaded Terragator 8144 on the US212 thin section during the fall season is:

$$LEF_f = \left(\frac{893}{733}\right)^5 = 2.7$$

Equation (6)

Rutting Load Equivalency Factors

The rutting LEF is calculated as the ratio of the number of repetitions of the 18,000-lb single axle truck over the number of repetitions of a given vehicle-load level combination to cause 0.5 inches surface rutting. This process requires the determination of the rut depth generated by each of the layers and then sums up all layer contributions to evaluate the total rut depth. Since the vertical strains are needed for this calculation, the theoretical data base will be used to give a sample calculation.

The rutting LEF for Terragator empty on a flexible pavement of HMA = 5" and CAB = 6" during the fall season is calculated as follows:

- Calculate the resilient compressive strains at the middle of the HMA and CAB layers and at 12" into the subgrade;

  $\mathbf{r}_r$ (HMA) = 181 microns
  $\mathbf{r}_r$ (CAB) = 613 microns
  $\mathbf{r}_r$ (SG) = 600 microns

- Use the resilient compressive strains in Equations 2 and 3 to calculate the plastic strains in each of the pavement layers at a given number of repetitions.

- Use the plastic strains in Equation 4 to calculate the permanent deformation from each of the pavement layers.

- Use the permanent deformations from each of the pavement layers in equation 5 to calculate the rut depth at the pavement surface.

- A trial and error procedure is used to identify the number of repetitions of the empty Terragator needed to generate the 0.5" surface rutting. In this example, the number of repetitions of the empty Terragator necessary to create 0.5" rut depth, $N_{Terragator}$ = 201,000.

A similar analysis conducted for the 18,000-lb single axle truck on the same pavement and during the same season, generated a N_{truck} = 221,000.

Therefore the rutting LEF for the empty Terragator on flexible pavement of HMA = 5" and CAB = 6" during the fall season would be:

$$LEF_{(Terragator\ empty,\ fall)} = \frac{N_{truck}}{N_{Terragator}} = \frac{221{,}000}{201{,}000} = 1.1$$

Equation (7)

Interpretation and Use of Load Equivalency Factors

Tables 12 and 13 summarize the LEFs for fatigue and rutting for all 160 pavement sections, respectively. The fatigue LEF data presented in Table 12 show “n/a” entries for the scraper on flexible pavements with HMA = 1.5" during the summer season. In these cases, the fatigue LEFs could not be calculated due to limitations of the theoretical model in calculating strains in very thin HMA layers when loaded with extremely large loads/contact areas such as the scraper. This also indicates that the fatigue damage of very thin flexible pavements caused by the scraper is extremely significant to the point that it can not be modeled.

Appendix D shows the variations of the LEFs. The data presented in Tables 12 and 13 and Appendix D clearly show that the LEFs are significantly impacted by soil class, vehicle type, and pavement structure. When analyzing the LEF data, it should be understood that they represent the damage (i.e. fatigue or rutting) that a given vehicle-load combination causes on a pavement structure in a given season relative to the 18,000-lb single axle truck. The LEF concept makes it difficult to identify general trends and correlations among the LEF values. For example, on a strong pavement structure, the impacts of both a given vehicle-load combination and the 18,000-lb single axle truck may be small, but the ratio between them may be higher than their ratio on a weak pavement structure. This situation may generate a strong pavement’s LEF that is higher than the weak pavement’s LEF. However, this can not be translated into an observation that the vehicle-load combination is more damaging to strong pavements than weak pavements. In light of this discussion, it can be concluded that the fatigue and rutting LEFs can be best used to assess the relative impact of specified cases.

Since pavements can fail in either fatigue or rutting, the pavement engineer must always assess the potential for both failures and report the worst case. Therefore, for every situation a critical LEF is identified as the higher between the fatigue and rutting LEFs. The following present two cases on the use of the LEFs.

CASE I: It is desired to know the relative damage of the scraper on a pavement having 5" HMA over 6" CAB during the spring season. The LEFs would be identified from Tables 12 and 13 as follows:

Soil Class	Fatigue LEF	Rutting LEF
1	555	94
2	528	47
3	506	32
4	467	16

In this case the fatigue LEFs are significantly higher than the rutting LEFs. This requires the engineer to report the fatigue LEFs. Also the fatigue LEFs have lower variability which makes the engineer's decision less complicated.

CASE II: It is desired to know the relative damage of the loaded Terragator on a pavement having 3" HMA over 6" CAB during the spring season. The LEFs would be identified from Tables 12 and 13 as follows:

Soil Class	Fatigue LEF	Rutting LEF
1	6.2	15.1
2	5.7	4.8
3	5.3	2.0
4	4.9	1.0

This case represents a more complicated situation to the engineer for two reasons: a) the critical LEF depends on the soil class and b) the rutting LEFs are highly variable. Therefore, the engineer must know additional information as to the location of the pavement within the state before an appropriate LEF can be assigned. The critical LEF can be either rutting or fatigue depending on the type of soil at the specific site.

Numerous scenarios like the two above can be generated by analyzing the relative damages on different seasons, different pavement structures, different soil classes, etc. The figures in Appendix D show the expected ranges of the critical LEFs (i.e. higher of fatigue or rutting). Looking at the data in Appendix D leads to the following conclusions:

- Significant fatigue damage is caused on ultra-thin flexible pavements of 1.5" HMA over 6" and 12" CAB by all vehicle-load combinations during the summer season. The following observations can be made:

    - One trip of the empty Terragator is equivalent to 51-150 trips of the 18,000-lb single axle truck.
    - One trip of the loaded Terragator is equivalent to 230-605 trips of the 18,000-lb single axle truck.

Table 12: Fatigue Load Equivalency Factors

Soil	Pavement	Terragator Empty				Terragator Loaded				Grain Cart Legal				Grain Cart Over Legal				Scraper Empty			
Class	Thickness	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall
1	1.5-6 *	9.3	3.8	150	12.2	34.3	13.5	605	45.8	7.8	2.4	240	11.1	24.0	7.2	799	34.6	28.4	91.2	n/a	19.3
	1.5-12	11.8	4.8	110	15.9	42.4	15.8	424	58.0	10.1	3.0	163	14.9	31.0	9.0	528	45.6	15.1	51.6	n/a	9.1
	3-6	1.7	1.4	4.9	1.8	6.0	6.2	16.6	6.4	0.8	0.7	3.0	0.9	2.4	2.5	8.6	2.6	213	355	35.7	190
	3-12	1.8	1.4	5.7	1.9	5.6	5.4	17.1	5.9	0.8	0.7	3.2	0.8	2.2	2.0	8.6	2.3	155	278	19.0	129
	5-6	1.0	1.0	1.0	1.0	4.9	6.6	3.4	4.7	0.5	0.7	0.4	0.5	1.8	2.7	1.1	1.8	444	555	204	422
	5-12	0.9	1.0	0.9	0.9	4.0	5.6	2.4	3.8	0.4	0.6	0.3	0.4	1.4	2.2	0.7	1.3	382	498	137	350
	7-6	0.9	0.9	0.8	0.9	6.0	7.4	3.3	5.7	0.6	0.7	0.3	0.5	2.3	3.3	1.0	2.2	596	634	412	582
	7-12	0.9	0.9	0.7	0.8	5.0	6.6	2.1	4.7	0.5	0.6	0.2	0.4	1.8	2.7	0.5	1.6	551	602	326	528
2	1.5-6	9.6	4.1	98.4	12.6	35.4	14.0	419	47.8	8.1	2.5	157	11.7	25.0	7.6	532	36.5	26.2	74.8	n/a	17.7
	1.5 -12	11.5	4.8	82.9	15.1	42.1	15.9	338	56.5	10.0	3.0	125	14.3	30.8	9.1	414	44.5	16.0	50.3	n/a	10.7
	3-6	1.7	1.4	4.9	1.8	5.8	5.7	16.6	6.2	0.8	0.7	3.0	0.8	2.3	2.1	8.7	2.5	197	316	36.2	166
	3-12	1.8	1.4	5.3	1.9	5.5	5.2	16.9	5.9	0.8	0.6	3.2	0.8	2.1	1.9	8.7	2.3	152	264	23.5	126
	5-6	1.0	1.0	1.0	1.0	4.5	5.9	3.2	4.2	0.5	0.6	0.3	0.4	1.6	2.3	1.0	1.5	424	528	188	390
	5-12	0.9	1.0	0.9	0.9	3.9	5.3	2.5	3.6	0.4	0.5	0.3	0.4	1.3	2.0	0.7	1.2	374	488	139	339
	7-6	0.9	0.9	0.7	0.9	5.6	7.0	2.9	5.2	0.5	0.7	0.3	0.5	2.0	2.9	0.9	1.8	585	638	388	562
	7-12	0.9	0.9	0.6	0.8	4.8	6.4	2.1	4.4	0.4	0.6	0.2	0.4	1.7	2.5	0.5	1.4	548	613	323	522
3	1.5-6	9.8	4.3	84.2	12.8	36.4	14.5	364	48.9	8.3	2.7	134	12.0	25.9	8.0	454	37.6	24.5	65.1	n/a	16.9
	1.5 -12	11.4	4.8	74.3	14.8	41.9	15.9	310	55.9	9.9	3.0	112	14.1	30.6	9.1	375	44.1	16.6	49.4	n/a	11.4
	3-6	1.7	1.4	4.8	1.8	5.7	5.3	16.7	6.0	0.8	0.6	3.0	0.8	2.2	2.0	8.7	2.4	184	290	36.3	155
	3-12	1.8	1.4	5.2	1.9	5.5	5.0	16.9	5.9	0.7	0.6	3.1	0.8	2.1	1.8	8.7	2.3	149	255	25.6	124
	5-6	1.0	1.0	1.0	0.9	4.3	5.4	3.1	4.0	0.4	0.6	0.3	0.4	1.5	2.0	1.0	1.4	408	506	180	374
	5-12	0.9	1.0	0.9	0.9	3.8	5.0	2.5	3.5	0.4	0.5	0.3	0.4	1.3	1.8	0.7	1.1	368	477	140	334
	7-6	0.9	0.9	0.7	0.9	5.3	6.6	2.8	4.9	0.5	0.6	0.3	0.4	1.9	2.6	0.8	1.6	575	632	376	550
	7-12	0.9	0.9	0.6	0.8	4.7	6.2	2.0	4.3	0.4	0.6	0.2	0.4	1.6	2.3	0.5	1.4	544	613	322	517
4	1.5-6	10.3	4.7	50.7	14.0	38.4	15.5	229	54.9	8.9	2.9	76.9	13.6	27.7	8.8	264	43.3	21.8	52.2	n/a	14.0
	1.5 -12	11.2	4.9	51.0	13.9	41.6	16.0	228	54.2	9.8	3.1	77.0	13.4	30.5	9.2	264	42.6	17.6	47.7	n/a	14.3
	3-6	1.7	1.4	4.8	1.9	5.5	4.9	16.7	5.8	0.7	0.6	3.0	0.8	2.1	1.8	8.8	2.3	162	250	37.0	112
	3-12	1.8	1.4	4.8	1.9	5.4	4.8	16.8	5.8	0.7	0.6	3.0	0.8	2.1	1.7	8.8	2.3	144	240	35.1	116
	5-6	0.9	1.0	0.9	0.9	3.8	4.8	2.6	3.0	0.4	0.5	0.3	0.3	1.3	1.7	0.8	0.9	378	467	150	301
	5-12	0.9	1.0	0.9	0.9	3.6	4.6	2.6	3.1	0.4	0.5	0.3	0.3	1.2	1.6	0.8	0.9	356	458	145	306
	7-6	0.9	0.9	0.6	0.8	4.8	5.9	2.0	3.6	0.4	0.6	0.2	0.3	1.6	2.2	0.5	1.0	552	612	323	483
	7-12	0.8	0.9	0.6	0.8	4.4	5.8	2.0	3.7	0.4	0.5	0.2	0.3	1.4	2.1	0.5	1.0	534	606	315	488

