Response of Iowa Pavements to a Tracked Agricultural Vehicle

Final Report

Sponsored by the Highway Division
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Research and Education

Iowa State University

Iowa Department
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RESPONSE OF IOWA PAVEMENTS TO A TRACKED AGRICULTURAL VEHICLE

FINAL REPORT

Principal Investigator
Fouad Fanous
Professor of Civil and Construction Engineering
Iowa State University

Co-Principal Investigator
Brian Coree
Assistant Professor of Civil and Construction Engineering
Iowa State University

Co-Principal Investigator
Doug Wood
Manager, Engineering Research Lab
Iowa State University

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EXECUTIVE SUMMARY

The overall objective of the work summarized in this report and in the interim report was to study the effects of targeted implement-of-husbandry loads. This report is to complement phase I of this work, which was summarized in the interim report, entitled *Response of Iowa Pavements to Heavy Agricultural Loads* (December 1999). The response of newly constructed portland cement concrete (PCC) and asphalt cement concrete (ACC) pavements under semi-truck, single-axle single-tire grain wagon, single-axle dual-tire grain wagon, tandem and tridem honey wagons were summarized in the interim report. Phase II of this project, presented herein, was to complete the study in terms of how tracked agricultural vehicles relate to the reference 20,000-pound single-axle semi-truck. In this report the response of these two pavements under a tracked grain wagon is documented.

The analysis results illustrate that during the spring season, because of the larger track-pavement contact area, the load associated with the tracked wagon required to induce the same stress in the ACC and PCC pavements was significantly higher than that of a 20,000-pound single-axle dual-tire semi. For example, for a 36-inch wide and 116-inch long track-pavement contact area, analysis showed that an axle load of 82,000 pounds induced stress in the ACC pavement equal to that induced by a 20,000-pound reference semi. A tracked wagon loaded to the maximum-allowable gross vehicle load of 96,000 pounds induces a stress less than that induced by the single-axle dual-tire semi on PCC pavement.

The limited field test and analytical results demonstrated a similar response of the two newly constructed PCC and ACC pavements under tracked wagons. These vehicles induced lower stress and strain values in both types of pavements when compared to other loads. Therefore, one may conclude that these types of vehicles are more efficient in distributing their loads than are other types of vehicles of husbandry. However, in the authors' opinion, the roughness of the pavement surfaces, rutting, fatigue cracking, and other distress factors that could affect the performance of the pavements need to be investigated. This is necessary because the work summarized herein and in the interim report was limited to testing and analyzing two newly constructed pavements.

1 INTRODUCTION

1.1 Background

With House File 651, in 1999 the Iowa General Assembly initiated a phased program of weight restrictions for implements of husbandry. First, effective July 1, 1999, all implements of husbandry must comply with weight restrictions posted on bridges. Second, targeted implements of husbandry (fence-line feeders, grain carts, and tank wagons) manufactured on or after July 1, 2001, must be within 20 percent of commercial-vehicle axle-weight restrictions to travel legally on Iowa's roadways. Finally, all targeted implements of husbandry must be within 20 percent of commercial vehicle axle weight restrictions by July 1, 2005.

House File 2368 of March 2000 amended the previous 20 percent allowance to a seasonal load limit. The amendment stated that single-axle loads on fence-line feeders, tank wagons, and grain carts shall not exceed 24,000 pounds from February 1 through May 31 or 28,000 pounds from June 1 through January 31, provided that the maximum gross vehicle weight does not exceed 96,000 pounds. House File 2368 also instructed the Iowa Department of Transportation (Iowa DOT) to conduct a further study investigating the effects of tracked vehicles.

The phase-in schedule for compliance of vehicles of husbandry with axle-weight restrictions gives the legislature time to more carefully study axle-weight issues. To help the legislature in its task, this study was conducted to investigate the effects of variously configured grain carts, tank wagons, and tracked wagons on Iowa's roadways. Also examined were the possible mitigating effects of flotation tires and tracks on the transfer of axle weights to the roadway.

