

Effects of Tire Deflection on Rear-Axle Torque

ROBERT SIMONSON

Data were obtained in the study of an 18-wheel western-type log truck outfitted with central tire inflation (CTI) and carrying a highway load. Operating on grades of 20 and 25 percent, drive shaft torque was monitored to quantify stress levels on the drive train while varying tire deflection. Information is provided on the limits of additional traction to be gained through the use of tire deflection when operating on steep terrain—without excessive tire slip or vehicle maintenance. Torque levels for each grade and deflection combination are presented. A combination of steep topography and escalating road construction costs have led to the use of shorter, steeper roads. In order to reach landings of harvesting operations with a minimum road length, spur roads are often constructed in the 20 to 25 percent slope range. Haul roads exist with grades of 15 to 20 percent. An assist vehicle is often appraised when grades exceed 16 percent. Using the proper tire deflection for the application (based on speed and load) appears feasible through the use of CTI systems. Benefits have been seen in reduced vehicular damage to forest roads and increased tire life. An additional benefit realized with the use of CTI is improved traction on some road surface types because of the increased tire tread length.

A combination of steep topography and escalating road construction costs has led to the use of steeper roads. In reaching a needed elevation, steeper roads reduce the length of construction necessary. A road located along a ridgeline can significantly reduce resource impacts and excavation costs compared to a sidehill road.

In timber harvesting operations, spurs are often constructed in the 20 to 25 percent range to reach landings; with some in the Northwest containing pitches up to 30 percent (M. Rebar, unpublished data). Haul roads exist with grades of 15 to 20 percent. A cost allowance, and often a safety requirement is made to have a vehicle such as a road grader available to assist the log trucks in negotiating these steeper grades. The Forest Service routinely considers appraisal for an assist vehicle when grades exceed 16 percent (M. Rebar, unpublished data).

The U.S. Forest Service is evaluating the effects of tire deflection on tires, roads, and vehicles. Tire deflection is defined as the change in section height from the freestanding height to the loaded height (Figure 1). The percent deflection is the ratio of that change to the free standing section height ($\times 100$) (1).

Using the proper deflection for the application (based on speed and load) is feasible through the use of central tire inflation (CTI) systems.

CTI is a system incorporated in a wheeled vehicle that permits the vehicle tire pressures to be regulated by the vehicle driver from within the vehicle cab while on the move. Operation of the system is simple. Air enters through the air cleaner and is compressed and dried. A priority switch ensures that sufficient pressure is available for the brake system before allowing air to be used for the inflation system. The controller in the cab operates either a deflate or inflate valve, exhausting air out of the system or increasing system pressure. The controller circuitry makes this decision on the basis of the selection of the driver and sensors monitoring vehicle speed and current system pressure.

Readily apparent benefits have been seen in reduced vehicular damage to forest roads (2), which has prompted nationwide use of the concepts in select trials. This is of particular interest on steep roads, because road maintenance costs escalate with increased grades (3). Some types of maintenance equipment cannot be used on the steepest grades because of safety concerns.

An additional benefit realized with the use of CTI is improved traction on some road surface types because of the increased tire tread length. A CTI trial was conducted in which loaded trucks climbed grades of 18 percent—and at times 21 percent—under their own power (assist vehicles were attached as required by State regulations) (4). Although it appeared operationally feasible to climb these steep grades using increased tire deflection without assistance, concern remained that the effects of possible added strain on the truck drive-axle was unknown.

OBJECTIVE AND SCOPE

The hypothesis of this project was that impact loads on the rear-axle gear train decrease with an increase in tire deflection on steep adverse grades.

Data were obtained in the study of an 18-wheel western type log truck outfitted with CTI and carrying a highway load. Operating on grades of 20 to 25 percent, drive shaft torque was monitored to quantify stress levels on the drive train while varying tire deflection. Torque levels for each grade and deflection combination are presented.

Wheel slip on these tests would be similar to that on any crushed aggregate with roughly the same gradation and density. Experience has shown that traction on the surfaces used in this study should be fairly consistent from optimal moisture to a saturated condition (R. Young, unpublished data). Somewhere between optimal moisture and zero percent moisture, traction would decrease.

