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Central Tire Inflation: Demonstration Tests in the South

R. B. Rummer, C. Ashmore, D. L. Sirois, and C. L. Rawlins

SUMMARY

Tests of prototype Central Tire Inflation (CTI) systems were conducted to quantify CTI performance, road wear, and truck vibration. The CTI systems were tested in both experimental and operational settings. Changes in the road surface that occurred during the tests could not be statistically attributed to reduced tire pressure. Vibration at the seat base, however, was significantly affected by tire pressure. In the operational tests, reduced tire pressure was associated with higher travel speeds. The implications of these findings for log transportation are discussed.

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INTRODUCTION

The USDA Forest Service has been investigating the application of Central Tire Inflation (CTI) technology to forest products transportation. CTI permits adjustment of tire pressure to optimize truck performance for varying road conditions. Reducing tire pressure (increasing tire deflection) increases tire footprint, which increases traction and reduces road contact pressure. Anticipated benefits of CTI include improved driver comfort and reductions in truck maintenance, road maintenance, and road construction costs. A number of studies have examined various aspects of the CTI concept (Gililland and Ryburn 1986, Nevada Automotive Test Center 1987, Taylor 1987).

As part of the National Forest Service CTI testing program, demonstration tests were conducted in Alabama and Oklahoma between October 1987 and April 1988. Two 10-wheel trucks were equipped with prototype onboard CTI systems and radial tires. During tests conducted in Alabama, the trucks were configured as three-axle log trucks (fig. 1). For further testing in Oklahoma, the trucks were configured as tractor/trailer combinations with pole-type trailers (fig. 2). The objectives of the southern tests were to: (1) quantify CTI performance, road wear, and truck vibration and (2) demonstrate CTI technology in the southern region to encourage technology transfer. Some aspects of these regional tests have been previously reported (Ashmore and Sirois 1987). The quantitative analysis of the remaining road wear and truck vibration data from the southern regional tests is presented in this report.

PREVIOUS FINDINGS

The southern tests consisted of three distinct evaluations: (1) a forest road test course, (2) drawbar pull tests, and (3) an operational trial on a production harvesting job. The forest road test course was used to examine road wear, vehicle mobility, and ride vibration. The drawbar pull tests studied the tractive capability of the CTI trucks as a function of tire deflection and road surface material. Finally, the harvesting operation trial examined the performance of the CTI systems and tire life over an extended operating period in a production environment. Ashmore and Sirois (1987) described the CTI systems and the procedures followed in these tests. Their report also described the performance characteristics of the prototype CTI systems.

Forest Road Test Course

The forest road test course used by Ashmore and Sirois (1987) was a 2.1-mile stretch of a native-surfaced, sandy road divided into three test sections along its length (fig. 3), with a turnaround area at each end. The CTI trucks traveled back and forth over the road in an accelerated loop test, changing tire pressures for each test section. The loaded trucks had a gross vehicle weight of approximately 50,000 lb. Tire pressures were varied to obtain 10-, 20-, and 30-percent tire deflection for the respective road sections. From this test, the authors observed that:

1. Significant road damage occurred in the low-deflection (high tire pressure) test section (fig. 4).
2. Lateral rocking of the trucks in the high-deflection (low tire pressure) test section produced a lateral "washboard" effect.
3. In the turnaround areas, mobility differences between high and low tire deflection were apparent. At low deflection, the trucks could become stuck in wet conditions. Increasing tire deflection permitted the trucks to drive out after becoming immobilized.
4. Driving with greater tire deflection produced a road-healing effect in rutted areas.

Drawbar Pull Tests

The drawbar pull tests were conducted on two native-surfaced roads—a sandy road and a clay road. Tests on the clay road were conducted with the surface in a saturated state. The results of the drawbar pull tests showed that:

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Figure 1.—*Three-axle log trucks equipped with central tire inflation systems.*

Figure 2.—*Tractor/trailer equipped with a central tire inflation system.*

1. Drawbar pull on both road surfaces was increased by lowering tire pressure to obtain 20-percent deflection. The increase in drawbar pull was greater on the sandy surface.
2. Further increasing deflection from 20 to 30 percent did not result in increased drawbar pull.

Operational Evaluation

The operational tests were conducted on timber harvesting operations in Oklahoma. The two CTI trucks, configured with pole trailers, were operated for approximately 1,000 miles over a private road network. An additional 8,000 miles were logged with a CTI system installed on a third tractor/trailer combination using tires from the earlier tests. Thus, 18 tires were operated in CTI systems for about 10,000 miles.