Table 13: Rutting Load Equivalency Factors

Soil Class	Pavement Thickness	Terragator Empty				Terragator Loaded				Grain Cart Legal				Grain Cart Over Legal				Scraper Empty			
		Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall	Win.	Spr.	Sum.	Fall
1	0-6 *	1.0	1.6	2.5	2.0	1.0	8.6	25.1	16.3	1.0	2.2	4.7	3.3	1.0	7.5	20.1	13.3	85.8	279	1021	259
	0-12	1.0	0.6	1.0	0.8	1.0	4.9	1.9	8.5	1.0	0.6	1.0	0.8	1.0	2.4	1.0	3.8	67.7	135	658	2459
	1.5-6	1.0	1.7	1.5	1.3	1.0	19.0	4.1	5.6	1.0	2.3	2.6	2.2	1.0	10.4	6.0	6.3	41.5	750	7.4	22.5
	1.5-12	1.0	2.0	1.4	1.2	1.0	43.0	3.4	4.2	1.0	2.8	2.2	1.9	1.0	18.6	4.8	4.7	16.2	830	7.5	103
	3-6	1.0	1.0	2.2	2.4	1.0	15.1	6.7	11.3	1.0	1.2	3.2	3.7	1.0	9.2	7.3	10.6	4.7	1626	42.0	321
	3-12	1.0	1.0	1.8	1.9	1.0	8.1	3.6	6.9	1.0	1.0	2.4	2.7	1.0	4.2	4.0	6.6	1.9	1312	20.5	187
	5-6	1.0	1.0	1.3	1.2	1.0	1.0	3.4	3.7	1.0	1.0	1.7	1.5	1.0	1.0	3.3	3.5	1.0	94.4	22.6	45.8
	5-12	1.0	1.0	1.5	2.1	1.0	1.0	2.8	3.6	1.0	1.0	1.8	3.2	1.0	1.0	2.7	3.4	1.0	95.4	17.8	42.8
	7-6	1.0	1.0	0.9	1.1	1.0	1.0	1.8	2.4	1.0	1.0	0.9	1.4	1.0	1.0	1.5	2.0	1.0	8.0	16.6	27.7
	7-12	1.0	1.0	1.0	1.1	1.0	1.0	2.1	3.4	1.0	1.0	1.1	1.3	1.0	1.0	2.2	4.2	1.0	8.5	17.4	28.3
2	0-6	1.0	1.5	1.0	1.7	1.0	7.2	13.0	18.0	1.0	2.1	1.5	2.7	1.0	7.3	9.1	14.2	61.6	64.0	574	74.9
	0-12	1.0	0.5	1.0	1.0	1.0	4.7	1.0	5.8	1.0	0.4	1.0	1.0	1.0	2.1	1.0	2.3	57.1	149	552	2896
	1.5-6	1.0	1.4	1.5	1.2	1.0	22.2	3.7	4.4	1.0	1.8	2.4	1.9	1.0	10.5	5.3	5.0	25.9	680	6.9	29.9
	1.5-12	1.0	1.6	1.4	1.2	1.0	33.4	3.3	3.9	1.0	1.8	2.2	1.9	1.0	11.6	4.6	4.4	13.0	745	7.9	92.1
	3-6	1.0	1.0	2.1	2.3	1.0	4.8	5.6	8.2	1.0	1.0	3.0	3.3	1.0	2.4	6.3	8.0	2.4	965	33.4	230
	3-12	1.0	1.0	1.8	1.9	1.0	3.7	3.7	6.6	1.0	1.0	2.5	2.7	1.0	1.7	4.0	6.4	1.4	993	19.6	165
	5-6	1.0	1.0	1.3	1.1	1.0	1.0	3.0	2.8	1.0	1.0	1.6	1.3	1.0	1.0	2.9	2.7	1.0	47.4	19.3	31.5
	5-12	1.0	1.0	1.5	1.9	1.0	1.0	2.8	3.7	1.0	1.0	1.8	3.1	1.0	1.0	2.9	3.4	1.0	58.6	17.1	37.7
	7-6	1.0	1.0	1.0	1.1	1.0	1.0	1.8	2.4	1.0	1.0	1.0	1.4	1.0	1.0	1.6	2.0	1.0	3.1	16.1	24.2
	7-12	1.0	1.0	0.9	1.0	1.0	1.0	2.2	3.6	1.0	1.0	1.0	1.2	1.0	1.0	2.2	3.8	1.0	4.0	16.7	25.3
3	0-6	1.0	1.4	1.0	1.5	1.0	5.0	8.1	16.0	1.0	1.9	1.0	2.3	1.0	6.5	5.7	12.3	49.3	38.9	484	62.8
	0-12	1.0	0.5	1.0	1.0	1.0	4.2	1.0	4.8	1.0	0.4	1.0	1.0	1.0	1.7	1.0	1.7	51.8	152	520	2865
	1.5-6	1.0	1.2	1.4	1.2	1.0	20.9	3.6	4.0	1.0	1.3	2.4	1.8	1.0	8.2	5.1	4.5	17.7	767	7.2	34.2
	1.5-12	1.0	1.3	1.4	1.3	1.0	24.8	3.3	4.0	1.0	1.3	2.3	2.0	1.0	7.7	4.7	4.5	11.4	606	8.2	92.5
	3-6	1.0	1.0	2.1	2.3	1.0	2.0	5.3	7.4	1.0	1.0	2.9	3.2	1.0	1.0	5.9	7.3	1.5	717	30.6	200
	3-12	1.0	1.0	1.8	1.9	1.0	2.5	3.7	6.6	1.0	1.0	2.6	2.8	1.0	1.1	4.1	6.4	1.2	870	19.3	159
	5-6	1.0	1.0	1.3	1.1	1.0	1.0	2.9	2.7	1.0	1.0	1.6	1.3	1.0	1.0	2.9	2.7	1.0	31.5	18.4	28.1
	5-12	1.0	1.0	1.4	1.9	1.0	1.0	2.8	3.6	1.0	1.0	1.8	2.9	1.0	1.0	2.9	3.4	1.0	42.6	16.7	35.5
	7-6	1.0	1.0	1.0	1.1	1.0	1.0	1.9	2.3	1.0	1.0	1.1	1.3	1.0	1.0	1.6	2.1	1.0	1.6	15.8	22.7
	7-12	1.0	1.0	0.9	1.0	1.0	1.0	2.2	3.6	1.0	1.0	1.0	1.2	1.0	1.0	2.2	3.6	1.0	2.6	16.4	24.7
4	0-6	1.0	1.2	1.0	1.2	1.0	2.0	2.3	10.7	1.0	1.5	1.0	1.6	1.0	3.4	1.8	8.4	32.1	33.5	275	21.0
	0-12	1.0	0.5	1.0	1.0	1.0	3.6	1.0	3.0	1.0	0.3	1.0	1.0	1.0	1.4	1.0	1.0	47.4	155	451	1876
	1.5-6	1.0	1.0	1.4	1.1	1.0	10.5	3.3	3.3	1.0	1.0	2.2	1.7	1.0	3.2	4.5	3.8	10.0	574	8.3	29.1
	1.5-12	1.0	1.0	1.4	1.2	1.0	18.7	3.3	3.9	1.0	1.0	2.2	1.9	1.0	5.2	4.4	4.2	10.1	479	9.4	90.9
	3-6	1.0	1.0	2.0	2.2	1.0	1.0	4.8	6.5	1.0	1.0	2.7	3.0	1.0	1.0	5.3	6.4	1.0	507	24.3	140
	3-12	1.0	1.0	1.7	2.2	1.0	1.8	3.8	7.1	1.0	1.0	2.5	3.1	1.0	1.0	4.2	6.7	1.0	761	20.6	175
	5-6	1.0	1.0	1.3	1.1	1.0	1.0	2.8	2.5	1.0	1.0	1.6	1.3	1.0	1.0	2.7	2.4	1.0	16.3	15.8	21.9
	5-12	1.0	1.0	1.5	1.9	1.0	1.0	2.7	3.1	1.0	1.0	1.8	2.9	1.0	1.0	2.6	2.9	1.0	30.3	15.8	30.4
	7-6	1.0	1.0	1.0	1.0	1.0	1.0	1.8	2.1	1.0	1.0	1.0	1.2	1.0	1.0	1.6	2.0	1.0	1.0	14.7	19.3
	7-12	1.0	1.0	1.0	1.0	1.0	1.0	2.0	2.8	1.0	1.0	1.0	1.2	1.0	1.0	2.1	3.4	1.0	1.8	15.7	22.0

*HMA=0" Base=6"

- S One trip of the legally loaded grain cart is equivalent to 77-240 trips of the 18,000-lb single axle truck.
- S One trip of the grain cart over legal is equivalent to 264-799 trips of the 18,000-lb single axle truck.
- S The empty scraper is detrimental to ultra-thin flexible pavements.

• On unpaved roads and flexible pavements that are not ultra-thin (HMA = 3"-7"), the following observations can be made:

- S One trip of the empty Terragator is equivalent to 1-3 trips of the 18,000-lb single axle truck.
- S One trip of the loaded Terragator is equivalent to 2-20 trips of the 18,000-lb single axle truck.
- S One trip of the legally loaded grain cart is equivalent to 1-5 trips of the 18,000-lb single axle truck.
- S One trip of the grain cart over legal is equivalent to 1-20 trips of the 18,000-lb single axle truck.
- S One trip of the empty scraper is equivalent to 20-2900 trips of the 18,000-lb single axle truck.

The above observations express the relative damage in terms of ranges of equivalent trips. The lower end of each range represents the number of trips expected on thick pavements over strong subgrade soils, while the upper end of the range represents the number of trips expected on thin pavements over weak subgrade soils.

These observations lead to the same conclusions derived from the field testing program, which recommended that the movement of loaded Terragators, grain cart over legal, and the empty scraper over gravel and flexible pavements be regulated. In addition, these observations point out the extreme vulnerability of ultra-thin pavements to fatigue damage as they are subjected to loadings from off-road agricultural and construction equipment.

Task 9: Review Results and Refine Plans

Meet with the technical panel to review the results of Tasks 6-8 and to refine plans for remaining tasks.

A third meeting with the project panel was held on October 18, 2001, in Pierre, SD. The analysis of field data and the expanded pavement damage data were presented and discussed with the project panel. The following represent the major recommendations:

- Further investigate the Terragators and grain carts through a comparative Damage•Cost analysis process.
- The scraper should not be investigated further because of its extremely high damage potential.

- The tracked tractor should not be investigated further because of its low damage impact.

Task 10: Estimate Pavement Damage Costs

Estimate pavement damage costs attributable to loads applied by off-road equipment tires and tracks, as well as the economic benefits to users of the equipment, and compare them.

The original research plan called for estimating pavement damage costs caused by off-road equipment tires and tracks and comparing such costs to the benefit of operating the off-road equipment on unpaved and flexible pavements. The originally planned analysis would have estimated the overall impact of off-road equipment as a function of its anticipated number of repetitions and relative to the overall life of the pavement. After presenting this approach to the technical panel under Task 9, the panel concluded that developing recommendations based on the anticipated number of repetitions would be very difficult to implement and justify since such regulations are not being implemented for standard highway traffic. Therefore, the scope of this task was changed to conduct a comparative Damage•Cost analysis.

Based on the recommendations of the technical panel, this task concentrated on the pavement damage caused by the Terragators and the grain cart. The load equivalencies determined for each vehicle-load level combination indicated that pavement damage caused by off-road equipment is significantly impacted by load level, season, and pavement structure, while the soil type was only significant for unpaved and ultra-thin pavements.

- *Load Level*—The LEFs associated with the axle load level indicated that the empty Terragators and the grain cart loaded at legal limit cause minor pavement damage relative to the 18,000-lb single axle truck, while the loaded Terragators and the grain cart loaded over legal caused significant damage.

- *Season*—The seasonal LEFs showed that the impact of the season depends on the failure mode. In the case of rutting failure, the spring season was the most significant. This is supported by the fact that under heavy loads such as those evaluated in this study, the base and subgrade layers become the predominant contributors to permanent deformation. During the spring season, these layers are at their weakest state due to their wet condition and they exhibit more permanent deformation than during the other seasons. In the case of fatigue failure, the summer season was the most significant. Again, heavy loads generate high tensile strains during the summer season, which accelerate fatigue damage of the HMA layer.

- *Pavement Structure*—The structure of the pavement showed a significant impact as the LEFs were compared among the unpaved, ultra-thin (1.5" HMA), thin (3" HMA), and thick (5"-7" HMA) pavements. The unpaved roads only experience rutting damage. The ultra-thin flexible pavements were extremely vulnerable to fatigue damage. Both fatigue and rutting damage can occur on thin and thick flexible pavements, depending on load level and season.

- *Soil Type*—As the in-situ strength of the subgrade soil increased, the LEFs decreased for the unpaved and ultra-thin pavements. For thin and thick pavements the LEFs were virtually unaffected by the in-situ strength of subgrade soil.

Comparative Damage•Cost Study

The objective of this effort was to assess the damage relative to the cost of transporting the commodities on the Terragators and grain carts. This analysis assumed that equipment operators have the following two options:

- transport the commodities on Terragators and grain carts, or
- transport the commodities on standard highway vehicles.

It is clear that the first option creates additional pavement damage, while the second imposes additional expense to the equipment operators. The goal of the Damage•Cost analysis was to assess the combined importance of the two attributes by minimizing the Damage•Cost multiplier. Minimizing the product of cost and damage tends to minimize the combination of the two, rather than minimizing one on the expense of the other, therefore achieving a balance. In addition, minimizing the product does not require that the two quantities be in the same units of measurements. The Damage•Cost analysis was conducted under the following guidelines:

- Group the pavement structure into four categories: a) unpaved; b) ultra-thin; c) thin; and d) thick.

- Select the critical LEF (i.e. rutting or fatigue) and average the LEF over all seasons.

Damage•Cost Analysis for Terragators

A loaded Terragator can carry a net load of 16,000 lb of chemicals. Considering that some jobs can be small while others can be large, multiple scenarios were analyzed: a) jobs requiring a single Terragator load; b) jobs requiring double Terragator loads; and c) jobs requiring triple Terragator loads.

For jobs requiring a single Terragator load, the equipment operators have five choices: a) transport the chemicals on the Terragator; b) transport the chemicals on a trailer pulled by the Terragator at a cost of \$0.10/mile; c) transport the chemicals on a single axle truck at a cost of \$0.50/mile; d) transport the chemicals on a tandem axle truck at a cost of \$0.65/mile; and e) transport the chemicals on a tridem axle truck at a cost of \$0.72/mile.

For jobs requiring double Terragator loads, the equipment operators have six choices: a) transport the chemicals on the Terragator with two trips; b) transport the chemicals on a trailer pulled by the Terragator with two trips at a cost of \$0.10/mile for the first trip and \$0.60/mile for the second trip; c) transport the chemicals on a single axle truck with two trips at a cost of \$0.50/mile; d) transport the chemicals on a tandem axle truck with two trips at a cost of $0.65/mile; e) transport the chemicals on a tridem axle truck with one trip at a cost of $0.72/mile; and f) transport the chemicals on a semitrailer truck at a cost of $1.50/mile.

For jobs requiring triple Terragator loads, the equipment operators have six choices: a) transport the chemicals on the Terragator with three trips; b) transport the chemicals on a trailer pulled by the Terragator with three trips at a cost of $0.10/mile for the first trip and $0.60/mile for the second and third trips; c) transport the chemicals on a single axle truck with three trips at a cost of $0.50/mile; d) transport the chemicals on a tandem axle truck with two trips at a cost of $0.65/mile; e) transport the chemicals on a tridem axle truck with two trips at a cost of $0.72/mile; and f) transport the chemicals on a semitrailer truck at a cost of $1.50/mile.

The damage caused by the single, tandem, and tridem axles were determined using the AASHTO LEF for a single axle at 20,000 lb to be 1.5, for a tandem axle at 30,000 lb to be 0.65, and at 34,000 lb to be 1.1, and for a tridem axle at 30,000 lb to be 0.15 and at 42,000 lb to be 0.60 for all pavement structures and soil types. The damage caused by the loaded Terragator was determined using the LEFs established in this study. The pulled trailer was assumed to have two single-tired axles carrying 11,000 lb each. The LEF for the pulled trailer axles were determined using the AASHTO and SDDOT study No. SD92-06 (17). The SD92-06 study recommended that single tires LEF can be estimated by multiplying the AASHTO LEF for dual tires by a factor of 2.18. Using this approach, the total LEF for the two trailer axles was determined to be 0.65 at 11,000 lb/axle. The cost of the pulled trailer includes both the operating cost of the Terragator and trailer. Therefore, the cost of the pulled trailer for the first trip is lower than for the second and third trips since the Terragator will have to make the first trip to the job site anyway.

Table 14 summarizes the load levels and the corresponding number of trips required for each job for the various alternatives along with the estimated costs. The objective of this analysis was to identify the optimum method of transporting chemicals to the job site which produces minimum damage at the lowest possible cost. For this purpose, the Damage•Cost multiplier was defined as the damage caused by each alternative times the corresponding cost. Therefore, the vehicle type generating the lowest multiplier was considered the optimum transportation method. The following represent the calculations of the Damage•Cost multipliers.