1.2 Objective

The overall objective of this study is to determine the effects of the previously listed implements of husbandry on Iowa's paved county roadways. A full study to determine the relative damaging power of different vehicle configurations on a wide array of pavement structures would require several years. Such a study should consider the seasonal variations in the material of the supporting soil properties, the dynamic characteristics of an implement, roughness of the pavement surface, nonlinear nature of pavement and soil materials, and the uncertainty associated with these variables. Such a full study was clearly impossible to accomplish given the time constraints of this study. Therefore, the work presented herein serves to provide only preliminary results based on limited experimental and analytical work under pseudo-static loading, that is, crawling moving loads.

In this report, the response of a newly constructed PCC pavement and a newly constructed ACC pavement under tracked grain wagons is summarized. The responses of these two pavements under semi-truck and other types of husbandry loads were summarized in the interim report (*1*). That report was submitted to the Highway Division of the Iowa Department of Transportation in December 1999.

2 FIELD TESTING AND ANALYSIS OF JONES COUNTY PCC PAVEMENT

The ACC pavement on county road K-52 in Sioux County, Iowa, and the PCC pavement on E-29 in Jones County, Iowa, used in phase I of this study (*1*) were also used to complete the objective of phase II. For information regarding the instrumentation used in conjunction with the test and analytical modeling, the reader is referred to Fanous, Coree, and Wood (*1*).

2.1 Loading

The PCC pavement on highway E-29 in Jones County was tested under a KINZE 1040 tracked grain wagon. The dimension of the track-pavement contact area is 36 inches by 116 inches. The wagon was loaded by 70,140 pounds. A photo of the loading used during testing both the PCC and ACC pavements is illustrated in Figure 1. The distances between the tires and the contact areas of the semi-truck and the tracked vehicle are illustrated in Figures 2 and 3, respectively.

FIGURE 1 KINZE 1040 tracked wagon used in pavement testing.

2.2 Testing Results

The pavement was tested at least twice under each loading at crawling speed. Data collections of the strains induced in the pavement started a few seconds before and continued a few seconds after each vehicle passed over the instrumented 15-foot by 22-foot slab. These results were recorded for all locations of the strain gages shown in Figure 1 of the interim report (*1*). Figure 4 of this report shows the typical time-strain relationships as the vehicle was traveling along the pavement.

2.3 Analytical Study

2.3.1 Software Selection

The software KENSALBS, developed by Huang (*2*), and ANSYS (*3*) were used to analyze the PCC pavement under the tracked vehicle and the reference semi loading. These two programs were used for the reasons summarized in the interim report (*1*).

2.3.2 Modulus of Subgrade Reaction

The modulus of subgrade reaction used in this study was 230 pounds per square inch (psi)/inch. This was obtained from the field test conducted by Iowa DOT personnel in summer of

1999 using several soil samples obtained from E-29 in Jones County. However, modified values need to be used when analyzing the PCC pavement under different seasonal conditions. This is necessary to account for the differences in the soil properties from one season to another. In this work, the subgrade reaction for the spring season was assumed to be 115 psi/inch. This was assumed because the moisture sensor beneath the slab indicated a moisture value of 22 percent, which is very close to saturated conditions.

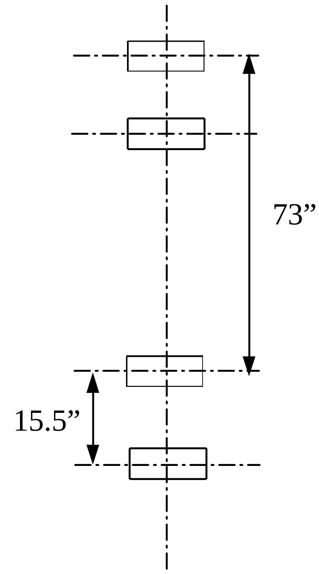

FIGURE 2 Typical configurations for single-axle semi-truck, axle weight of 20,000 pounds.