Subjective observations during the Oklahoma tests revealed that:

1. Low-pressure tires had better traction on push-out roads, frozen roads, and adverse grades.
2. Rocks became wedged between the dual tires during high-pressure operation, causing potential tire damage and truck delays. This was not a factor during low-pressure operation.
3. Tire damage and wear did not appear to be accelerated by appropriate low-pressure operation.

In addition to the results previously reported by Ashmore and Sirois (1987), further data were collected during the southern demonstration tests. In the forest road test course, road cross-sections were measured to quantify changes in the road surface. Ride meter readings were also taken to measure the effect of tire deflection on the whole-body vibration of the

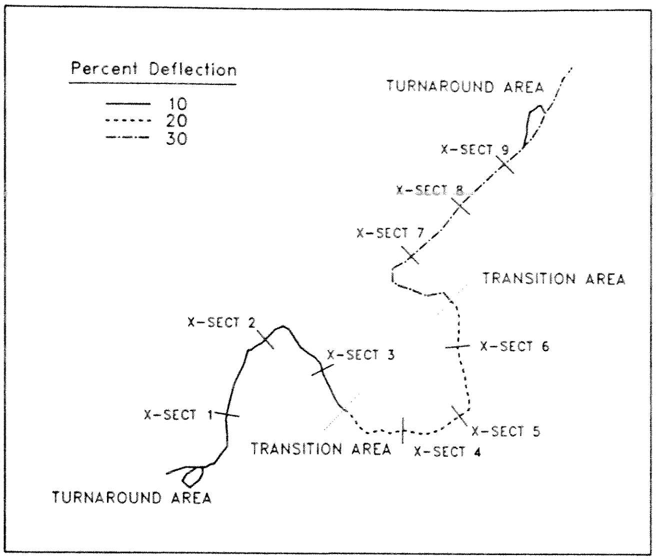

Figure 3.—*Layout of the forest road test course identifying the three tire deflection test sections and the nine road cross-section sample points.*

driver. During the Oklahoma test, data relating tire pressure to travel speed were also recorded. The collection, analysis, and evaluation of the additional information is described in this report.

METHODOLOGY

Road Cross-Section Changes

Traffic on forest roads can alter the road cross-section through compaction and displacement of the surface material. Analysis of the road structure during the forest road tests examined changes in both the cross-sectional elevations of the road and in the bulk density of the road surface material. These changes were examined as functions of tire deflection, number of trips, and moisture content of the road surface material.

Elevational changes in road cross-sections were measured by establishing three sample cross-sections within each of the three road test sections (fig. 3). At each cross-section, stakes were firmly embedded on each side of the road to serve as elevation benchmarks. A rill meter resting on the reference stakes was used to measure elevations at 2-inch intervals along each cross-section. Relative elevations, recorded to the nearest 0.1 inch at each point along the cross-section, were measured weekly during the road course tests. Figure 5 illustrates typical cross-section elevations measured in the 20-percent deflection test section.

The individual weekly measurements at each cross-section were reduced to single number indices of cross-section change. At each measurement point along the cross-sections, the current elevation was subtracted from the elevation at that point the previous week. The average absolute value of the elevation changes was calculated for each cross-section to provide an index of total cross-section change:

$$\text{Index} = \frac{\sum_{i=1}^{n} | CE_i - PE_i |}{n}$$

Figure 4.—*Road deterioration in the 10-percent tire deflection road section.*

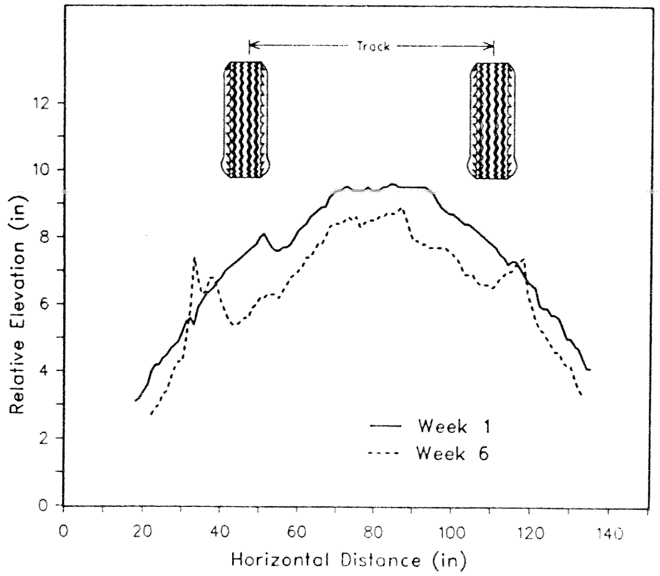

Figure 5.—*Cross-section elevations at the beginning and end of the test in the 20-percent tire deflection road section.*

where: CE = current elevation of cross-section point i,
PE = elevation of cross-section point i the previous week, and
n = number of cross-section points.