Job Requiring One Terragator Load

Vehicle Type: Pulled trailer
First Trip: [(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.10, cost of 1st trip
Total Damage•Cost multiplier: 0.22

Vehicle Type: Single axle truck
First Trip: (1.5, damage from single axle truck) x $0.50, cost of 1st trip
Total Damage•Cost multiplier: 0.75

Vehicle Type: Tandem axle truck
First Trip: (0.65, damage from tandem axle truck) x $0.65, cost of 1st trip
Total Damage•Cost multiplier: 0.42

Vehicle Type: Tridem axle truck
First Trip: (0.15, damage from tridem axle truck) x $0.75, cost of 1st trip
Total Damage•Cost multiplier: 0.11

Job Requiring Two Terragator Loads

Vehicle Type: Pulled trailer
First Trip: [(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.10, cost of 1st trip
Second Trip: [(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.60, cost of 2nd trip
Total Damage•Cost multiplier: 1.51

Vehicle Type: Single axle truck
First Trip: (1.5, damage from single axle truck) x $0.50, cost of 1st trip
Second Trip: (1.5, damage from single axle truck) x $0.50, cost of 2nd trip
Total Damage•Cost multiplier: 1.50

Vehicle Type: Tandem axle truck
First Trip: (0.65, damage from tandem axle truck) x $0.65, cost of 1st trip
Second Trip: (0.65, damage from tandem axle truck) x $0.65, cost of 2nd trip
Total Damage•Cost multiplier: 0.85

Vehicle Type: Tridem axle truck
First Trip: (0.60, damage from tridem axle truck) x $0.75, cost of 1st trip
Total Damage•Cost multiplier: 0.45

Vehicle Type: Semitrailer
First trip: (1.30, damage from semitrailer) x $1.15, cost of 1st trip
Total Damage•Cost multiplier: 1.50

Job Requiring Three Terragator loads

Vehicle Type: Pulled trailer

First Trip:	[(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.10, cost of 1st trip
Second Trip:	[(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.60, cost of 2nd trip
Third Trip:	[(1.5, damage from Terragator) +(0.65 , damage from pulled trailer)] x $0.60, cost of 3rd trip
	Total Damage•Cost multiplier=2.80

Vehicle Type: Single axle truck

First Trip:	(1.5, damage from single axle truck) x $0.50, cost of 1st trip
Second Trip:	(1.5, damage from single axle truck) x $0.50, cost of 2nd trip
Third Trip:	(1.5, damage from single axle truck) x $0.50, cost of 3rd trip
	Total Damage•Cost multiplier=2.25

Vehicle Type: Tandem axle truck

First Trip:	(0.65, damage from tandem axle truck) x $0.65, cost of 1st trip
Second Trip:	(0.65, damage from tandem axle truck) x $0.65, cost of 2nd trip
Third Trip:	(0.65, damage from tandem axle truck) x $0.65, cost of 3rd trip
	Total Damage•Cost multiplier=1.27

Vehicle Type: Tridem axle truck

First Trip:	(0.60, damage from tridem axle truck) x $0.75, cost of 1st trip
Second trip:	(0.15, damage from tridem axle truck) x $0.75, cost of 2nd trip
	Total Damage•Cost multiplier=0.56

Vehicle Type: Tractor-Semitrailer

First trip: (2.2, damage from semitrailer) x $1.15, cost of 1rst trip

Total Damage•Cost multiplier=2.53

Table 14: Summary of Loads, Number of Trips and Additional Costs

	Terragator	Pulled Trailer	Single Axle Truck	Tandem Axle Truck	Tridem Axle Truck	Tractor-Semitrailer Truck
Empty weight (lb)	31,000	6,000	12,000	20,000	23,000	30,000
Loaded weight (lb)	46,000	22,000	28,000	40,000	55,000	78,000
Net load (lb)	16,000	16,000	16,000	20,000	32,000	48,000
# of trips to transport 1 Terragator load	1	1	1	1	1	na
# of trips to transport 2 Terragator loads	2	2	2	2	1	1
# of trips to transport 3 Terragator loads	3	3	3	3	2	1
Additional cost: $/mile/trip	none	$0.10 first trip $0.60 per additional trip	$0.50	$0.65	$0.75	$1.15

Table 15 summarizes the Damage•Cost multipliers for all possible alternatives. The damage caused by the Terragators showed a range for the unpaved and ultra-thin pavements, reflecting the impact of the subgrade soil on these pavements. The lower value represents the strong soil and the higher value represents the weak soil. The data presented in Table 15 show that transporting the chemicals on the Terragator is definitely not the optimum method, since it causes significant pavement damage under all cases.

Based on the above analysis, it can be recommended that the tridem axle truck is the best transportation alternative for jobs requiring single, double and triple Terragator loads.

Damage•Cost Analysis for Grain Carts

A fully loaded 800-bushel grain cart can carry a net load of 48,000 lb of grain. Such a load can be transported using the following scenarios: a) three trips of a single axle truck at $0.50/mile; b) two trips of a tandem axle truck at $0.65/mile; c) two trips of a tridem axle truck at $0.75/mile; or c) one trip of a tractor-semitrailer at $1.15/mile. The Damage•Cost analysis was conducted using the AASHTO LEFs for the standard trucks and the established LEFs for the grain cart over legal weight.

Table 16 summarizes the comparative Damage•Cost data for the grain cart. The damage caused by the grain cart showed a range for the unpaved, ultra-thin, and thin pavements, reflecting the impact of the subgrade soil on these pavements. The lower value represents the strong soil and the higher value represents the weak soil. The objective of this analysis was to identify the optimal method of transporting grain to storage bins or to commercial grain elevators which produces minimum damage at the lowest possible cost. The data presented in Table 16 show that transporting grain on the grain cart is definitely not the optimal method because it causes significant pavement damage under all cases. Based the analysis, it can be seen that a tridem axle truck is the optimum method for transporting grains.

<u>Task 11: Develop Recommendations for Regulation</u>

Develop recommendations for regulating transportation of off-road equipment over state and local highways, in consideration of the balance between associated costs and benefits.

Based on the analysis of the field data, the expanded data base derived from modeling, and the findings of the Damage•Cost analysis, it can be concluded that loaded Terragators and grain carts loaded over legal are damaging to unpaved and flexible pavements while the scraper is significantly damaging to unpaved and flexible pavements. It is recommended that the following regulations should be considered.

- Scrapers should not be allowed to travel over unpaved roads and flexible pavements throughout the state of South Dakota. Transporting scrapers on multi-axle trucks meeting legal load limits causes far less pavement damage.

Table 15: Damage•Cost Analysis for the Terragators

		Terragator		Pulled Trailer			Single Axle			Tandem Axle			Tridem Axle			Semitrailer		
Road	Job	Damage	Cost	Damage	Cost	Multiplier	Damage	Cost	Multiplier	Damage	Cost	Multiplier	Damage	Cost	Multiplier	Damage	Cost	Multiplier
unpaved	single	5-17	none	2.15	0.10	0.22	1.50	0.50	0.75	0.65	0.65	0.42	0.15	0.75	0.11	na	na	na
	double	10-34	none	4.30	0.70	1.51	3.00	1.00	1.50	1.30	1.30	0.85	0.60	0.75	0.45	1.30	1.15	1.50
	triple	15-51	none	6.45	1.30	2.80	4.50	1.50	2.25	1.95	1.95	1.27	0.75	1.50	0.56	2.20	1.15	2.53
ultra-thin	single	100-220	none	2.15	0.10	0.22	1.50	0.50	0.75	0.65	0.65	0.42	0.15	0.75	0.11	na	na	na
	double	200-440	none	4.30	0.70	1.51	3.00	1.00	1.50	1.30	1.30	0.85	0.60	0.75	0.45	1.30	1.15	1.50
	triple	300-660	none	6.45	1.30	2.80	4.50	1.50	2.25	1.95	1.95	1.27	0.75	1.50	0.56	2.20	1.15	2.53
thin	single	10	none	2.15	0.10	0.22	1.50	0.50	0.75	0.65	0.65	0.42	0.15	0.75	0.11	na	na	na
	double	20	none	4.30	0.70	1.51	3.00	1.00	1.50	1.30	1.30	0.85	0.60	0.75	0.45	1.30	1.15	1.50
	triple	30	none	6.45	1.30	2.80	4.50	1.50	2.25	1.95	1.95	1.27	0.75	1.50	0.56	2.20	1.15	2.53
thick	single	5	none	2.15	0.10	0.22	1.50	0.50	0.75	0.65	0.65	0.42	0.15	0.75	0.11	na	na	na
	double	10	none	4.30	0.70	1.51	3.00	1.00	1.50	1.30	1.30	0.85	0.60	0.75	0.45	1.30	1.15	1.50
	triple	15	none	6.45	1.30	2.80	4.50	1.50	2.25	1.95	1.95	1.27	0.75	1.50	0.56	2.20	1.15	2.53

Table 16: Damage•Cost Analysis for the Grain Cart

	Grain Cart		Single Axle Truck			Tandem Axle Truck			Tridem Axle Truck			Tractor-Semitrailer		
Road	Damage	Cost	Damage	Cost	Multiplier	Damage	Cost	Multiplier	Damage	Cost	Multiplier	Damage	Cost	Multiplier
unpaved	5-14	none	4.5	1.5	2.25	1.95	1.95	1.27	0.75	1.5	0.56	2.2	1.2	2.5
ultra-thin	85-215	none	4.5	1.5	2.25	1.95	1.95	1.27	0.75	1.5	0.56	2.2	1.2	2.5
thin	5-9	none	4.5	1.5	2.25	1.95	1.95	1.27	0.75	1.5	0.56	2.2	1.2	2.5
thick	3	none	4.5	1.5	2.25	1.95	1.95	1.27	0.75	1.5	0.56	2.2	1.2	2.5

- Terragators should only be allowed to travel empty on unpaved roads and flexible pavements. Transporting agricultural chemicals to the field using legally loaded trucks and loading onto Terragators at the job site causes far less pavement damage.

- The high pressure concentrations at the lugged tire-pavement interface (more than 150 psi) could be highly damaging to unpaved roads during extremely wet seasons and to flexible pavements in areas where high turning actions are anticipated. Therefore, it is recommended that the movement of Terragators on extremely wet unpaved roads should be regulated. Also Terragators should not be allowed to maneuver on flexible pavements during the hot summer season.

- Grain carts traveling on unpaved roads and flexible pavements should only be allowed to transport the legal load limit.

- Special load restrictions should be posted on flexible pavements having HMA layer equal or less than 1.5" thick (including blotter) to prevent severe fatigue damages caused by all types of off-road equipment during the summer season.

Task 12: Prepare Final Report

Prepare a final report summarizing research methodology, findings, conclusions and recommendations.

This task prepared a final report documenting the field testing, data analyses, findings, and recommendations of all the research tasks of this project. The final report was submitted to SDDOT for review and comments and then revised to incorporate these comments.

Task 13: Make Executive Presentation

Make executive presentation to SDDOT's Research Review Board and a meeting of industry associations at the conclusion of the project.

An executive presentation was made to the SDDOT Research Review Board in Pierre, SD on November 28, 2001. The executive presentation was prepared by the research team and presented by the SDDOT's project manager due to a scheduling conflict. The presentation covered all the research activities that were accomplished in this project and the resulting recommendations.

FINDINGS AND CONCLUSIONS

This research study evaluated the effects of off-road equipment tires on flexible and granular pavements through a combination of field testing and theoretical modeling. The combination of the two approaches allowed the investigation to cover a wide range of pavements, materials, and environmental conditions. Interactions among these conditions created unique situations under which the impact of the various equipment were evaluated. The analysis of the data generated from these experiments led to the following findings and conclusions.

- Off-road equipment using lugged tires generates very complex stress distributions at the lug-pavement interface leading to extremely high concentrated pressures in excess of 150 psi, even under the relatively low inflation pressures of 30 psi. Because lugs do not sink into the pavement surface as they do on soft soils to allow the full tire surface to bear load, these high stress distributions can be very damaging to HMA surfaces during warm seasons.

- The seasonal in-situ properties of the pavement layers play a major role in controlling the relative damage caused by the off-road equipment. The summer season representing a soft HMA layer is most critical for fatigue damage, while the spring season representing a wet base/subgrade is the most critical condition for rutting damage.

- Off-road equipment damage of unpaved roads can be in the forms of rutting and surface disintegration, while the damage caused on flexible pavements can be in the forms of rutting, fatigue, and surface disintegration. Reducing the axle load of off-road equipment significantly reduces the potential for all damage types on both unpaved roads and flexible pavements.

- Off-road equipment can be categorized into three groups: a) non-damaging, b) damaging, and c) significantly damaging. The non-damaging group includes the tracked tractor weighing less than 25,500 lb per axle, the empty Terragators, and the legally loaded grain carts. The damaging group includes the loaded Terragators and over legal grain carts. The significantly damaging group includes the empty scraper.

- The transportation of equipment within the damaging group on unpaved roads and flexible pavements could cause damage ranging from medium to significant depending on the season, the type of soil, and pavement structure. The equipment should be driven unloaded and use legally loaded standard highway vehicles to transport their commodities to the field. The transportation of the significantly damaging group, i.e. the scraper, on unpaved roads and flexible pavements could cause severe and detrimental damage.

- The ultra-thin flexible pavements, HMA.-1.5", are very vulnerable to fatigue damage under all combinations of vehicle-load levels. The transportation of the off-road equipment on such pavements should be highly controlled, especially during the summer season when the HMA layer is extremely soft due to the elevated temperatures.

IMPLEMENTATION RECOMMENDATIONS

The implementation recommendations from this research are the result of the combined efforts of field testing and theoretical modeling. Field testing provided pavement responses under specific agricultural equipment and a scraper. Theoretical modeling was used to expand the applicability of the research findings over the range of various pavements and environmental conditions throughout the state of South Dakota. Theoretical modeling used the load levels that were tested in the field along with their corresponding tire types and pressures to predict the pavement damage caused by the various agricultural and heavy construction equipment.

It should be recognized that theoretical modeling is not dependent on the vehicle type but rather is a function of the tire, axle load, and inflation pressure. Furthermore, the analysis of the data indicated that the most critical factors are tire lugs and the magnitude of the load. The lugs contributed significantly to the fatigue performance of flexible pavements while the load level was the most predominant factor on the rutting performance of both flexible and unpaved pavements.

The analysis conducted in this study compared the damage caused by agricultural and construction equipment relative to the 18,000-lb single axle truck. This approach was selected to stay consistent with current pavement design, analysis, and management technologies which use the 18,000 ESAL concept. However, it should be noted that the single axle legal load limit in South Dakota is 20,000-lb, which has a load equivalency factor of 1.5. Therefore, any recommendation concerning the damage caused by agricultural and construction equipment will be compared to both the 18,000-lb single axle truck and the 20,000-lb legal load limit.

Using the combined data from field testing and theoretical modeling, this research project supports implementation recommendations that are both vehicle-specific and generalized to any lugged tires under a certain load level. The following represent the recommendations resulting from this research.

Vehicle Specific Recommendations

- Scrapers as heavy or heavier than those tested in this study should not be allowed to travel over unpaved roads and flexible pavements throughout the state of South Dakota. Transporting scrapers to the project site with multi-axle trucks meeting the legal load limits creates far less pavement damage. This is supported by the extremely high damage caused by the empty scraper on all pavement sections and during all seasons. Both the front and rear axles of a scraper were significantly more damaging than the standard 18,000-lb single axle truck and the legal limit of 20,000-lb single axle.

- Terragators should only be allowed to travel empty on unpaved roads and flexible pavements. Loaded Terragators caused more damage than the 18,000-lb single axle trucks and the legal limit of 20,00- lb single axle when operated during the summer, fall, and spring seasons. Transporting chemicals to the field using legally loaded axles and loading them onto Terragators at the job site creates far less pavement damage. For jobs requiring single or multiple Terragator loads, a tridem axle truck would be the most effective method of transporting the chemicals.

- Grain carts traveling on unpaved roads and flexible pavements should only be allowed to transport the legal load limit. This study found that grain carts loaded over the legal load limit impose more damage than the 18,000-lb single axle truck and the legal limit of 20,000-lb single axle during the summer, fall, and spring seasons. Transporting grain with legally-loaded tridem axle trucks creates far less pavement damage.