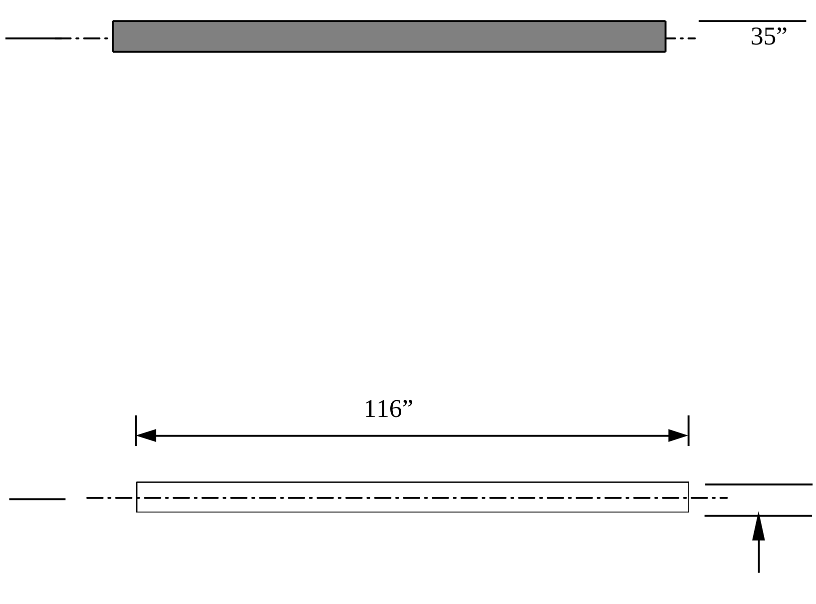

FIGURE 3 Configurations of the tracked loads used in testing the pavements.

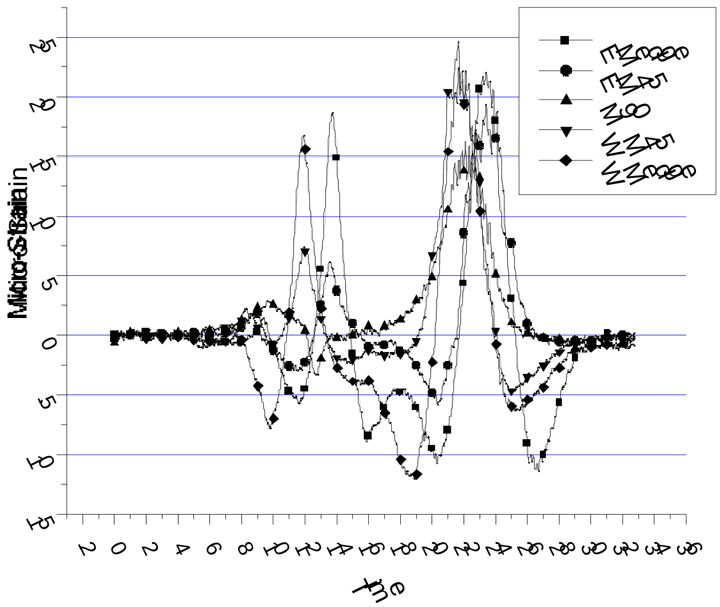

FIGURE 4 Field-test strain data for the PCC pavement under tracked vehicle, cart weight of 70,140 pounds.

2.3.3 Results of the Analytical Study

The maximum measured strain and the maximum strain obtained from the finite element results caused by each load are summarized in Table 1. As can be noticed, there are slight discrepancies between the measured and the calculated strains. These differences can be attributed to the location of the tire loads with respect to the location of the strain gage, the unknown exact values of the modulus subgrade reaction, the constructed thickness of the pavement and the actual compressive strength, and the concrete modulus of elasticity.