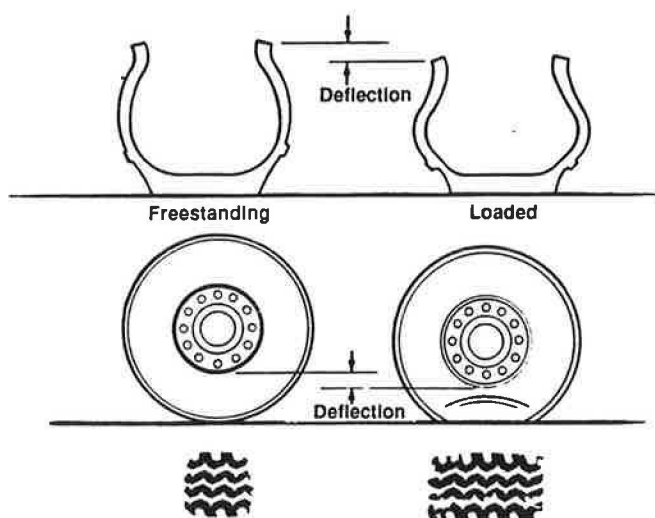


FIGURE 1 Tire deflection.

TORQUE

Axles are rated for a continuous torque on the highway (on the basis of a 3 percent grade, 60 mph, and rolling resistance from normally inflated tires on asphalt) and an intermittent climbing torque (not to exceed three times the continuous torque) (B. Hicks, unpublished data). For an 80,000-lb GCW truck, the design torque for continuous operation would be 10,250 ft-lb, the intermittent torques not exceeding 30,750 ft-lb.

An informal survey of truck distributors indicated that, in the Northwest logging industry, Eaton two-speed axles account for about 85 percent of the trucks purchased in 1989 (Dillon, Egge, Helms, and Spies, unpublished data). For this size logging vehicle, the Eaton DT440, or the DT461 tandem would be typical.

For a calculation of torque before testing, an approximation can be made based solely on the force required to overcome the weight of the vehicle. This simplification does not consider acceleration or rolling resistance. The vehicle weight in this test, of 75,600 lb acting vertically, may be broken into two components; a normal force, and a force F parallel to the road surface. With a road grade of 20 percent this force is

$$F = 75,600 * \sin[\arctan(0.20)] = 14,826 \text{ lb}$$

To generate the force F at the road surface with tires having a radii of 21 in. requires a total tandem axle torque of

$$T = 14,826 * 21/12 = 25,946 \text{ ft-lb}$$

STUDY SITE

The study site is the Mapleton District of the Siuslaw National Forest. Two roads were chosen by district engineers as typical—both surfaced with dense basalt, one with 1½-in. (–) material, and the other with 3-in. (–). This surfacing material

is used on 90 percent of the roads with grades exceeding 16 percent on the Siuslaw National Forest. It is also the recommended material for steep grade construction throughout the Forest Service in the Northwest (H. Rickard, unpublished data).

The first series of tests was conducted on Billy Creek Road, which is typical of steep, maintained National Forest roads. The test grade here was 20 percent, and it was surfaced with a 1½-in. (–) material with 89 percent passing the half-inch sieve. Alignment was straight. Moisture content was 7.4 percent at the 2-in. depth. The road was in excellent shape before testing and no additional preparation was needed.

The second series of tests were on the Prong Spur, which was typical of a steep short spur with surfacing placed for temporary use. Its grade was 25 percent, and it was surfaced with a 3-in. (–) material with 59 percent passing the half-inch sieve. Moisture content averaged 7.6 percent at the 2-in. depth. This road was graded to remove material which had recently sloughed off of the cut bank onto the roadway.

Each section was tested once at the beginning of the project for gradation, Atterberg Limits, the Los Angeles Abrasion, Durability Index, and Sand Equivalent, since truck tests ran for only one week. Testing was performed in a materials laboratory on a representative sample.

Each test section was sampled for aggregate density and moisture content. Values were obtained by taking nuclear densometer readings in each of three randomly selected locations and averaging for each section.

TEST EQUIPMENT

Although the test vehicle had axles and a drive line of lighter duty than those commonly used in the industry, the torques required to propel any log truck with the same approximate loaded weight distribution would be similar.

The vehicle tested was a Diamond RE0 with tandem axles and a wheel base of 207 in. It was originally a 10-yard dump truck that was converted by Page Equipment to a conventional logging truck. Because the engine size, transmission, drive axle unit and tire size remained unchanged after the conversion, the tractive effort capability remained unchanged. It does not change when the truck is coupled with various trailers and loading (5).

The test vehicle was highway loaded with logs to 75,600 lb GCW for testing. A GCW of 76,000 lb is average for the Mapleton area (D. Upton, unpublished data); 74,805 lb GCW was the average log truck weight in the Oregon Coast range as reported by Stryker (6). The load distribution of the test vehicle was 10,880 lb on the steer axle, 33,540 lb on the drivers, and 31,180 lb on the trailer.

The truck is powered by a 350-hp engine and the drive train consists of an Allison five-speed automatic transmission coupled by drive shafts to Eaton 34DT two-speed axles. The interaxle differential lockout remained engaged throughout the testing. The low-end differential ratio is 7.60:1. The truck is equipped with Michelin XZY 11R24.5 tubeless tires.