General Recommendations

- Tires designed with rectangular lugs should not be allowed to carry more than 20,000 lb/axle. This is supported by the high load equivalency factors that were computed for lugged tires on loaded vehicles as compared to the lugged tires on empty vehicles over the entire range of pavements and environmental conditions.

- The load per unit width of tire regulation should not be applied to the entire area of lugged tires due to the high ratio of gross to net contact areas of such tires. If such a regulation is desired it should only apply to the net area of the lugged tires.

- The low inflation pressure of lugged tires, 30 psi as compared to 100 psi for standard tires, should not be considered to offset heavier axle loads. This is supported by the fact that the low tire inflation pressure of 30 psi results in contact stresses at the lug-pavement interface in excess of 150 psi. Therefore, special consideration for lugged tires on the basis of low tire inflation pressure is not warranted.

- Special load restrictions should be posted on flexible pavements having HMA layer equal or less than 1.5" thick (including blotter) to prevent severe fatigue damages caused by all types off-road equipment during the summer season. The data from this study showed that the ultra-thin flexible pavements can suffer severe fatigue damage when loaded with empty and loaded off-road equipment due to their extremely low resistance to bending stresses.

- The high pressure concentrations at the lugged tires-pavement interface (more than150 psi) could be highly damaging to unpaved roads during extremely wet seasons and to flexible pavements in areas where sharp turning movements are anticipated. Therefore, it is recommended that the movement of vehicles equipped with lugged tires on extremely wet unpaved roads should be regulated. Also such vehicles should not be allowed to maneuver on flexible pavements during the hot summer season.

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APPENDIX A: PAVEMENT RESPONSES UNDER VARIOUS EQUIPMENT

Table 17: Summary of Responses from the Gravel Pavement Section near US212 September 14-15, 2000 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Pressure @ 7" below Surface (psi)	Pressure @ 10" below Surface (psi)	Surface Deflection (mil)
Dump Truck (loaded)	17,900	110	40	14.5	4.2	65
Terragator 8103 (empty)	18,680	36	40	17.5	3.7	76
Terragator 8144 (empty)	18,100	36	40	18.2	4.8	89
Terragator 8103 (loaded)	32,900	36	40	30.8	9.2	148
Terragator 8144 (loaded)	30,920	36	40	30.2	7.6	143
Scraper Front Axle	59,740	55	20	39.4	9.3	284
Scraper Rear Axle	41,400	55	20	27.0	7.6	241
Grain Cart (legal load)	22,980	16	20	15.2	3.4	112
Grain Cart (over legal load)	33,220	16	20	17.6	4.4	129
Tracked Tractor	25,400		20	1.4	0.5	40

Table 18: Summary of Responses from the Blotter Pavement Section on 348th Avenue near SD26
September 14-15, 2000 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)
Dump Truck (loaded)	17,900	110	40	50.4	14.7	NR*
Terragator 8103 (empty)	18,680	36	40	58.4	17.7	NR
Terragator 8144 (empty)	18,100	36	40	63.8	18.7	NR
Terragator 8103 (loaded)	33,260	36	40	84.1	31.7	152
Terragator 8144 (loaded)	31,800	36	40	76.3	28.6	118
Dump truck (loaded)	17,900	110	20	76.5	20.0	96
Scraper Front Axle	59,740	55	20	76.5	33.7	220
Scraper Rear Axle	41,400	55	20	50.5	26.2	136
Grain Cart (legal load)	21,900	16	20	49.4	17.8	95
Grain Cart (over legal load)	28,900	16	20	54.7	19.6	153
Tracked Tractor	25,400		20	4.2	6.1	3

* NR: Data were collected but not reported.

Table 19: Summary of Responses from the Thin Flexible Pavement Section on US212
September 14-15, 2000 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,900	110	40	100	28.0	8.4	27	733
Terragator 8103 (empty)	18,680	36	40	98	22.2	9.7	31	709
Terragator 8144 (empty)	18,100	36	40	100	23.1.	9.9	32	883
Terragator 8103 (loaded)	32,900	36	40	94	NR	NR	NR	1050
Terragator 8144 (loaded)	30,920	36	40	95	28.2	14.9	41	893
Dump truck (loaded)	17,900	110	20	100	16.6	7.6	22	906
Scraper Front Axle	59,740	55	20	97	36.5	24.5	97	1286
Scraper Rear Axle	41,400	55	20	97	28.2	17.3	73	NR
Grain Cart (legal load)	20,200	16	20	100	16.1	9.6	35	525
Grain Cart (over legal load)	33,220	16	20	99	16.6	12.0	43	526
Tracked Tractor	25,400		20	97	8.5	6.4	20	395

Table 20: Summary of Responses from the Thick Flexible Pavement Section on US212
September 14-15, 2000 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,900	110	40	100	17.8	4.9	26	760
Terragator 8103 (empty)	18,680	36	40	98	18.0	6.0	29	513
Terragator 8144 (empty)	18,100	36	40	100	19.5	5.1	25	433
Terragator 8103 (loaded)	32,900	36	40	94	NR	NR	NR	598
Terragator 8144 (loaded)	30,920	36	40	95	24.4	8.9	37	728
Dump truck (loaded)	17,900	110	20	100	14.7	4.6	27	1085
Scraper Front Axle	59,740	55	20	97	39.8	14.1	80	1297
Scraper Rear Axle	41,400	55	20	97	32.6	10.5	66	797
Grain Cart (legal load)	20,200	16	20	100	15.5	5.8	31	403
Grain Cart (over legal load)	33,200	16	20	99	16.7	7.4	38	531
Tracked Tractor	25,400		20	97	6.3	4.3	14	406

**Table 21: Summary of Responses from the Thin Flexible Pavement Section on SD26
September 14-15, 2000 Testing**

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB(psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,900	110	40	86	8.7	5.9	28	46
Terragator 8103 (empty)	18,680	36	40	95	8.3	7.0	28	56
Terragator 8144 (empty)	18,100	36	40	96	8.4	7.1	28	72
Terragator 8103 (loaded)	33,260	36	40	91	12.2	9.8	48	50
Terragator 8144 (loaded)	31,800	36	40	94	12.0	9.5	50	141
Dump truck (loaded)	17,900	110	20	98	7.9	6.5	32	64
Scraper Front Axle	59,740	55	20	92	20.6	17.5	78	NR
Scraper Rear Axle	41,400	55	20	92	11.9	10.0	55	100
Grain Cart (legal load)	20,460	16	20	91	5.4	4.8	23	48
Grain Cart (over legal load)	28,900	16	20	97	11.6	10.7	42	97
Tracked Tractor	25,400		20	96	5.4	4.5	24	42

Table 22: Summary of Responses from the Thick Flexible Pavement Section on SD26
September 14-15, 2000 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,900	110	40	86	5.8	2.7	23	79
Terragator 8103 (empty)	18,680	36	40	95	5.5	2.9	28	84
Terragator 8144 (empty)	18,100	36	40	96	6.1	2.8	25	86
Terragator 8103 (loaded)	33,260	36	40	91	8.4	3.7	39	96
Terragator 8144 (loaded)	31,800	36	40	94	9.2	3.7	45	103
Dump truck (loaded)	17,900	110	20	98	5.1	2.2	26	93
Scraper Front Axle	59,740	55	20	92	15.1	6.9	92	188
Scraper Rear Axle	41,400	55	20	92	11.1	4.6	66	112
Grain Cart (legal load)	20,460	16	20	91	3.8	1.8	17	17
Grain Cart (over legal load)	28,900	16	20	97	8.4	3.9	42	98
Tracked Tractor	25,400		20	96	3.5	1.7	18	53

Table 23: Summary of Responses from the Gravel Pavement Section near US212
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Pressure @ 7" below Surface (psi)	Pressure @ 10" below Surface (psi)	Surface Deflection (mil)
Dump Truck (loaded)	18,250	100	40	19.8	8.2	69
Terragator 8103 (empty)	18,650	30	40	30.0	8.4	94
Terragator 8144 (empty)	17,900	30	40	29.0	9.6	102
Terragator 8103 (loaded)	33,900	30	40	42.7	12.1	176
Terragator 8144 (loaded)	30,550	30	40	31.8	10.1	144
Scraper Front Axle	72,900	60	20	58.1	18.7	289
Scraper Rear Axle	44,750	60	20	43.0	10.6	207
Grain Cart (legal load)	20,050	30	20	NC*	NC	NC
Grain Cart (over legal load)	33,500	30	20	21.3	8.0	174
Tracked Tractor	25,400		20	4.2	1.9	38

* NC: Data were not collected

Table 24: Summary of Responses from the Blotter Pavement Section on 348th Avenue near SD26
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Pressure @ Center of CAB(psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)
Dump Truck (loaded)	18,300	100	40	79.8	11.5	83
Terragator 8103 (empty)	18,650	30	40	78.9	27.1	142
Terragator 8144 (empty)	17,900	30	40	60.6	23.2	137
Terragator 8103 (loaded)	33,900	30	40	78.5	41.2	222
Terragator 8144 (loaded)	30,550	30	40	72.9	35.3	219
Dump Truck (loaded)	18,300	100	20	59.4	14.3	132
Scraper Front Axle	72,900	60	20	114.2	62.3	470
Scraper Rear Axle	44,750	60	20	106.7	47.5	194
Grain Cart (legal load)	19,100	30	20	36.3	22.8	253
Grain Cart (over legal load)	32,700	30	20	46.5	27.3	217
Tracked Tractor	25,400		20	6.1	7.3	34

Table 25: Summary of Responses from the Thin Flexible Pavement Section on US212
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,250	100	40	39	5.1	4.3	33	301
Terragator 8103 (empty)	18,650	30	40	40	4.3	4.8	29	361
Terragator 8144 (empty)	17,900	30	40	40	5.6	4.4	36	288
Terragator 8103 (loaded)	33,900	30	40	40	9.5	7.7	66	530
Terragator 8144 (loaded)	30,550	30	40	40	8.7	6.9	66	384
Dump truck (loaded)	18,250	100	20	39	5.3	4.8	35	349
Scraper Front Axle	72,900	60	20	40	24.2	13.6	170	729
Scraper Rear Axle	44,750	60	20	40	17.0	7.5	137	638
Grain Cart (legal load)	20,050	30	20	40	4.0	4.1	32	275
Grain Cart (over legal load)	33,500	30	20	41	NR*	7.5	68	317
Tracked Tractor	25,400		20	41	4.0	4.4	37	123

* NR: Data were collected but not reported.

Table 26: Summary of Responses from the Thick Flexible Pavement Section on US212
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,250	100	40	39	5.1	1.9	17	207
Terragator 8103 (empty)	18,650	30	40	40	4.7	2.0	16	229
Terragator 8144 (empty)	17,900	30	40	40	5.8	2.7	17	196
Terragator 8103 (loaded)	33,900	30	40	40	8.4	3.2	37	389
Terragator 8144 (loaded)	30,550	30	40	40	8.3	3.6	35	331
Dump truck (loaded)	18,250	100	20	39	6.1	2.0	18	251
Scraper Front Axle	72,900	60	20	40	20.4	8.2	87	738
Scraper Rear Axle	44,750	60	20	40	15.4	5.5	68	627
Grain Cart (legal load)	20,050	30	20	40	4.9	2.0	21	246
Grain Cart (over legal load)	33,500	30	20	41	9.3	4.2	46	310
Tracked Tractor	25,400		20	41	5.4	2.4	24	81

Table 27: Summary of Responses from the Thin Flexible Pavement Section on SD26
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,300	100	40	39	2.9	2.4	15	32
Terragator 8103 (empty)	18,650	30	40	40	4.0	2.7	18	30
Terragator 8144 (empty)	17,900	30	40	40	3.0	2.9	17	23
Terragator 8103 (loaded)	33,900	30	40	45	NR*	6.2	45	120
Terragator 8144 (loaded)	30,550	30	40	45	5.4	5.5	39	100
Dump truck (loaded)	18,300	100	20	39	2.9	2.4	15	32
Scraper Front Axle	72,900	60	20	40	12.6	8.5	128	276
Scraper Rear Axle	44,750	60	20	40	6.3	2.3	65	185
Grain Cart (legal load)	22,850	30	20	52	4.7	4.4	38	68
Grain Cart (over legal load)	32,700	30	20	61	7.3	6.7	54	101
Tracked Tractor	25,400		20	52	3.7	3.5	27	39

* NR: Data were collected but not reported.

Table 28: Summary of Responses from the Thick Flexible Pavement Section on SD26
April 4-5, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,300	100	40	39	2.1	0.8	11	50
Terragator 8103 (empty)	18,650	30	40	40	2.4	1.1	14	48
Terragator 8144 (empty)	17,900	30	40	40	2.7	1.1	11	44
Terragator 8103 (loaded)	33,900	30	40	45	4.7	1.4	25	76
Terragator 8144 (loaded)	30,550	30	40	45	4.6	1.5	26	73
Dump truck (loaded)	18,300	100	20	39	2.1	0.8	11	50
Scraper Front Axle	72,900	60	20	40	9.0	3.1	59	196
Scraper Rear Axle	44,750	60	20	40	7.7	5.4	42	152
Grain Cart (legal load)	22,850	30	20	52	2.9	1.5	22	99
Grain Cart (over legal load)	32,700	30	20	61	5.1	2.3	34	118
Tracked Tractor	25,400		20	52	2.6	1.1	20	74

Table 29: Summary of Responses from the Blotter Pavement Section on 348th Avenue near SD26
August 28-29, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Pressure @ Center of CAB(psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)
Dump Truck (loaded)	17,600	100	40	65.4	16.3	131
Terragator 8103 (empty)	17,350	36	40	71.0	26.1	180
Terragator 8144 (empty)	14,550	36	40	55.9	17.8	181
Terragator 8103 (loaded)	27,500	36	40	112.0	NR	277
Terragator 8144 (loaded)	25,050	36	40	107.2	NR	246
Grain Cart (legal load)	20,850	30	20	54.0	18.1	272
Grain Cart (over legal load)	49,800	30	20	66.4	28.5	317

* NR: Data were collected but not reported.

Table 30: Summary of Responses from the Thin Flexible Pavement Section on US212
August 28-29, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,300	110	40	106	16.5	8.3	67	853
Terragator 8103 (empty)	17,350	36	40	104	NR	10.3	64	672
Terragator 8144 (empty)	14,550	36	40	104	NR	8.2	53	670
Terragator 8103 (loaded)	29,900	36	40	107	24.8	13.4	85	694
Terragator 8144 (loaded)	27,100	36	40	107	22.6	12.6	79	910
Grain Cart (legal load)	18,700	30	20	106	15.2	10.8	59	467
Grain Cart (over legal load)	49,550	30	20	107	22.5	19.6	136	836

* NR: Data were collected but not reported.