This index is intended to indicate only the amount of change in the cross-section relative to the previous week. It does not indicate whether the change was in the form of rutting or uniform compaction across the road surface. This value was used as a dependent variable in the analysis of tire deflection effects on the road cross-section.

The second dependent variable, bulk density of the surfacing, was also measured weekly at each cross-section location. Two density readings, one in each wheel track, were taken from a 6-inch depth at each cross-section. An average of the two values was used as the dependent variable. The bulk density values were obtained with a Troxler Model 3411[1] single-probe nuclear gauge.

Several independent variables assumed to affect changes in the road prism were also measured. Standard Proctor tests (ASTM D698-78) were run on a soil sample from each of the cross-sections to determine the optimum moisture content for compaction. A gradation analysis was also performed on several of the samples. Weekly measurements of soil moisture content were taken with the Troxler nuclear gauge. Moisture content was sampled in both wheel tracks, and the average moisture content value was used in the statistical analysis. Rainfall records were collected with a Belfort continuously recording rain gauge located at the site. The data obtained from these measurements were summarized into the variables listed in table 1. Linear regression methods were used to statistically evaluate the effects of the independent variables on changes in track bulk density and cross-section elevations.

Ride Vibration Measurements

Altering the dynamic properties of the tires through reduced inflation pressure changes the vibration experienced by the truck and driver. If these changes reduce the vibration energy or shift the vibration into less sensitive frequency ranges, wear and tear on the truck and driver could be reduced. A number of studies (e.g., Gruber 1976, Rosegger and Rosegger 1960, Spear and others 1975) have indicated an association between occupational exposure to whole-body vibration (WBV) and the development of certain musculoskeletal and gastrointestinal disorders. Measurements taken by Wilcox, Doyle, and Tubbs (1988) in two conventional log trucks found WBV levels that exceeded the 8-hour fatigue-decreased proficiency curve of ISO 2631 (ISO 1978). Based on the vibration levels and physiological manifestations observed in their study, the National Institute of Occupational Safety and Health researchers recommended vibration reduction measures in the trucks. Reducing WBV levels in log trucks would improve the driver's work environment and may reduce the incidence of long-term occupational injuries in log trucking.

Table 1.—*Variables used in the analysis of road cross-section changes*

Variable
Dependent Variables
Change in the cross-section elevations
Track bulk density
Independent Variables
Track moisture content
Average moisture content of the tracks and the center of the road
Proctor moisture content
Difference between moisture content and the Proctor optimum
Number of passes during a given week
Cumulative passes from the beginning of the test through the given week
Average daily rainfall during a given week
Total rainfall from the beginning of the test through the given week
Road test section that corresponds to a tire deflection level
Cross-section within the test sections
Week within the test period

[1]The use of trade or firm names in this publication is solely for the information of the reader and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Forest Road Test Course.—On the forest road test course, ride vibration was measured with the Waterways Experiment Station (WES) Ride Meter (Lins 1972). The WES Ride Meter measures ride vibration as a function of absorbed power, defined as the product of the force input to the driver and the velocity of the driver (Lee and Pradko 1968). The ride meter displays the time-weighted average absorbed power at the end of a data collection period. Vibration measurements were taken separately in both trucks at two locations: the operator/seat interface and the seat attachment point.

A vibration measurement period consisted of the time required for the truck to traverse a test section. At the end of the test section, the average absorbed power value, measured at the accelerometer mounting location, was recorded by a data collector; the ride meter was then cleared for the next measurement period. The data collector also observed the speedometer during the measurement period and recorded an average truck speed. The ride meter was randomly rotated between the two trucks and the two mounting locations. Absorbed power values at the two locations were examined as a function of the independent variables listed in table 2.

Operational Evaluation.—An indirect evaluation of ride vibration was conducted during the operational trials in Oklahoma by measuring truck speed and tire inflation pressure. Assuming that one of the factors limiting the travel speed of a log truck is the WBV of the driver, there should be a statistically significant difference between the overall average travel speeds at high and low tire deflections. Low tire deflection, for example, would be associated with lower travel speeds because of higher vibration levels.

An Omnidata Model 516 Polycorder measured vehicle speed through a speedometer drive splitter and tachometer generator. Tire inflation pressure was sensed by a pressure transducer in the onboard CTI system. At regular intervals throughout the day, the Omnidata measured and recorded the data. The data were summarized by tire pressure, and an analysis of variance was used to evaluate the difference in average travel speeds.