TABLE 1 Summary of Calculated and Measured Longitudinal Strains in the E-29 PCC Pavement

Load Configuration	Calculated Strain (μ)	Measured Strain (μ)	Ratio of Calculated Strain/ Measured Strain	Ratio of Calculated Strain/ Measured Semi Strain
Semi, 17,000 lb/axle	26	31*	0.82	1.00
Tracked wagon, 70,140 lb	26	24	1.08	0.77

*Obtained from the interim report (*1*). Note that the result in the interim report was doubled because of a calibration error that was discovered after publishing the interim report. Furthermore, the result here was adjusted to account for the effect of soil subgrade reaction since the PCC pavement was not tested under a semi load in the spring season.

As can be seen in Table 1, the calculated and the measured strains are in close agreement. In other words, the finite-element model and the field data revealed similar behavior of the PCC pavement under both loads. Notice that the tabulated results for the semi load correspond to a load of 17,000 pounds rather than the 20,000-pound reference semi. This was the axle load used in testing the pavement in phase I.

In summary, the limited test results summarized in Table 1 also demonstrated that tracked wagons are less harmful than any other loading system. This was expected since tracked vehicles transfer the applied load to the pavement over a larger contact area when compared to other loads.

3 ANALYSIS OF ADDITIONAL PCC PAVEMENTS

Three additional PCC pavements, with thicknesses of seven, eight, and nine inches, were analyzed under the spring seasonal conditions. The spring condition was selected because it is associated with the lowest soil subgrade reaction, 115 psi/inch. Each slab was subjected to the type of loading shown in Figures 2 and 3. The concrete modulus of elasticity (E_c) of 4,000,000 psi, which corresponds to a design concrete compressive strength ($f\__c$) of 5,000 psi, was used.

In pavement technology, the reference design vehicle configuration is an 18,000-pound single-axle vehicle. Conventionally, other axle configurations are reduced to an equivalent number of these reference loads in terms of equal damaging power or equivalent single-axle loads (ESALs). In comparing the relative damaging power of different axle configurations and weights, they must be expressed in terms of ESALs. One needs to realize that axle weight alone is no determinant of damaging power; the configuration of the load (contact area, tire pressure, suspension, wheel spacing, etc.) as well as average daily traffic (ADT) and temperature contribute decisively to damage. This approach, however, was not employed herein because of the uncertainty associated with the variables that enter into the equation used to determine the ESALs. Another alternative is to determine the load that can be applied to a given axle configuration that induces stress, strain, or deflection equal to that induced in the same pavement when subjected to a single-axle load. For simplicity, the latter approach was selected and used to determine the effects of husbandry loads on Iowa highway pavements. In this work, a single-axle dual-tire vehicle of 20,000 pounds was used as a basis for comparison with other loads.

3.1 Analysis of the Additional PCC Pavement Using KENSLABS

In this analysis, a 15-foot long by 22-foot wide PCC slab with three different thicknesses was modeled for the analysis of the PCC pavement by the KENSLAB program (*2*). Symmetry conditions were employed when possible. This existed only when analyzing a pavement under symmetrical loads such as these considered herein. The dimensions of the elements in the vicinity of the applied loads were determined following the procedure described in the interim report (*1*). Applied loads of the tracked wagon were increased to the maximum-allowed load of 96,000 pounds. The maximum stresses in the pavement reached a value less than that induced by the 20,000-pound single-axle dual-tire semi.

3.2 Analysis of Additional PCC Pavement Using ANSYS

The additional PCC pavements described above were also analyzed with the ANSYS (*3*) finite-element software. Each pavement was modeled by several plate elements supported on an elastic foundation. The finite-element model was loaded with loads similar to those used in the simplified analyses described above. The element size was limited to the dimensions listed in the previous work (*1*).

3.3 Summary of Spring Season Results

The results obtained from analyzing the PCC pavements using KENSLABS and the ANSYS finite-element programs are listed in Tables 2 and 3.