Table 31: Summary of Responses from the Thin Flexible Pavement Section on SD26
August 28-29, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,600	100	40	107	11.2	7.0	48	125
Terragator 8103 (empty)	17,350	36	40	112	14.8	8.9	50	158
Terragator 8144 (empty)	14,550	36	40	112	13.9	8.3	45	198
Terragator 8103 (loaded)	27,500	36	40	112	20.3	12.5	87	298
Terragator 8144 (loaded)	27,100	36	40	112	19.7	11.5	75	256
Grain Cart (legal load)	21,400	30	20	110	16.4	9.9	92	222
Grain Cart (over legal load)	49,200	30	20	110	24.7	18.1	176	432

* NR: Data were collected but not reported.

Table 32: Summary of Responses from the Thick Flexible Pavement Section on US212
August 28-29, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	18,300	110	40	106	16.8	4.2	19	781
Terragator 8103 (empty)	17,350	36	40	104	17.3	5.4	15	593
Terragator 8144 (empty)	14,550	36	40	104	17.2	4.1	14	574
Terragator 8103 (loaded)	29,900	36	40	107	22.8	7.7	29	523
Terragator 8144 (loaded)	27,100	36	40	107	23.1	7.4	28	678
Grain Cart (legal load)	18,700	30	20	106	15.6	5.6	15	445
Grain Cart (over legal load)	49,550	30	20	107	29.8	11.2	52	837

Table 33: Summary of Responses from the Thick Flexible Pavement Section on SD26
August 28-29, 2001 Testing

Vehicle	Load (lb/axle)	Tire Pressure (psi)	Speed (mph)	Avg Pav Temp (F)	Pressure @ Center of CAB (psi)	Pressure @ 4" into Subgrade (psi)	Surface Deflection (mil)	Tensile Strain (microns)
Dump Truck (loaded)	17,600	100	40	107	6.7	3.5	24	90
Terragator 8103 (empty)	17,350	36	40	112	7.6	4.3	28	109
Terragator 8144 (empty)	14,550	36	40	112	7.6	3.8	22	188
Terragator 8103 (loaded)	27,500	36	40	112	13.2	5.4	41	242
Terragator 8144 (loaded)	27,100	36	40	112	11.8	5.4	40	215
Grain Cart (legal load)	21,400	30	20	110	8.5	5.0	39	214
Grain Cart (over legal load)	49,200	30	20	110	15.6	7.8	85	381

APPENDIX B: PAVEMENT RESPONSE RATIOS UNDER VARIOUS EQUIPMENT

Table 34: Pavement Response Ratios for the Gravel Section near US212

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	1.21		1.17
	Terragator 8144 (empty)	1.26	1.14	1.37
	Terragator 8103 (loaded)	2.12	2.19	2.28
	Terragator 8144 (loaded)	2.08	1.81	2.20
	Scraper Front Axle	2.72	2.21	4.37
	Scraper Rear Axle	1.86	1.81	3.71
	Grain Cart (legal)	1.05		1.72
	Grain Cart (over legal)	1.21		1.98
	Tracked Tractor			0.62
Spring 2001 (April/01)	Terragator 8103 (empty)	1.52	1.02	1.36
	Terragator 8144 (empty)	1.46	1.14	1.48
	Terragator 8103 (loaded)	2.16	1.48	2.55
	Terragator 8144 (loaded)	1.61	1.23	2.09
	Scraper Front Axle	2.93	2.28	4.19
	Scraper Rear Axle	2.17	1.29	3.00
	Grain Cart (legal)			
	Grain Cart (over legal)	1.08	0.98	2.52
	Tracked Tractor			0.55

Table 35: Pavement Response Ratios for the Blotter Section on 348th Avenue near SD26

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	1.16	1.20	
	Terragator 8144 (empty)	1.27	1.27	
	Terragator 8103 (loaded)	1.67	2.16	1.58
	Terragator 8144 (loaded)	1.51	1.95	1.23
	Scraper Front Axle	1.00	1.69	2.29
	Scraper Rear Axle	0.67	1.31	1.42
	Grain Cart (legal)	0.65	0.89	1.00
	Grain Cart (over legal)	0.72	0.98	1.59
	Tracked Tractor		0.31	
Spring 2001 (April/01)	Terragator 8103 (empty)	0.99	2.36	1.71
	Terragator 8144 (empty)	0.76	2.02	1.65
	Terragator 8103 (loaded)	0.98	3.58	2.67
	Terragator 8144 (loaded)	0.91	3.07	2.64
	Scraper Front Axle	1.92	4.36	3.56
	Scraper Rear axle	1.80	3.32	1.47
	Grain Cart (legal)	0.61	1.59	1.92
	Grain Cart (over legal)	0.78	1.91	1.64
	Tracked Tractor	0.10	0.51	0.26
Summer 2001 (August/01)	Terragator 8103 (empty)	1.09	1.60	1.37
	Terragator 8144 (empty)	0.85	1.10	1.38
	Terragator 8103 (loaded)	1.71		2.11
	Terragator 8144 (loaded)	1.64		1.88
	Grain Cart (legal)	0.83	1.11	2.08
	Grain Cart (over legal)	1.02	1.75	2.42

Table 36: Pavement Response Ratios for the US212 Thin Section

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio	Tensile Strain Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	0.79	1.15	1.15	0.97
	Terragator 8144 (empty)	0.83	1.15	1.19	1.20
	Terragator 8103 (loaded)				1.43
	Terragator 8144 (loaded)	1.00	1.77	1.52	1.22
	Scraper Front Axle	2.20	3.22	4.41	1.42
	Scraper Rear Axle	1.70	2.28	3.32	NR
	Grain Cart (legal)	0.97	1.26	1.59	0.58
	Grain Cart (over legal)	1.00	1.58	1.95	0.58
	Tracked Tractor	0.51	0.84	0.91	0.44
Spring 2001 (April/01)	Terragator 8103 (empty)			0.88	1.20
	Terragator 8144 (empty)	1.10		1.09	0.96
	Terragator 8103 (loaded)	1.86	1.79	2.00	1.76
	Terragator 8144 (loaded)	1.71	1.60	2.00	1.28
	Scraper Front Axle	4.57	2.83	4.86	2.09
	Scraper Rear Axle	3.20	1.56	3.91	1.83
	Grain Cart (legal)			0.91	0.79
	Grain Cart (over legal)		1.56	1.94	0.91
	Tracked Tractor			1.06	0.35
Summer 2001 (August/01)	Terragator 8103 (empty)		1.24	0.96	0.79
	Terragator 8144 (empty)		1.00	0.79	0.79
	Terragator 8103 (loaded)	1.50	1.61	1.27	0.81
	Terragator 8144 (loaded)	1.37	1.52	1.18	1.07
	Grain Cart (legal)	0.92	1.30	0.88	0.55
	Grain Cart (over legal)	1.36	2.36	2.03	0.98

Table 37: Pavement Response Ratios for the US212 Thick Section

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio	Tensile Strain Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	1.01	1.22	1.12	0.68
	Terragator 8144 (empty)	1.10	1.04	0.96	0.57
	Terragator 8103 (loaded)				0.79
	Terragator 8144 (loaded)	1.37	1.82	1.42	0.96
	Scraper Front Axle	2.71	3.07	2.96	1.20
	Scraper Rear Axle	2.22	2.19	2.44	0.73
	Grain Cart (legal)	1.05	1.26	1.15	0.37
	Grain Cart (over legal)	1.14	1.61	1.41	0.49
	Tracked Tractor	0.43		0.52	0.37
Spring 2001 (April/01)	Terragator 8103 (empty)			0.94	1.11
	Terragator 8144 (empty)	1.14		1.00	0.95
	Terragator 8103 (loaded)	1.65		2.18	1.88
	Terragator 8144 (loaded)	1.63		2.06	1.60
	Scraper Front Axle	3.34		4.83	2.94
	Scraper Rear Axle	2.52		3.78	2.49
	Grain Cart (legal)			1.17	0.98
	Grain Cart (over legal)	1.52		2.56	1.24
	Tracked Tractor	0.89		1.33	0.32
Summer 2001 (August/01)	Terragator 8103 (empty)	1.03	1.29	0.79	0.76
	Terragator 8144 (empty)	1.02	0.98	0.74	0.73
	Terragator 8103 (loaded)	1.36	1.83	1.53	0.67
	Terragator 8144 (loaded)	1.38	1.76	1.47	0.87
	Grain Cart (legal)	0.93	1.33	0.79	0.57
	Grain Cart (over legal)	1.77	2.67	2.74	1.07

Table 38: Pavement Response Ratios for the SD26 Thin Section

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio	Tensile Strain Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	0.95	1.19	1.00	1.22
	Terragator 8144 (empty)	0.97	1.20	1.00	1.57
	Terragator 8103 (loaded)	1.40	1.66	1.71	1.09
	Terragator 8144 (loaded)	1.38	1.61	1.79	3.07
	Scraper Front Axle	2.61	2.69	2.44	NR
	Scraper Rear Axle	1.51	1.54	1.72	1.56
	Grain Cart (legal)	0.68		0.72	0.75
	Grain Cart (over legal)	1.47	1.65	1.31	1.52
	Tracked Tractor	0.68		0.75	0.66
Spring 2001 (April/01)	Terragator 8103 (empty)			1.20	0.94
	Terragator 8144 (empty)			1.13	0.72
	Terragator 8103 (loaded)			3.00	3.75
	Terragator 8144 (loaded)			2.60	3.13
	Scraper Front Axle	**	**	8.53	8.63
	Scraper Rear Axle	**		4.33	5.78
	Grain Cart (legal)			2.53	2.13
	Grain Cart (over legal)	**	**	3.60	3.16
	Tracked Tractor			1.80	1.22
Summer 2001 (August/01)	Terragator 8103 (empty)	1.32	1.27	1.04	1.26
	Terragator 8144 (empty)	1.24	1.19	0.94	1.58
	Terragator 8103 (loaded)	1.81	1.79	1.81	2.38
	Terragator 8144 (loaded)	1.76	1.64	1.56	2.05
	Grain Cart (legal)	1.46	1.42	1.92	1.78
	Grain Cart (over legal)	2.21	2.59	3.67	3.46

** only these vehicles generated pressures above 5 psi.

Table 39: Pavement Response Ratios for the SD26 Thick Section

Season	Vehicle	Base Pressure Ratio	Subgrade Pressure Ratio	Surface Deflection Ratio	Tensile Strain Ratio
Fall 2000 (Sept/00)	Terragator 8103 (empty)	0.95		1.22	1.06
	Terragator 8144 (empty)	1.05		1.09	1.09
	Terragator 8103 (loaded)	1.45		1.70	1.22
	Terragator 8144 (loaded)	1.59		1.96	1.30
	Scraper Front Axle	2.96	**	3.54	2.02
	Scraper Rear Axle	2.18		2.54	1.20
	Grain Cart (legal)			0.65	0.18
	Grain Cart (over legal)	1.65		1.62	1.05
	Tracked Tractor			0.70	0.57
Spring 2001 (April/01)	Terragator 8103 (empty)			1.27	0.96
	Terragator 8144 (empty)			1.00	0.88
	Terragator 8103 (loaded)			2.27	1.52
	Terragator 8144 (loaded)			2.36	1.46
	Scraper Front Axle	**		5.36	3.92
	Scraper Rear Axle	**		3.82	3.04
	Grain Cart (legal)			2.00	1.98
	Grain Cart (over legal)			3.09	2.36
	Tracked Tractor			1.82	1.48
Summer 2001 (August/01)	Terragator 8103 (empty)	1.13		1.17	1.21
	Terragator 8144 (empty)	1.13		0.92	2.09
	Terragator 8103 (loaded)	1.97	**	1.71	2.69
	Terragator 8144 (loaded)	1.76	**	1.67	2.39
	Grain Cart (legal)	1.27		1.63	2.38
	Grain Cart (over legal)	2.33	**	3.54	4.23

** only these vehicles generated pressures above 5 psi.

APPENDIX C: VERIFICATION OF THE 3D-MOVE MODEL

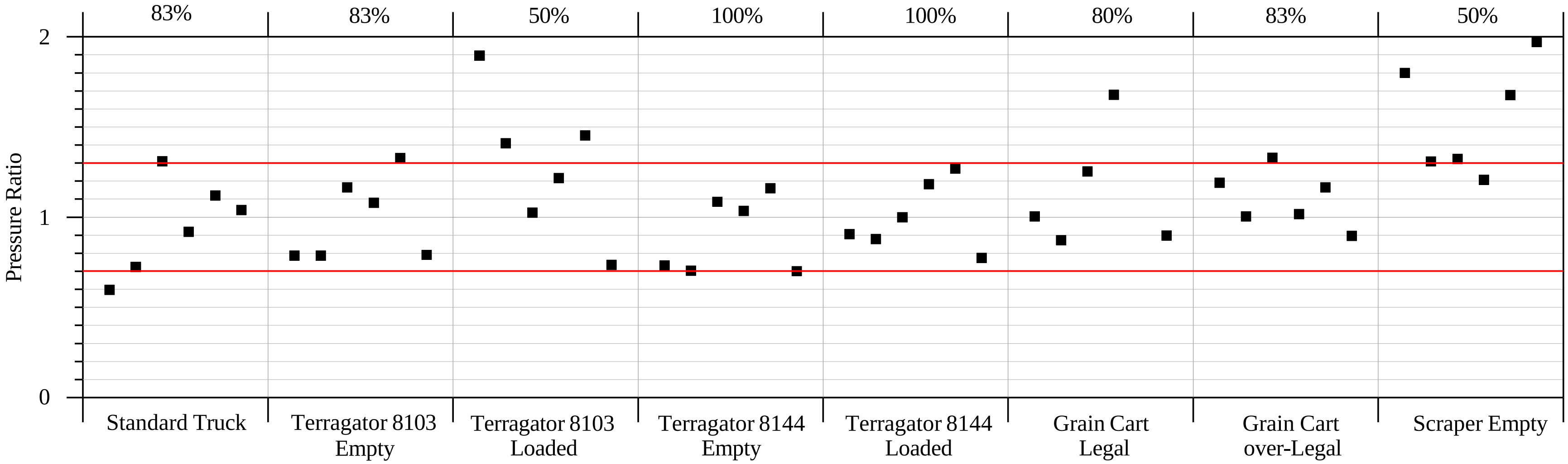

Figure 33: Pressure Ratio (Computed/Average Measured) in the Middle of CAB Layer September 2000