Table 2.—*Independent variables examined in the analysis of ride vibration*

Variable	Description
Truck	Includes differences between trucks, suspensions, seating, and drivers
Road test section	Corresponds to different tire deflection levels as well as physical differences among the road sections
Cross-section	Accounts for physical differences among the individual sample cross-sections
Travel speed	Average travel speed during the measurement period
Cumulative passes	Total passes from the beginning of the test

RESULTS

Road Cross-Section Changes

The initial Proctor and gradation tests quantified characteristics of the road surface material. The native material was a uniformly graded sand (fig. 6). Optimum moisture content for compaction ranged from 9.5 to 13.2 percent across the nine cross-sections (fig. 7). Track moisture content values varied from 13 to 21 percent during the course of the study.

Changes in the road cross-section were evaluated by analyzing the two dependent variables—track bulk density and cross-section elevation change. The statistical analysis procedures are described more fully in the appendix. The regression analysis of elevation change found a significant inverse relationship between track moisture content and elevation—as track moisture content increased above the optimum moisture content for compaction, the magnitude of the elevational change decreased. This is consistent with standard moisture-density relationships if compaction of the road surface is a factor in altering the cross-sections. Figure 8 illustrates the regression equation plotted against the actual cross-section elevation data.

The elevation change data were adjusted to account for the effect of track moisture content, and an analysis of variance was used to determine if further variability in the data could be explained by differences among weeks, road sections, or cross-sections. The analysis found no significant differences due to road section (tire deflection effect) or cross-section. The