TABLE 2 Maximum Stresses in PCC Pavements with Different Thickness: KENSLABS Results Spring Season

Load Configuration (Axle Load)	Stress (psi)		
	7-in Thick Pavement	8-in Thick Pavement	9-in Thick Pavement
Single-axle dual-tire semi, 20,000 lb	435	358	300
Tracked wagon, 96,000 lb	242	215	204

TABLE 3 Maximum Stresses in PCC Pavements with Different Thickness: ANSYS Results Spring Season

Load Configuration (Axle Load)	Stress (psi)		
	7-in Thick Pavement	8-in Thick Pavement	9-in Thick Pavement
Single-axle dual-tire semi, 20,000 lb	441	363	304
Tracked wagon, 96,000 lb	246	236	220

As can be noticed, the simplified analyses and the finite-element results are in good agreement. The slight differences between the simplified and the finite-element results could have been due to the element size used in the two analyses. The results listed in Tables 2 and 3 illustrate that a tracked wagon loaded by the maximum allowed load of 96,000 pounds induces a stress less than that induced by the single-axle dual-tire semi.

3.4 Effect of Soil Subgrade Reaction: Fall Season Analysis Using ANSYS

Seven-, eight-, and nine-inch thick concrete pavements were also analyzed considering fall conditions. This was accomplished using soil subgrade reactions of 175 psi/inch. The analysis was accomplished using the ANSYS (*3*) finite-element program, and the results are summarized in Table 4. The table illustrates that the stress in the concrete pavement decreases as the soil subgrade reaction increases. This was expected since the deflections and hence the strains decrease as the subgrade reaction increases.

TABLE 4 Maximum Stresses in PCC Pavements with Different Thickness: ANSYS Results Fall Season

Load Configuration (Axle Load)	Stress (psi)		
	7-in Thick Pavement	8-in Thick Pavement	9-in Thick Pavement
Single-axle dual-tire semi, 20,000 lb	379	312	261
Tracked wagon, 96,000 lb	164	158	154

3.5 Summary of PCC Pavement Analysis

The results documented above illustrate that tracked wagons induce lower stresses and strains when compared with the semi loading. Therefore, one may conclude that this type of vehicle is more efficient that the other types of husbandry vehicles considered in the interim report (*1*). However, these results must be interpreted with caution since the analysis and testing employed only two newly constructed pavements.

4 FIELD TESTING AND ANALYSIS OF SIOUX COUNTY ACC PAVEMENT

4.1 Loading

The ACC pavement on county road K-52 in Sioux County, Iowa, was tested under a KINZE 1040 tracked grain wagon. The wagon was loaded with 65,920 pounds. The distances between the tires and the contact areas are illustrated in Figure 3.

4.2 Testing Results

The ACC pavement was tested under the load listed above while the vehicle was driven over the instrumented locations at crawl speed. Data were collected continuously by the data acquisition system when triggered by the passage of the leading axle over a trip tape placed before the instrumented locations. Figure 5 shows the strain-time relationship as the vehicle traveled over the instrumented pavement. The peak strain recorded for each load configuration is reported in Table 5.