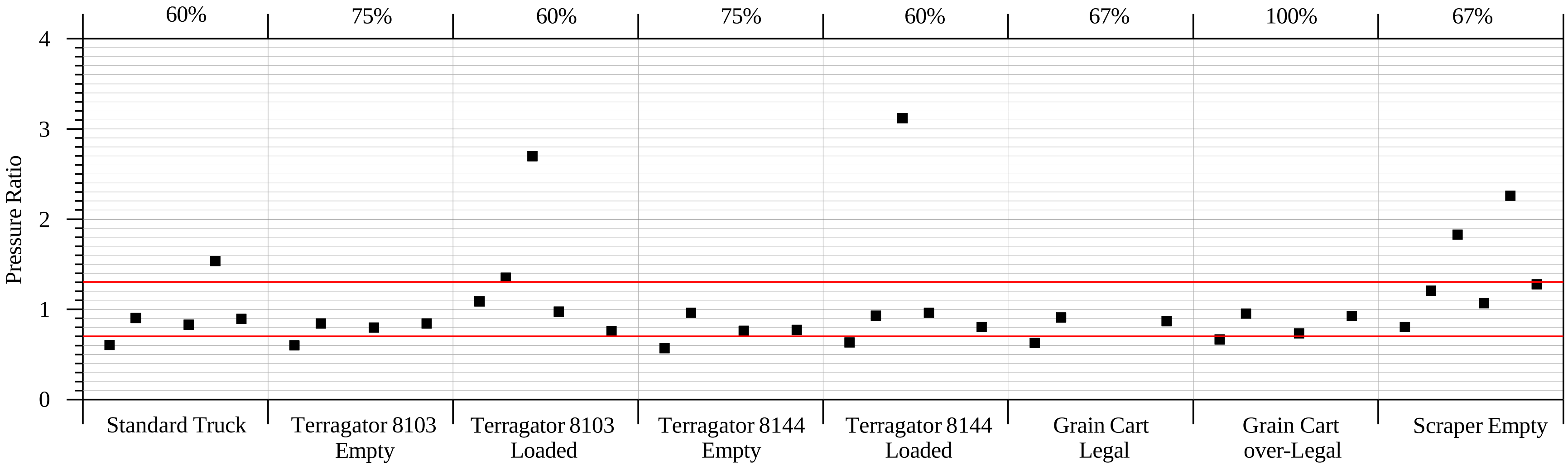

Figure 34: Pressure Ratio (Computed/Average Measured) in the Subgrade September 2000

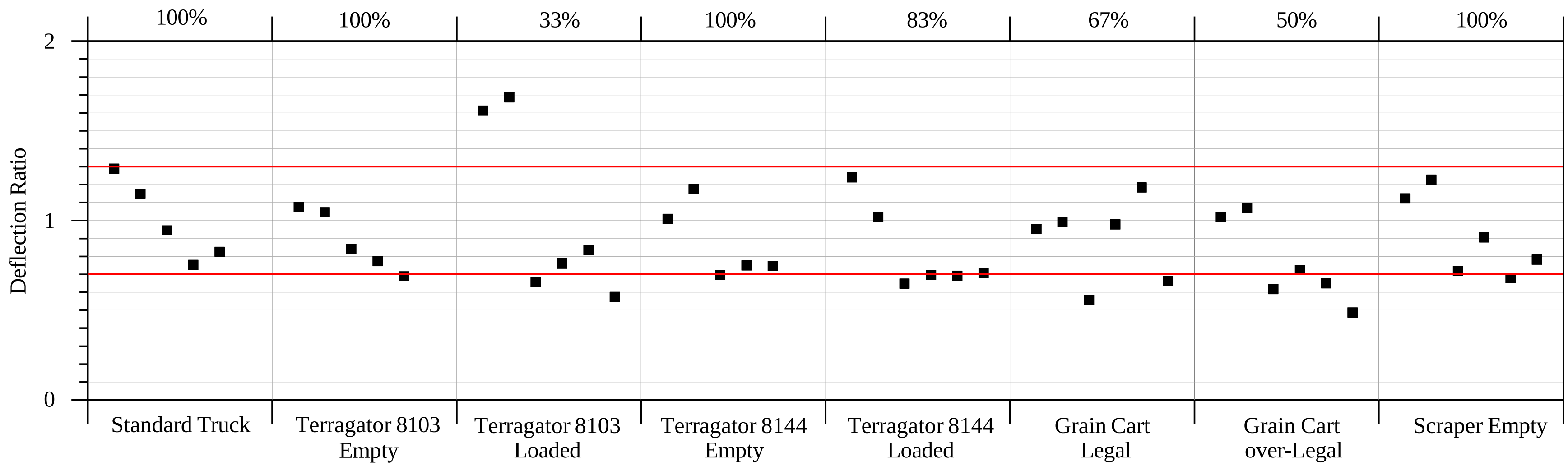

Figure 35: Surface Deflection Ratio (Computed/Average Measured)
September 2000

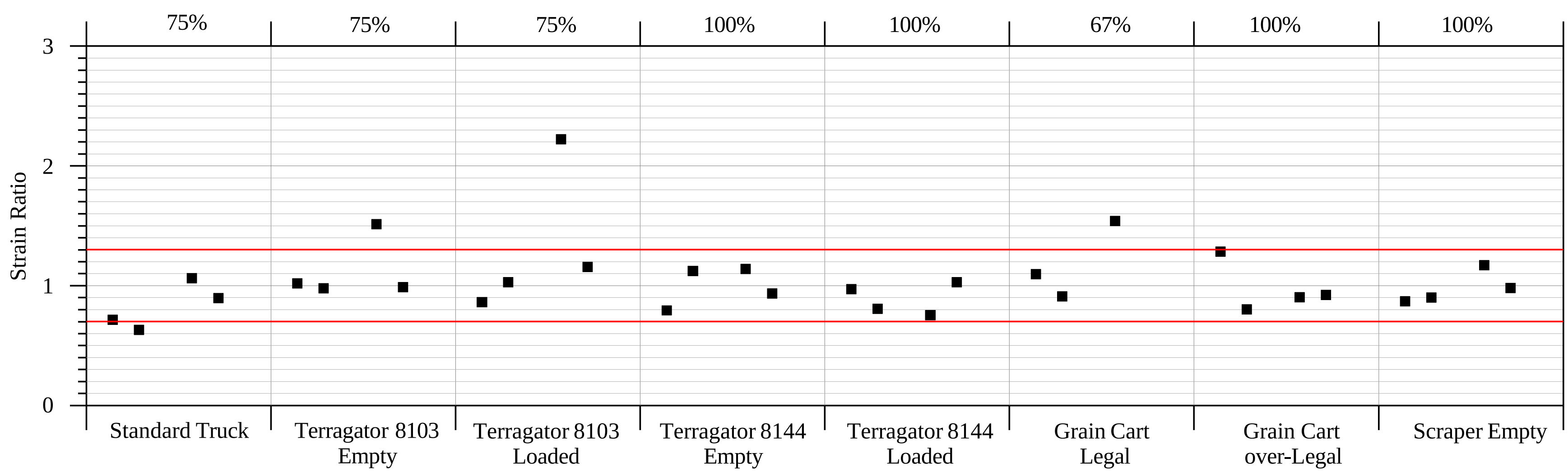

Figure 36: Tensile Strain Ratio (Computed/Average Measured) at the Bottom of the New HMA Layer
September 2000

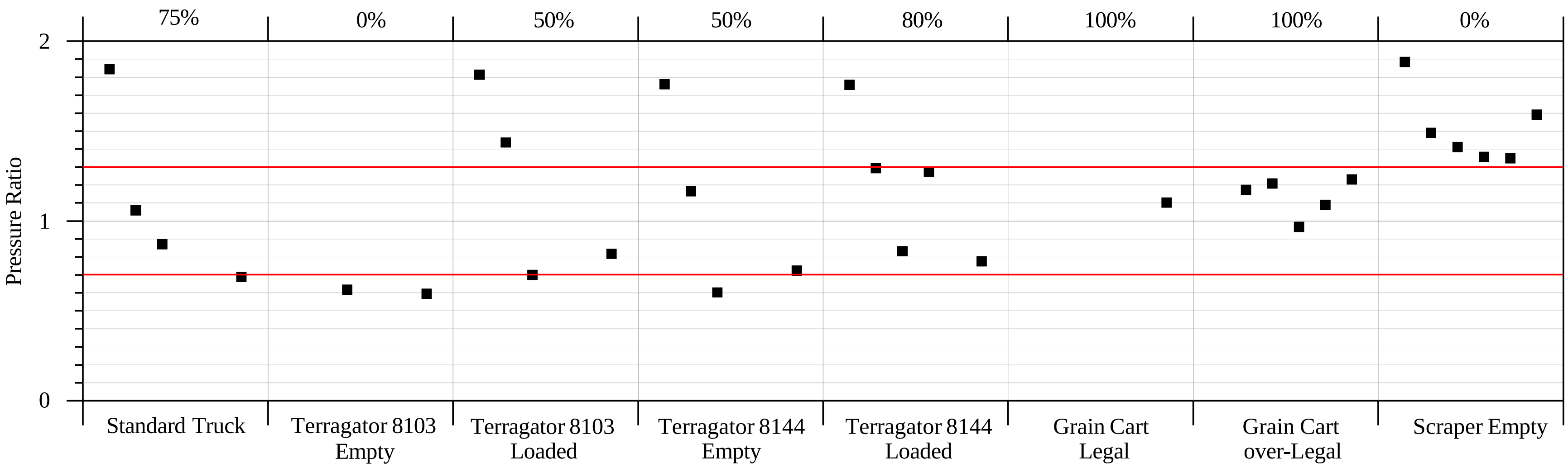

Figure 37: Pressure Ratio (Computed/Average Measured) in the Middle of CAB layer April 2001

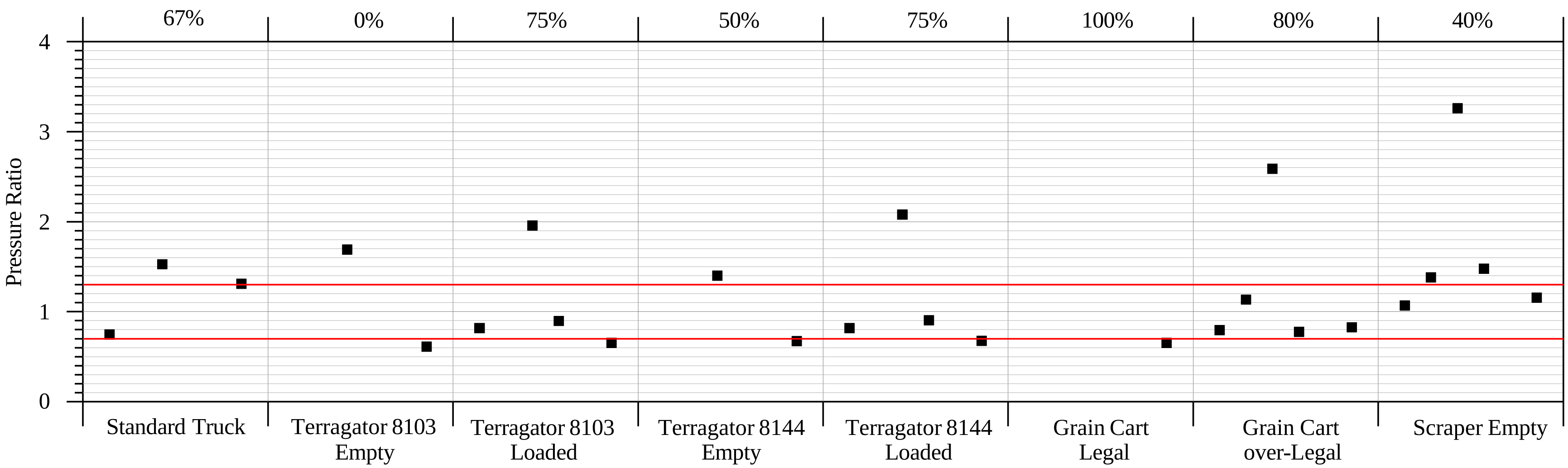

Figure 38: Pressure Ratio (Computed/Average Measured) in the Subgrade April 2001

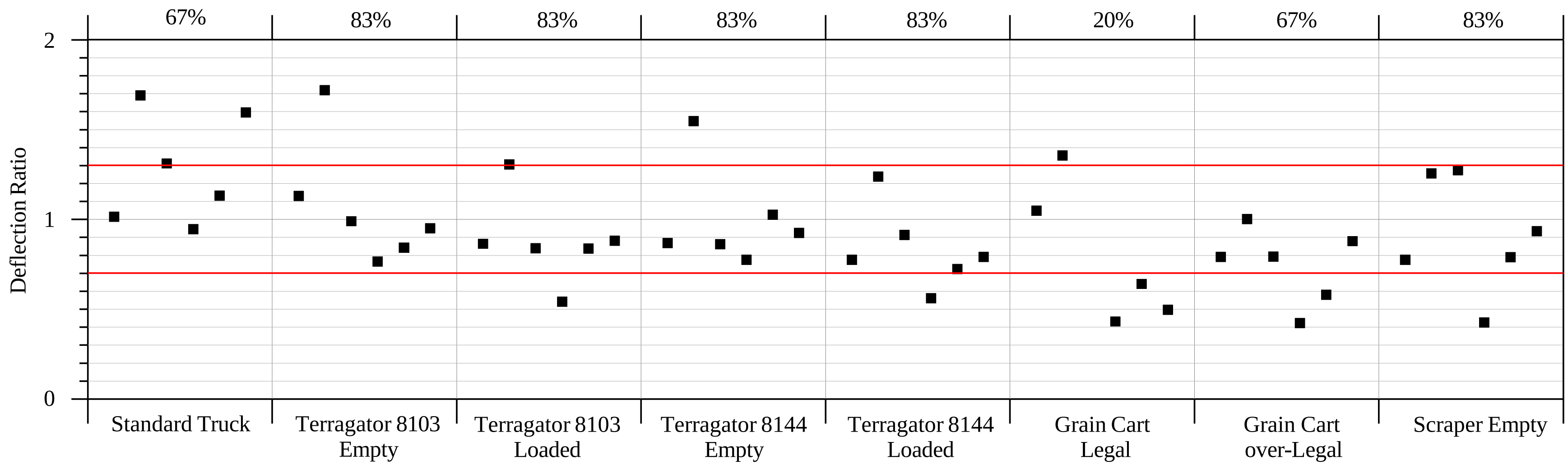

Figure 39: Surface Deflection Ratio (Computed/Average Measured)
April 2001

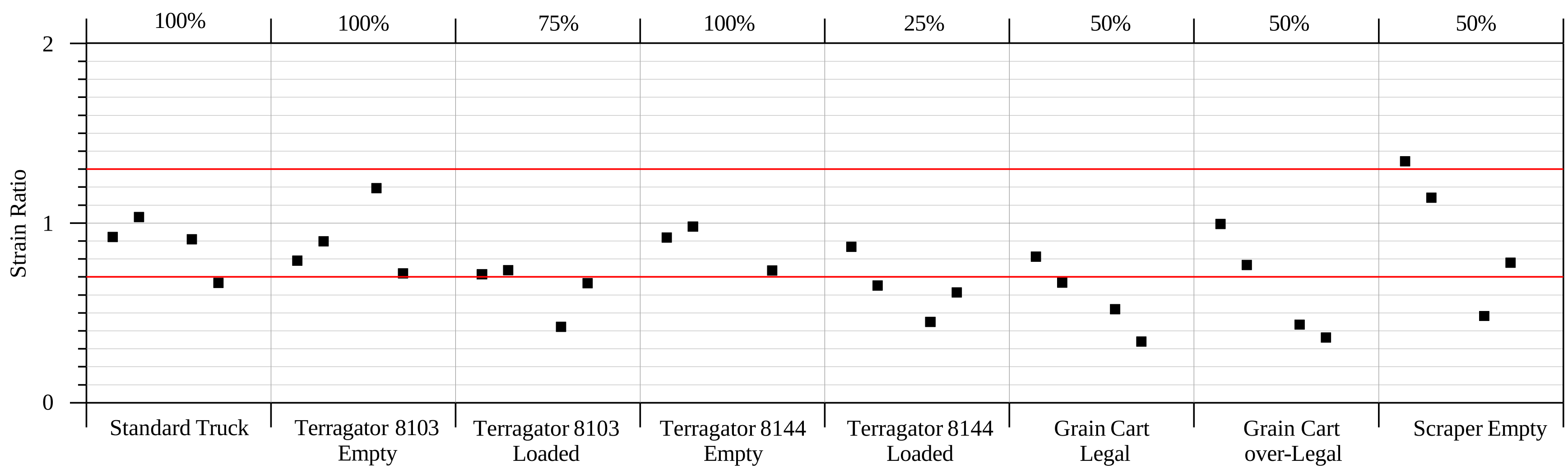

Figure 40: Tensile Strain Ratio (Computed/Average Measured) at the Bottom of the New HMA Layer
April 2001