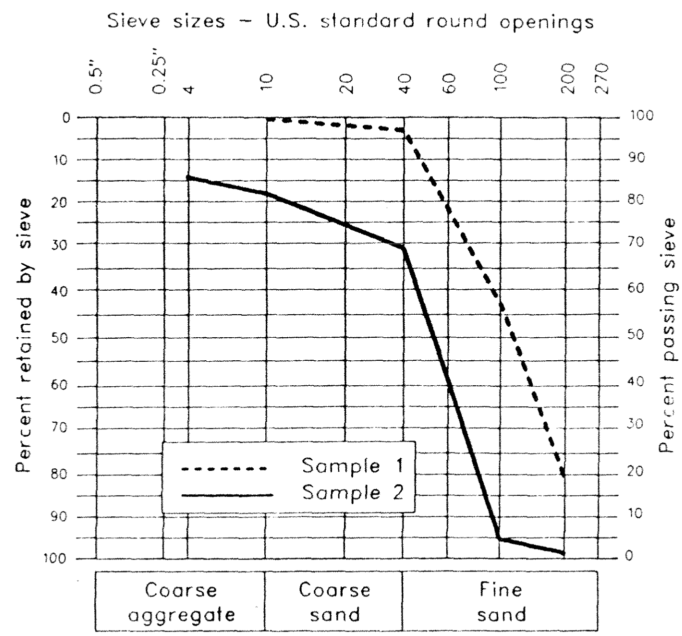

Figure 6.—*Gradation analysis of samples from the forest road test course.*

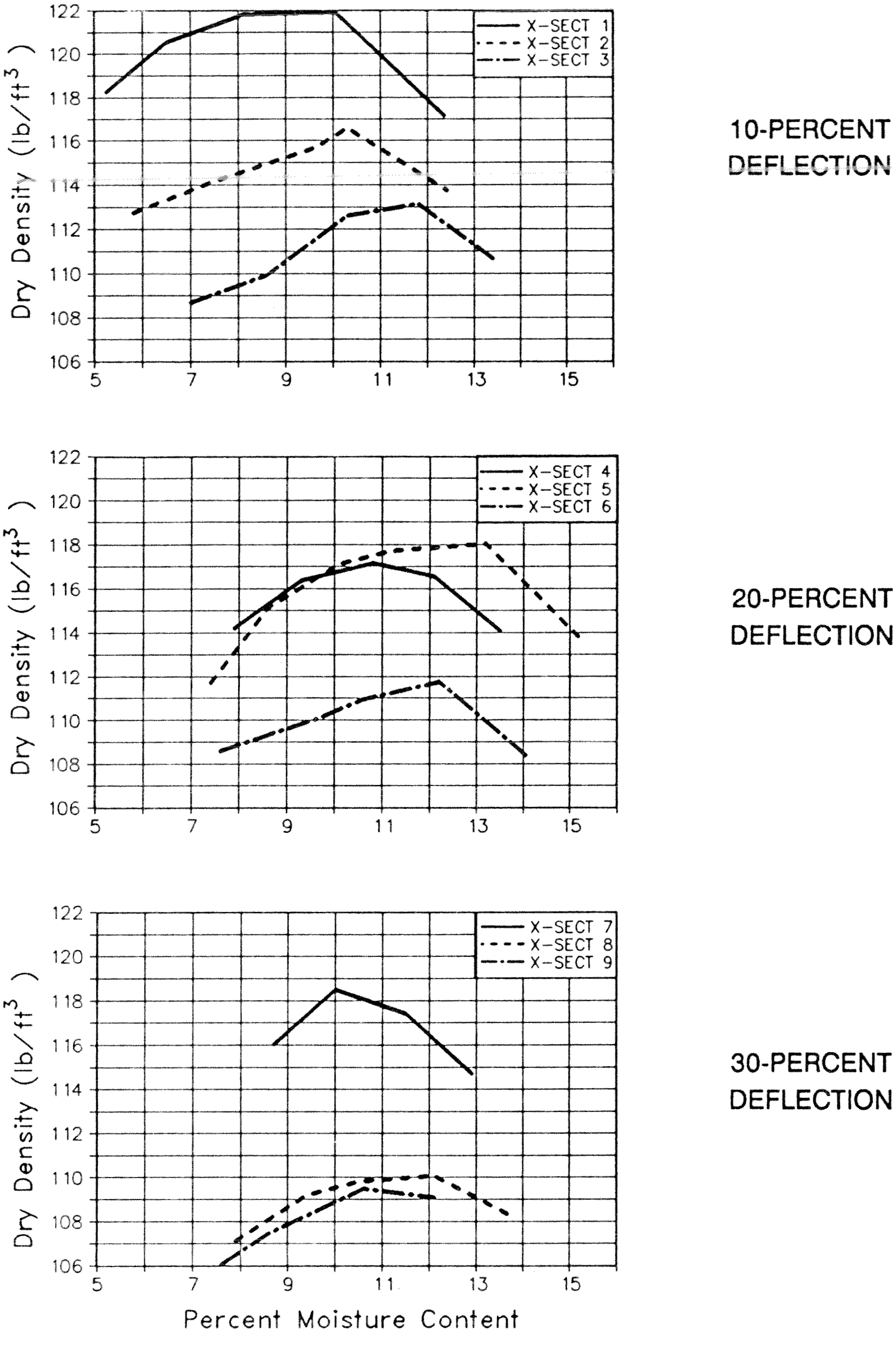

Figure 7.—*Proctor curves for the surface material of the forest road at the individual road cross-sections.*

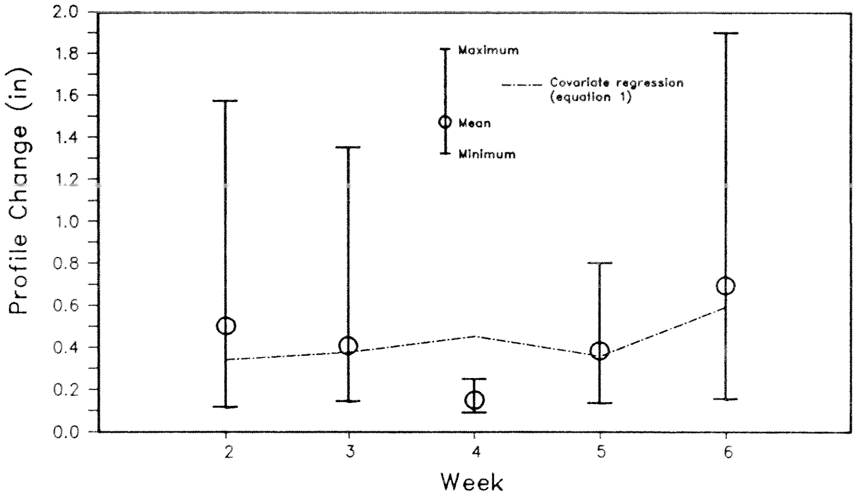

Figure 8.—*Regression equation for cross-section elevation changes compared to the range of the actual data.*

only significant factor was differences among weeks, suggesting that there were significant weekly differences that were not explained by traffic level or moisture regime.

A similar statistical procedure was used to evaluate the effect of the independent variables on changes in track bulk density. Regression analysis found that the trend of increasing bulk density observed during the test period was largely a function of the number of passes and moisture (fig. 9). Again, this is consistent with standard moisture-density relationships. The bulk density data were adjusted to remove the effect of passes and moisture and further evaluated in an analysis of variance. None of the remaining independent variables (week, road section, or cross-section) were significant in explaining the variability in bulk density.