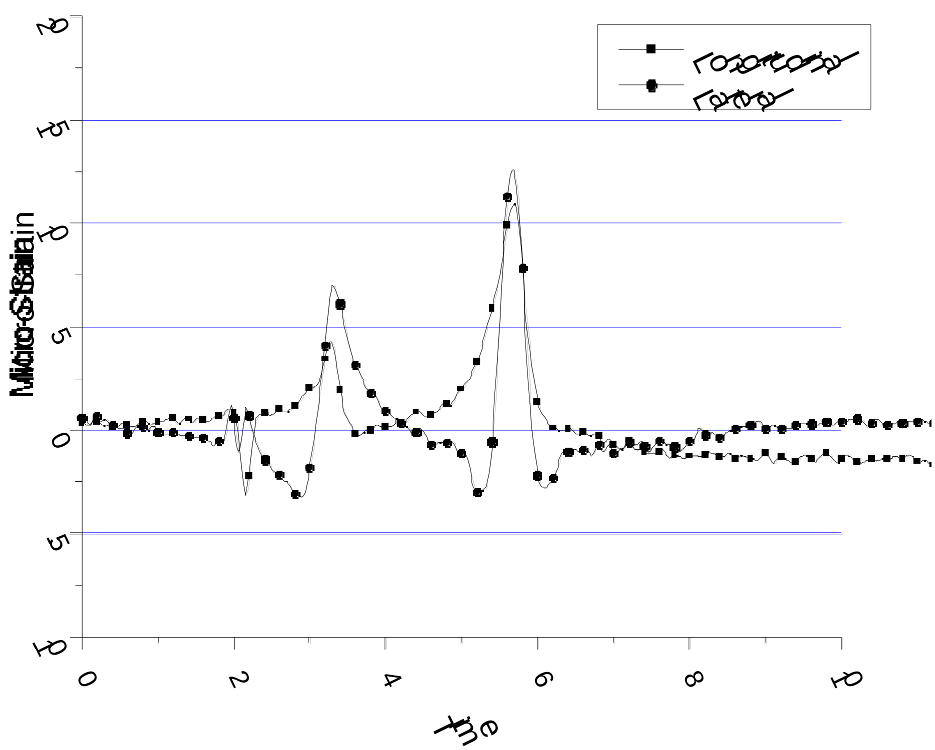

FIGURE 5 Field test strain data for the ACC pavement under tracked vehicle, cart weight of 65,920 pounds.

TABLE 5 Measured Strains in the ACC Pavement under the Different Loading Configuration

Vehicle	Peak Strain (με)
KINZE 1040 tracked grain cart	12.3
Single-axle dual-tire semi	13.6*

* Strain value is twice of that documented in interim report (*1*). This is due a calibration error that was discovered after publishing the interim report.

4.3 Analytical Study

4.3.1 Software Selection

For reasons similar to those for the PCC pavement analysis, the software package KENLAYER developed by Huang (*2*) was used. This software is based on Burmister's multilayer elastic analysis. It assumes a circular loading contact with a uniform distribution of pressure within the contact area. All layers are assumed to have fully frictional interfaces and all materials are assumed to be linear elastic.

4.3.2 Material and Seasonal Effects

The generic pavement analyzed was taken to be a three-layer system comprising an asphalt layer overlying a thin, granular base on top of the subgrade. The asphalt layer was analyzed as an eight-inch thickness, the granular layer at a nominal six-inch thickness, and the subgrade was assumed to be semi-infinite. It may be arguable whether granular bases are in common or universal use; however, the top six inches of subgrade are frequently significantly different than the remainder of the subgrade soil, so that the assumption of this layer is in no way unrealistic.

Previous work undertaken by the authors of this work, analyzing the full 12-month year, examined the effects at the four seasons (summer, fall, winter, and spring). The elastic modulus assigned to each structural layer for the four seasons is given in Table 6. These analyses confirmed that the spring condition is the most critical. However, since not all implements of husbandry are used in the spring of the year, it was decided to study the response of the ACC pavement in the fall conditions also. Fall was selected over the summer and winter seasons because it represents the season when implements of harvest are used.

TABLE 6 Material Modulus for Different Seasons

Material	Summer (psi)	Fall (psi)	Winter (psi)	Spring (psi)
Asphalt	350,000	500,000	2,000,000	500,000
Granular base	50,000	50,000	50,000	50,000
Subgrade	25,000	17,500	50,000	10,000

4.3.3 Field Trial Validation

In order to validate the computation analysis, the same procedure that would be used for the overall analysis was used to estimate the strains at the five-inch depth under the various vehicle types. The calculated strains would then be compared to the measured strains to provide some degree of validation. In this case, the temperature of the asphalt was known from field measurements (40°F) and its modulus could be reasonably estimated. The summer value of the subgrade modulus was used because of the fact that there had been little or no precipitation during the previous two months, resulting in an unusually dry condition. The ground had certainly not yet become frozen.

Usually, the spring of the year is considered to be the weakest in terms of subgrade support strength; however, the conditions experienced during the spring of 2000 around the testing time were abnormally mild and dry. As a consequence, the subgrade conditions were significantly stronger than normal. A subgrade modulus of 25,000 psi was used in the analytical comparison instead of 10,000 psi. The two load configurations were entered into the KENLAYER program, and the horizontal strains were computed at the five-inch depth, corresponding to the location of the instrumentation. The results are reported in Table 7.