APPENDIX D: DISTRIBUTIONS OF THE LOAD EQUIVALENCY FACTORS

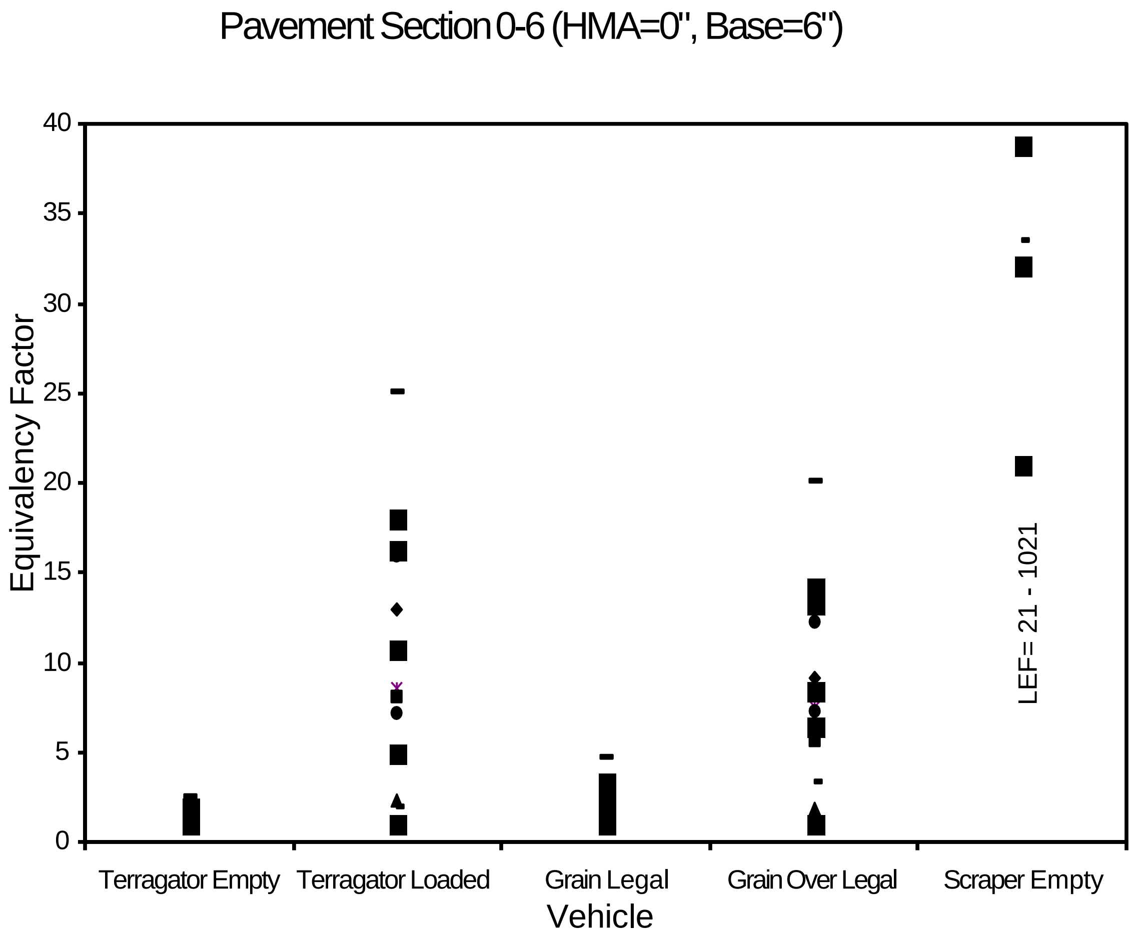

Figure 41: Distribution of Fatigue and Rutting Load Equivalency Factors

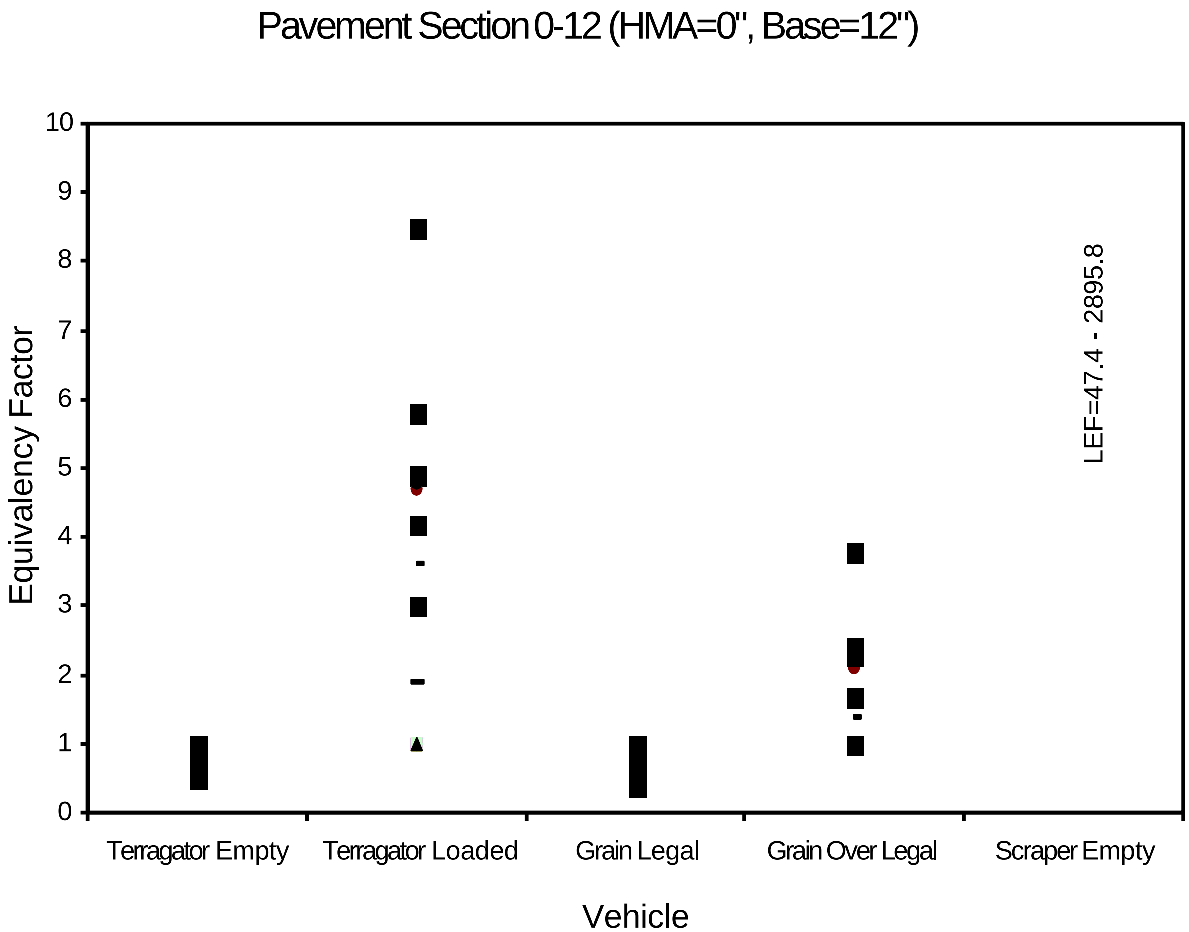

Figure 42: Distribution of Fatigue and Rutting Load Equivalency Factors

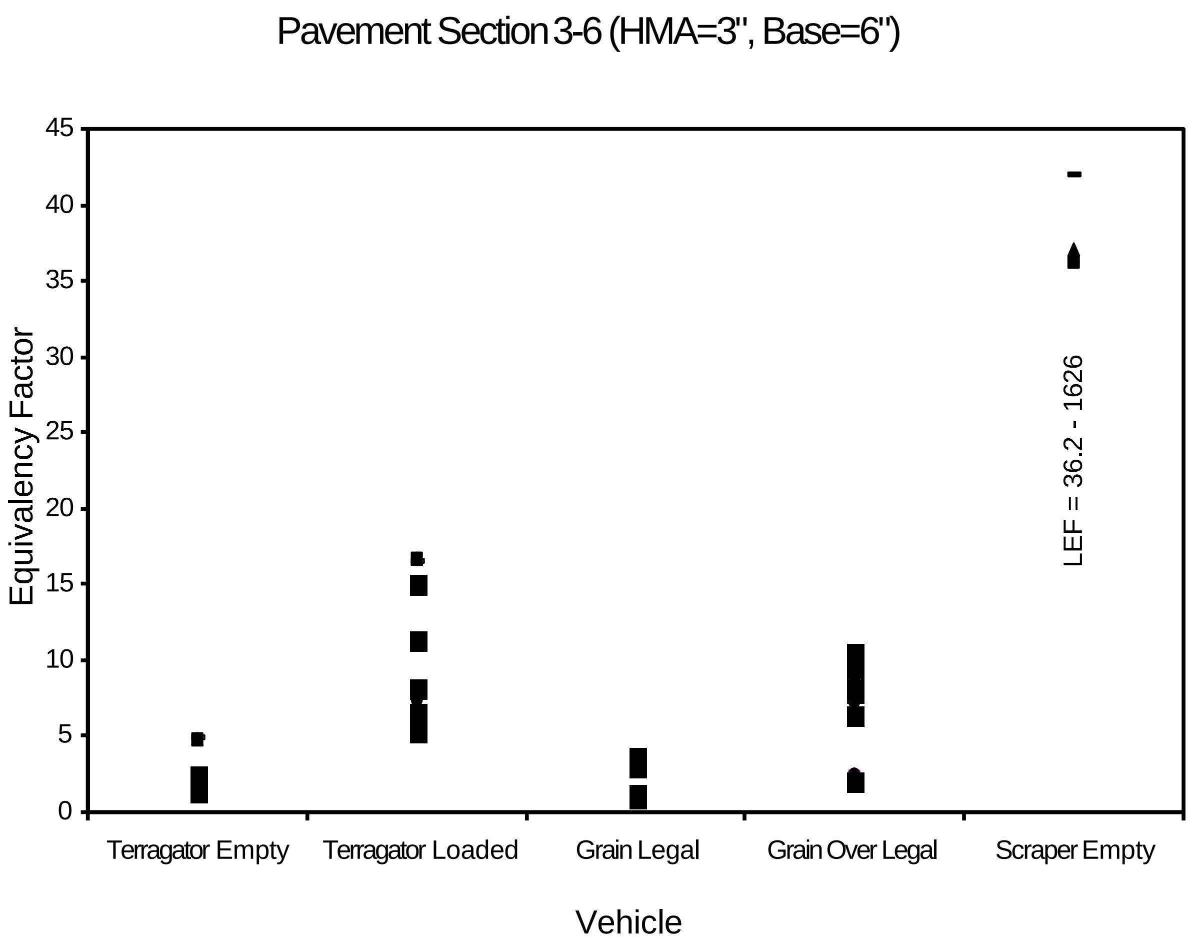

Figure 43: Distribution of Fatigue and Rutting Load Equivalency Factors

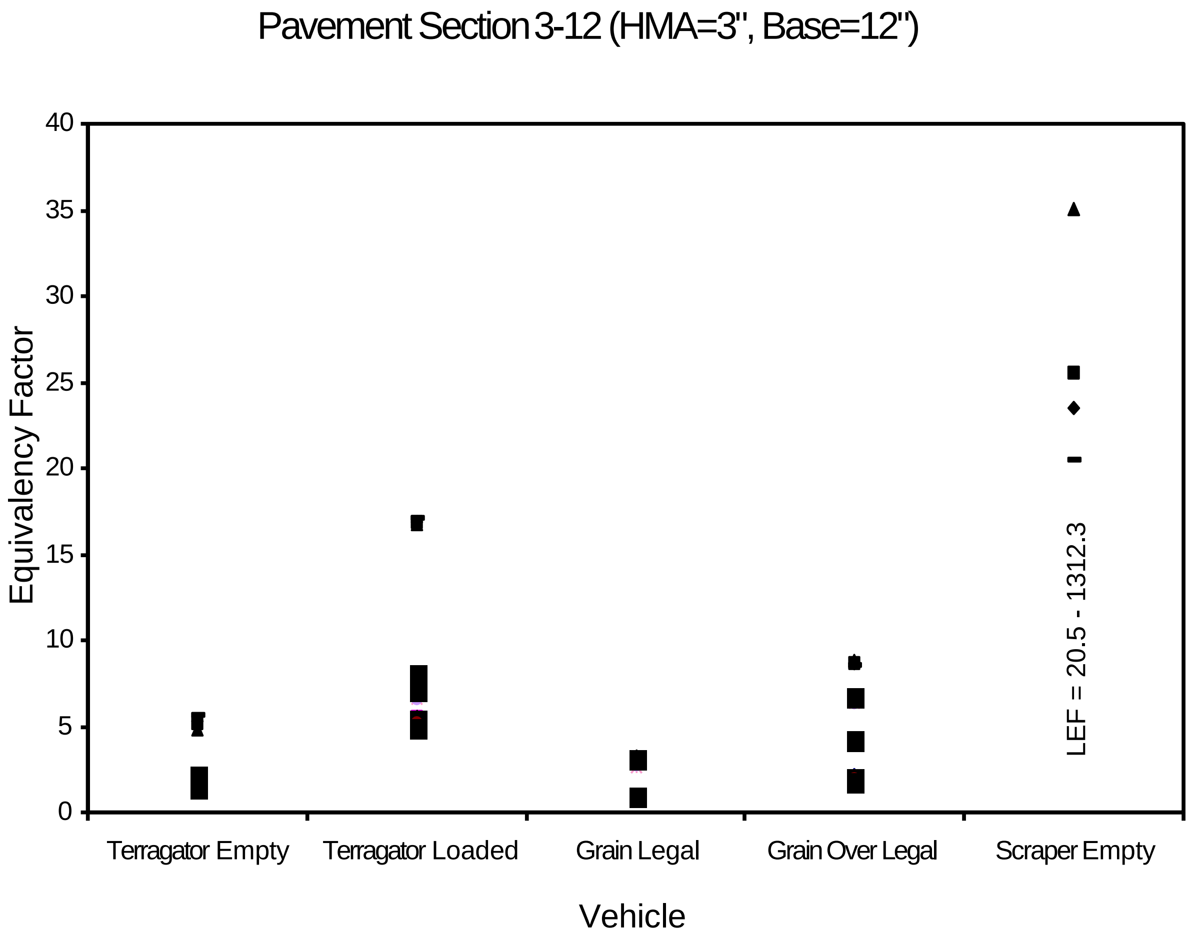

Figure 44: Distribution of Fatigue and Rutting Load Equivalency Factors