Ride Vibration

WES Ride Meter Data.—The ride meter data were statistically analyzed in a manner similar to the analysis of the cross-section change data. Figure 10 illustrates the range of absorbed power values that were recorded during the tests. There were statistically significant differences in absorbed power readings among the road sections. The highest absorbed power values measured at the seat base occurred on the 10-percent deflection section, while the highest values measured on the seat occurred on the 30-percent deflection section. Because the absorbed power values at the two accelerometer mounting locations (seat and seat base) were measured on different passes, the data were analyzed separately by mounting location.

The ride meter values were initially examined as a function of travel speed and cumulative number of passes. For the seat base location, neither of these factors nor variations of the factors were significant in explaining the variability in the absorbed power values. Regression analysis of the data from the seat, however, showed that speed and cumulative passes did have a significant effect on the absorbed power transmitted to the driver. Travel speeds were significantly different among the road sections and directly related to the tire deflection—the 10-percent deflection section had a lower average travel speed than the 30-percent deflection. In addition, increased travel speed and/or increased number of passes over the road were associated with higher absorbed power values on the seat.

The ride meter data were further analyzed to determine the effect of truck, test section, and individual cross-section differences. All three of these factors significantly affected the absorbed power values measured at the seat base. However, analysis of the data measured on the seat, adjusted for the effect of travel speed and cumulative passes, found that the only significant effect that could be identified was due to differences between the trucks. There was no detectable difference in absorbed power at the seat due to tire deflection.

Operational Evaluation.—The data from the operational trials consisted of simultaneous readings of travel speed, inflation pressure in the front tires, and inflation pressure in the rear tires. The inflation pressure values were averaged and categorized as either high or low. The travel speeds were statistically examined to determine the effect of differences between trucks and between the two levels of inflation pressure. Both of these factors were found to significantly affect travel speed, with higher travel speeds associated with lower tire pressures.

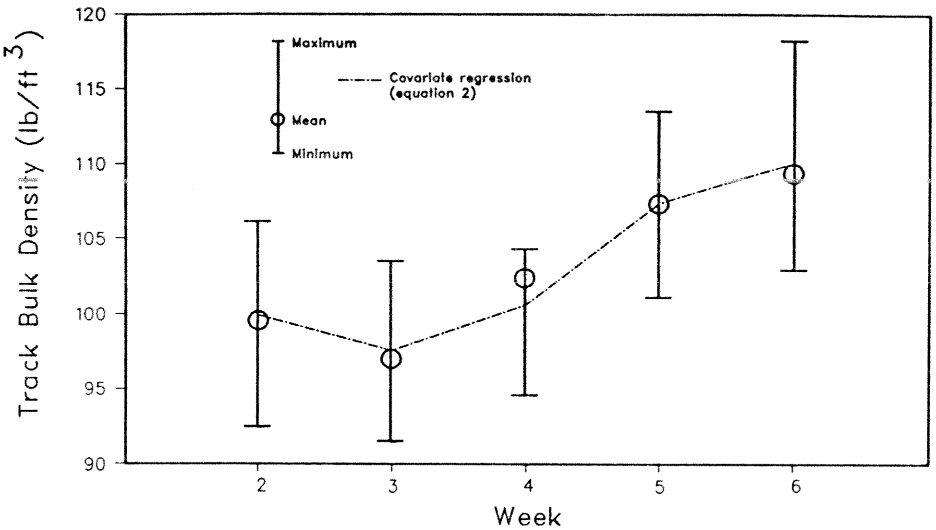

Figure 9.—*Regression equation for changes in track bulk density compared to the range of the actual data.*

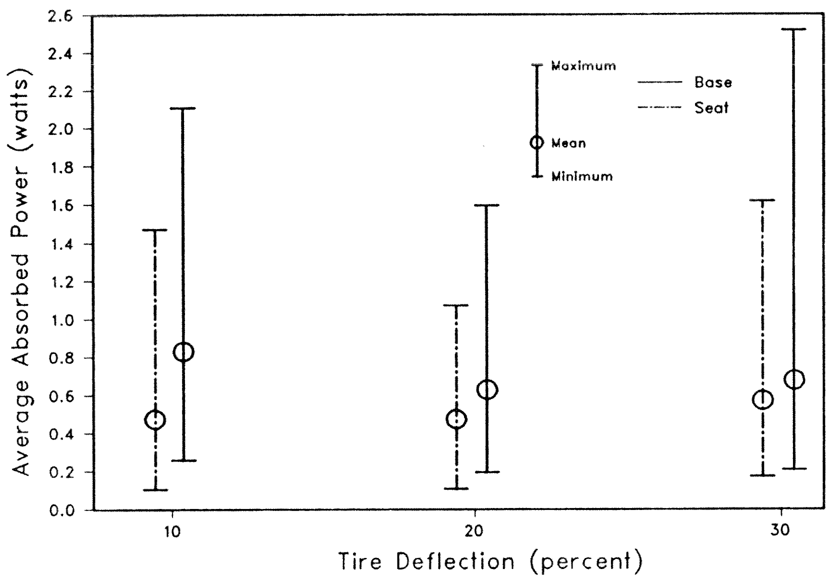

Figure 10.—*The range of absorbed power values measured at the seat base and on the seat at three different tire deflections.*

DISCUSSION

Road Cross-Section Changes

Elevational changes were observed in the road cross-sections, but these changes could only be attributed to unexplained weekly differences and the effects of traffic and moisture. No statistically significant changes in cross-section elevation could be attributed to tire deflection.