TABLE 7 Comparison of Calculated versus Measured Strains (Spring 2000)

Vehicle	Calculated Strain (με)	Measured Strain (με)	Ratio of Calculated Strain/ Measured Strain	Ratio of Calculated Strain/ Measured Semi Strain
Single-axle dual-tire semi	13.6	13.6	1.00	1.00
KINZE 1040 tracked grain cart	13.3*	12.3	1.09	0.98

*The analytic software used (KENLAYER) performs the analysis using circular contact areas. The footprint of the tracked grain cart is decisively rectangular and cannot easily be modeled using this software. However, by superimposing a number of smaller circular areas within the overall rectangular area, it is possible to provide an estimate of the resulting strains in the pavement.

As can be seen from Table 7, the measured and the calculated strains are in close agreement. These results demonstrate that notwithstanding various sources of uncertainty the analytical method and assumptions are appropriate.

5 ANALYTICAL STUDY OF ACC PAVEMENT

The strains measured and modeled above pertained to a depth of five-inches in an eight-inch thickness of ACC pavement. Critical strains, however, occur at the interface between the ACC layer and the underlying unbound materials. Consequently, the pavements were reanalyzed in order to determine the critical horizontal strains at this interface under the reference load—a regulation semi-trailer with a tire pressure of 100 psi and an equivalent single-axle load of 20,000 pounds. The results are reported in Table 8 for both fall and spring conditions.

For the reasons previously stated, the effects of the tracked grain wagon can only be estimated approximately. The surface contact strains under the tracked wagon can be estimated with some confidence as 7.6 μ. The measured strain at the five-inch depth was –15.0 μ. Appealing to linear elasticity, the corresponding strain at the eight-inch depth can be estimated as –28.7 μ. (Negative strains indicate tensile conditions). This strain corresponds to a vehicle load of 65,920 pounds. Again appealing to the elastic linearity of the pavement system, it can be shown that a fall loading of 93,800 pounds and a spring loading of 81,700 pounds would bring the strains at the eight-inch interface to values expected under the reference single-axle semi vehicle. Performing the analysis with circular areas contained within the rectangular footprint, we obtained similar values within 10 percent (16 circular areas).

TABLE 8 Effect of Seasonal Conditions on ACC Pavement Capacity under Different Implements

Season	Reference Axle	Tracked Wagon
Spring	20,000	81,700
Fall	20,000	93,800

In summary, the fall and spring field-testing provided reasonable agreement between measured and computed responses at the five-inch depth within the pavement. The analysis to determine the axle weights in the various implements that equate to equal damage from a reference single-axle semi loading are given in Tables 7 and 8. From the limited analyses considered herein, one can conclude that the tracked vehicles are by far the least structurally damaging to pavement, and the "allowable" load in fact exceeds the nominal maximum gross vehicle weights allowed by legislation.

6 CONCLUSION

The overall objective of the study was to study the effects of targeted husbandry loads. The response of newly constructed PCC and ACC pavements under semi-truck, single-axle single-tire grain wagon, single-axle dual-tire grain wagon, tandem and tridem honey wagons were summarized in the interim report. Phase II of this project, presented herein, was to complete the study in terms of how tracked agricultural vehicles relate to a reference 20,000-pound single-axle semi-truck.

The analysis results illustrate that during the spring season, because of the larger track-pavement contact area, the load associated with the tracked wagon required to induce the same stress in the ACC and PCC pavements was significantly higher than that of a 20,000-pound single-axle dual-tire semi. The limited field test and analytical results demonstrated a similar response of the two newly constructed PCC and ACC pavements under a tracked wagon. These vehicles induced lower stress and strain values in both types of pavements when compared to other loads.

Other variables, such as the roughness of pavement surfaces, are yet to be investigated. Such a study could take several years and is beyond the scope of this project.

7 REFERENCES

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