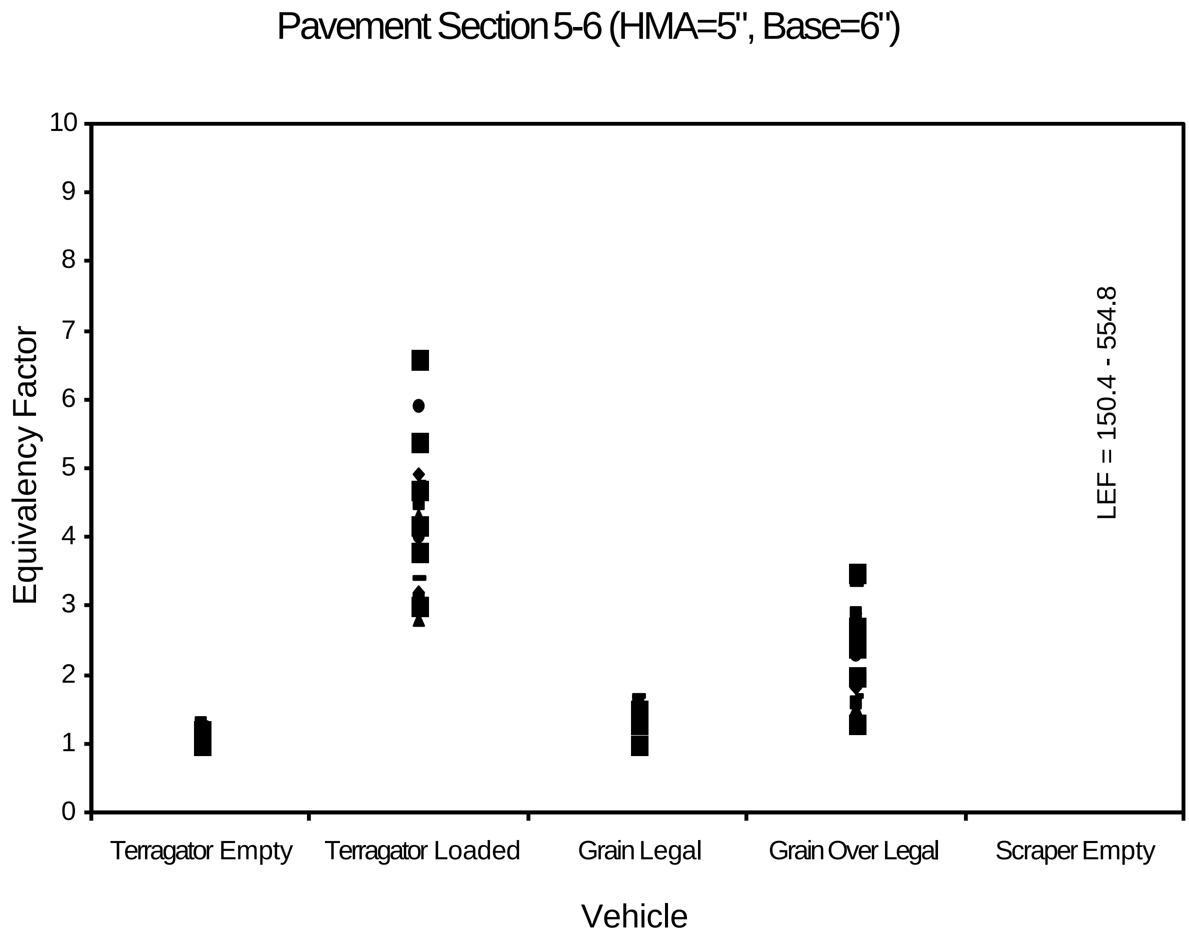

Figure 45: Distribution of Fatigue and Rutting Load Equivalency Factors

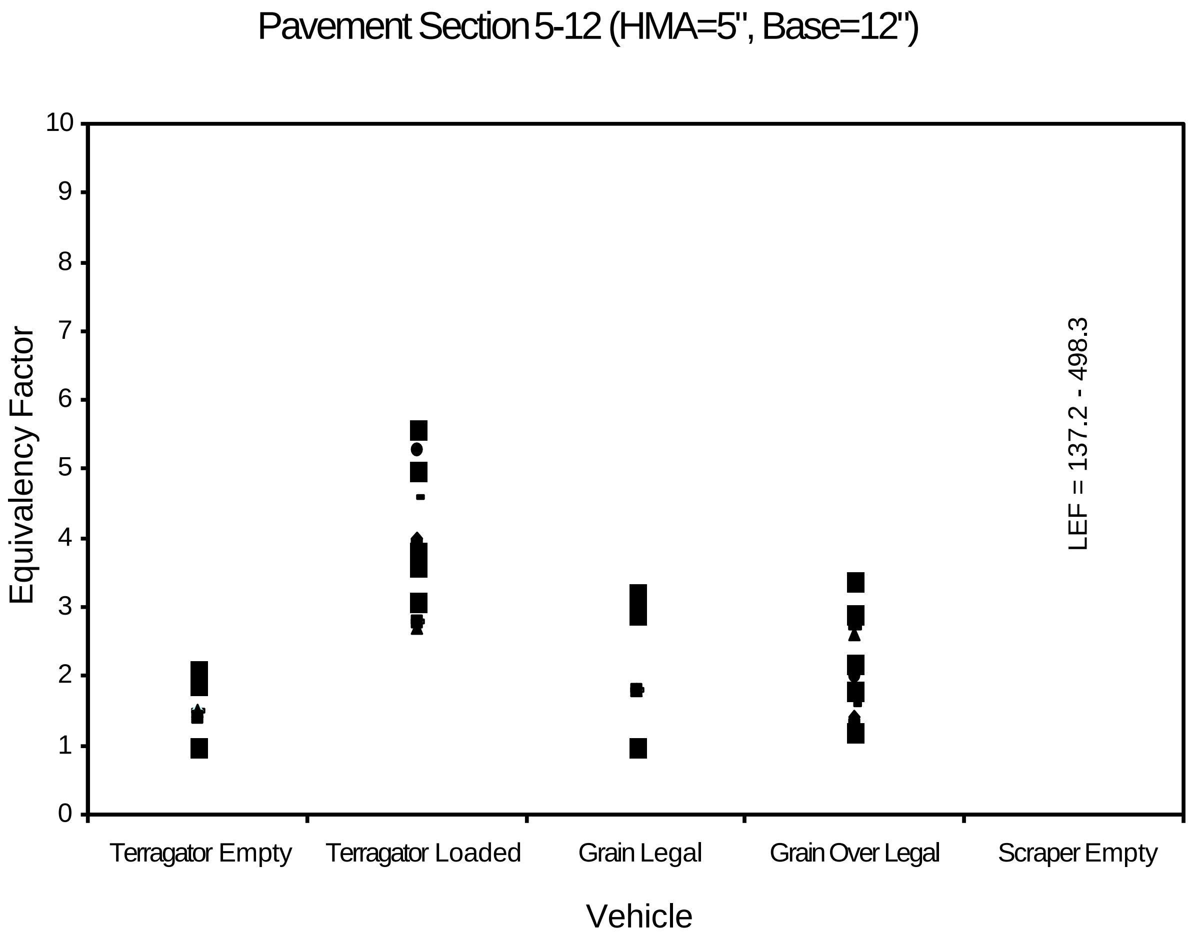

Figure 46: Distribution of Fatigue and Rutting Load Equivalency Factors

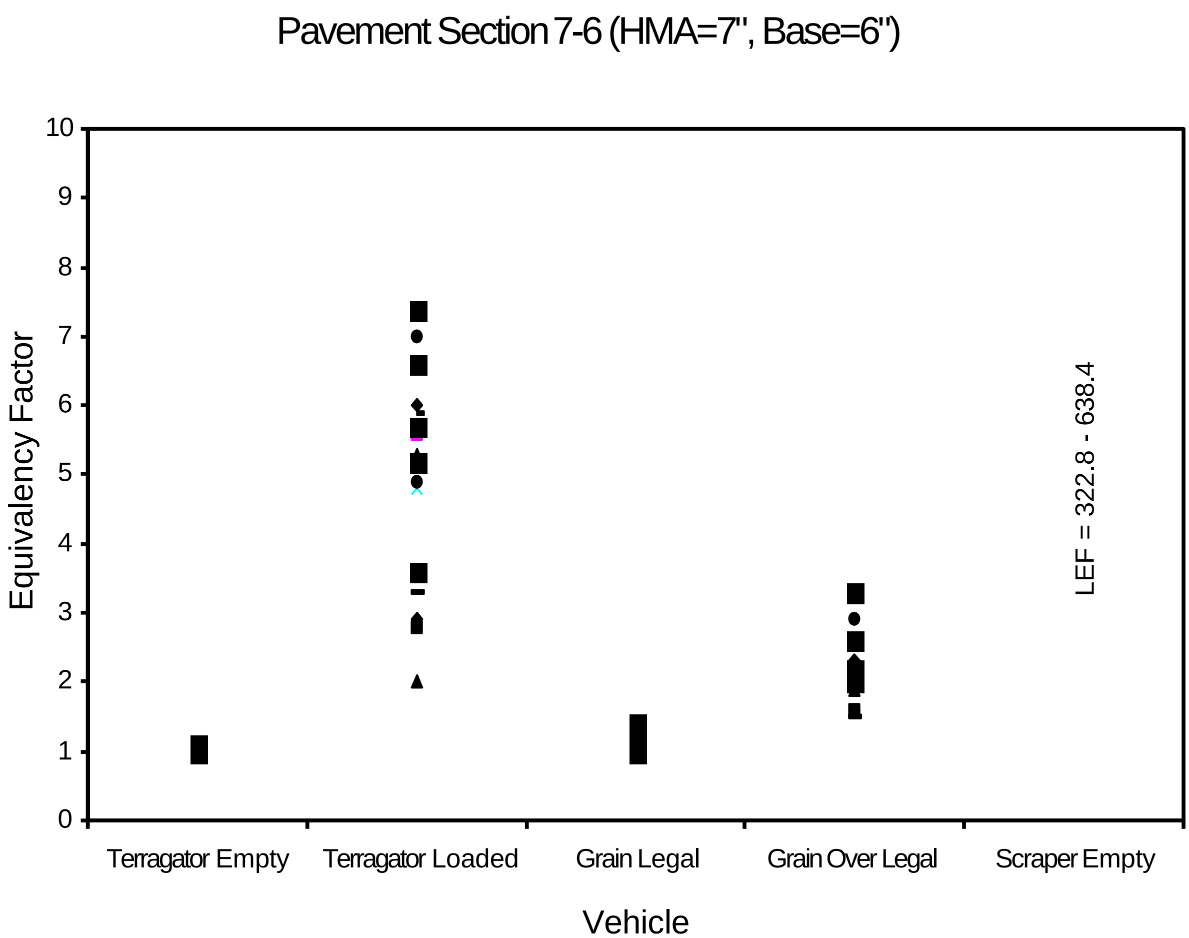

Figure 47: Distribution of Fatigue and Rutting Load Equivalency Factors

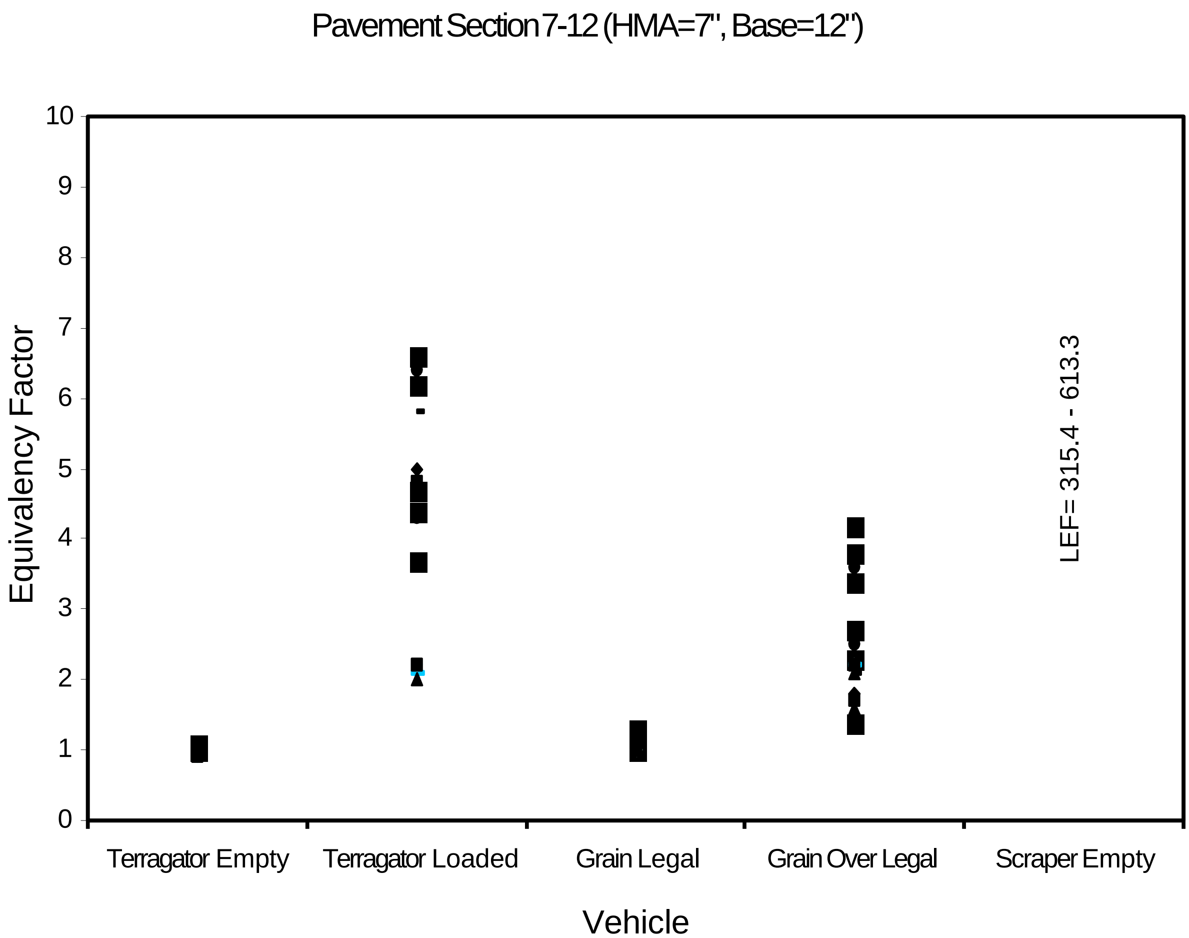

Figure 48: Distribution of Fatigue and Rutting Load Equivalency Factors