While the statistical analysis does not support a deflection-related effect, significant road damage occurred in the low-deflection test section. The damage simply did not occur at one of the three cross-sections within the test section. Future road surface testing protocols should include longitudinal profiles as well as lateral road cross-sections.

Changes in the surfacing bulk density were also observed. The data exhibited a trend of increasing bulk density through the testing period. The statistical analyses indicated that the change in bulk density was a function of traffic, moisture, and differences between the individual sample points. There was no statistically significant difference between the compaction that occurred in the different deflection sections. This data confirms that compaction processes are part of alterations in the cross-sections.

Ride Vibration Measurements

The ride meter data indicate the complex nature of the ride dynamics on a logging truck. Absorbed power values recorded at the floor exhibited wider range and greater maximum values than the absorbed power observed at the seat. The reduction in vibration between the two points is a frequency-dependent function of the seat suspension dynamics. The vibration input to the seat (seat base location) was a function of differences in trucks, test sections, and the individual cross-sections. However, the measured vibration at the operator/seat interface was only a function of differences between the trucks. The dissipation of vibration energy in the seat suspensions apparently reduced the variability due to tire deflection. While it appears that increasing tire deflection may not significantly reduce the vibration exposure of the driver, it clearly reduces the vibration levels to which the truck is subjected.

The operational trial data, like the forest road test course values, indicated a significant inverse relationship between travel speed and tire pressure. Lower tire pressures were associated with higher travel speeds. There are a number of possible implications. If travel speed was limited by a "vibration exposure threshold" of the drivers, then the data would suggest that tire deflection has a sufficient effect on ride vibration to affect the behavior of the driver. It is also possible that the effect on the driver is more indirect. For example, the rattling, banging, and shaking of the truck at higher tire pressures might induce the driver to reduce speed even if the ride vibration was at an acceptable level. Further testing is required to identify the processes involved. Any further testing should examine the dynamic system in more detail, recording spectral data at various points in the vibration transmission path between the tire and the operator.

CONCLUSIONS

The data observed in the various tests described in this report support the following conclusions:

1. Bulk density of the road surface increased with the number of trips over the road. This increase was independent of tire deflection.
2. Changes in the cross-section elevations were a function of traffic and moisture regime, not tire deflection. However, the sampling scheme missed significant road damage that may have been deflection-dependent.
3. Vibration on the seat (measured by the absorbed power criteria) was not significantly affected by tire deflection. Vibration at the seat mounting point was affected by tire deflection.
4. Travel speeds observed in both tests were directly related to tire deflection. Higher travel speeds were observed at higher tire deflection.

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Appendix

Statistical Analyses

The two dependent variables in the forest road test course, track bulk density and cross-section elevation change, were evaluated in a randomized complete block experimental design with cross-section nested within section, blocked by week. The measured quantitative independent variables (number of passes, moisture content, and rainfall) were examined for significant correlation with the dependent variables and treated as covariates.

Cross-Section Elevation Change.—Linear regression analysis was used to develop an equation that described the relationship between the cross-section elevation changes (CHG) and the covariates (equation A-1). Track moisture content (TMC), cumulative passes (CUMP), and cumulative rainfall (RTOT) were significant variables.

$$\begin{aligned} CHG = {} & 1.48266346 - 0.0690918(TMC) \\ & + 0.0000046(CUMP)^2(TMC) \\ & - 0.00006212(CUMP)^2 \\ & - 0.0671714(RTOT) \end{aligned} \qquad (A\text{-}1)$$

$$R^2 = 0.21$$

This equation is plotted against the range of data in figure 8. During week 4 one of the trucks broke down, and only half as many passes were applied to the road. This may account for the anomalous data point in week 4. The effect of weekly passes was not statistically significant.

Using equation A-1, the cross-section change data were adjusted to remove the effect of the significant covariates. The adjusted data were then examined in the randomized block design. The results of the analysis of variance (table A-1) indicate no significant effect associated with tire deflection (SECT). Even with weekly variability due to passes and track moisture content removed, the only significant variable was the blocking factor, week.

Track Bulk Density.—The track bulk density data were analyzed using a similar procedure. Linear regression analysis of the covariates showed that track bulk density (TBD) was significantly related to TMC, average rainfall during the week (RAVG), RTOT, and CUMP. Equation A-2 describes the regression relationship, which is plotted against the range of the data in figure 9.

$$\begin{aligned} TBD = {} & 100.6111887 + 1097.135756(RAVG) \\ & + 0.098728(CUMP) - 0.434632(TMC) \\ & - 157.088672(RTOT) \end{aligned} \qquad (A\text{-}2)$$

$$R^2 = 0.64$$

This equation was used to adjust the values of TBD to remove the variability due to the covariates. The resulting adjusted values were analyzed in the randomized block design to evaluate the main effects (table A-2).

With the variation due to the covariates removed, there was no significant difference attributable to tire deflection. The only main effect that proved significant was cross-section, which suggests that unspecified differences between the individual cross-sections contributed to the observed variation in TBD.

Ride Meter Data.—The ride meter data were separated by accelerometer mounting location and analyzed in a similar factorial experimental design. Average travel speed (SPEED) and CUMP were tested for significance as covariates. The covariates significantly affected absorbed power values measured on the seat, but not the data measured at the seat base. Equation A-3 defines the regression relationship for the seat data.

$$\begin{aligned} \text{Absorbed power} = {} & 0.13125 \\ & + 0.0000000738(CUMP)^3 \\ & + 0.01308331(SPEED) \end{aligned} \qquad (A\text{-}3)$$

$$R^2 = 0.16$$

Equation A-3 was used to adjust the absorbed power values recorded at the seat prior to the factorial analysis of the data.

Absorbed power at the seat base was significantly affected by differences between trucks, test sections, and individual cross-sections (table A-3). However, the analysis of variance of the adjusted seat data (table A-4) found that the only main effect significantly affecting the vibration on the seat was differences between trucks.

Operational Evaluation.—The data collected during the operational test in Oklahoma was analyzed in a 2^2 factorial design with the dependent variable travel speed as a function of truck and tire inflation pressure level. The analysis of variance (table A-5) shows that both of the independent variables had a significant effect on travel speed.

Table A-1.—*Analysis of variance for elevational changes in road cross-sections*

Source	d.f.	Sums of squares	Mean squares	F	p>F
Week	4	1.15733752	0.28933438	2.52	0.0602
Road section	2	0.14265773	0.07132887	0.62	0.5432
Cross-section(Section)	6	0.19842656	0.03307109	0.29	0.9381
Error	32	3.66896643	0.11465520		
Total	44	5.16738815			

Table A-2.—*Analysis of variance for changes in track bulk density*

Source	d.f.	Sums of squares	Mean squares	F	p>F
Week	4	41.0421882	10.2605470	1.36	0.2699
Road section	2	14.2671895	7.1335948	0.95	0.3992
Cross-section(Section)	6	309.3507537	51.5584589	6.83	0.0001
Error	32	241.5360765	7.5480024		
Total	44	606.1962078			

Table A-3.—*Analysis of variance for the absorbed power values measured at the seat base*

Source	d.f.	Sums of squares	Mean squares	F	p>F
Truck	1	10.6421735	10.6421735	107.89	0.0001
Road section	2	1.5750900	0.7875450	7.98	0.0004
Cross-section(Section)	6	4.4005077	0.7334180	7.44	0.0001
Error	234	23.0805395	0.0986348		
Total	243	39.5311787			

Table A-4.—*Analysis of variance for absorbed power values measured on the seat and adjusted for speed and number of passes*

Source	d.f.	Sums of squares	Mean squares	F	p>F
Truck	1	0.5565940	0.5565940	11.56	0.0008
Road section	2	0.1639144	0.0819572	1.70	0.1847
Cross-section(Section)	6	0.3426521	0.0571087	1.19	0.3148
Error	226	10.8857605	0.0481671		
Total	235	11.9489210			

Table A-5.—*Analysis of variance for travel speed as a function of inflation pressure*

Source	d.f.	Sums of squares	Mean squares	F	p>F
Truck	1	17899.60348	17899.60348	279.01	0.0008
Pressure	1	3462.78118	3462.78118	53.98	0.0001
Truck × Pressure	1	158.34230	158.34230	2.47	0.1166
Error	668	42855.14866	64.15441		
Total	671	64362.67987			

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Southern regional central tire inflation tests were conducted in Alabama and Oklahoma. The road wear and ride vibration data are analyzed in this report. Tire inflation pressure affects travel speed and truck vibration.

Keywords: Roads, rutting, tires, trucking, vibration.