The truck was instrumented with 11 transducers to measure

1. Drive shaft stress;
2. Left walking beam load, forward;

3. Left walking beam load, aft;
4. Front axle load;
5. RPM, left front wheel;
6. RPM, left front driver;
7. RPM, left rear driver;
8. Pressure, steer tires;
9. Pressure, drive tires;
10. Inclinometer, and
11. RPM, drive shaft.

Deflection (%)	Steer Tires (psi)	Drive/Trailer Tires (psi)
10	-	99
15	99	76
20	59	45

The drive shaft was chosen as the most easily instrumented link in the drive train assembly. Drive shaft stress was measured using gauges installed on a clear section of the drive shaft with orientation for torque sensitivity only. Output signals from the gauge bridge were wired to an FM transmitter. The FM signals were then wired to a shaft-mounted antenna. The drive shaft was calibrated off the truck on an assembly using a hydraulic ram to provide known torque loads.

STUDY METHODS

To test the hypothesis, tests were conducted by driving the same loaded logging truck over test sections on each of the test roads, using tire deflections of 10, 15, and 20 percent while monitoring the strain (torque) on the drive train. Tires were run at constant deflections rather than constant inflation pressures because it is desirable to keep the spring and damping rate of the tires constant, thus keeping the dynamic load experienced by the truck and road constant (7). Ten percent is the typical tire deflection of a loaded 18-wheel truck operating in the 90- to 100-psi tire inflation range common today. Twenty percent is the deflection the Forest Service is advocating for use by vehicles traveling at low speed on its low-standard unpaved roads and which has been approved by the Tire and Rim Association (8,9) for use in Forest Service trials. Fifteen percent was chosen as an intermediate point to test, because trucks inflate and deflate on the go and are therefore often operating in the range of 10 to 20 percent rather than at one or the other.

In a typical CTI-equipped truck, tire pressure settings to attain a desired deflection would be programmed in the control unit on the basis of that truck's typical load distribution. Because loads vary by a few thousand pounds, actual deflection on a given haul would only approximate the desired deflection. On this test, the actual deflection was measured and set for the exact test load.

Also in a typical CTI installation, there are two discrete pressure channels; one for the steer tires, another for the remaining 16 tires. Because no log load can be perfectly balanced, individual tire loads, and therefore individual tire deflections, vary because pressure from tire to tire within the same channel is the same. In a field sampling of load distributions, it is not uncommon to find axle end loads varying by 40 percent on the same truck (10). Individual axle end loads were not measured for this test. Measured deflection was averaged within each CTI control channel to attain the test deflections.

On this particular combination of truck, load, and tire, the cold pressures used for the desired deflections were as follows:

A pressure of 99 psi was the highest pressure obtainable with the particular model of CTI onboard the truck, therefore 10 percent deflection was not attainable on the steer tires.

Prior study of washboarding indicated that tire slip on logging vehicles occurred in the range of 12 Hz (L. Della-Moretta, unpublished data), therefore a sampling frequency of 15 Hz was chosen as sufficient to capture this phenomenon. It was decided that 20 samples were sufficient to capture an occurrence of interest, so the instrumentation sampled at a rate of 300 samples per second.

A number of ground rules were followed to maintain continuity of the analysis of the data gathered during specific tests.

The ground rules are as follows:

- All tests were conducted with the same driver to minimize driver variation.
- All tests were conducted when wind conditions were below 5 mph to keep the effect of wind resistance on the truck to a negligible level.
- Tests were conducted when precipitation was negligible (less than 0.03 in. per day) to avoid saturated road conditions.
- Preparation for all planned tests was preceded by a full checkout of all hardware/equipment.
- Before and after each test series, the instrumentation was turned on and data acquired for a period of 5 to 10 sec to assist in the validity of data analysis.
- Each test condition was repeated a minimum of four times.
- Tests were run in a sequence of decreasing deflection on the 25 percent adverse grade. This was because with decreased deflection, the truck lost traction sooner, and would not reach or be affected by the disturbed road surface resulting from the previous tests' traction loss. The sequence was reversed on the 20 percent adverse grade to verify that trends detected in the tests were indeed based on deflection, and not testing sequence.
- Tests were conducted as close as feasible to a steady 3 mph. This minimized the effects of wind resistance and acceleration.

An assist grader was on site at all times for safety, but was not used during test runs.

SLIP AND TORQUE

Vehicles propel themselves by transferring the energy developed by the engine quite efficiently through the gear train to force on the rotating tire. The transmission of this force is dependent on the driven tire loading and the coefficient of friction between the tire and road surface (11). However, at the contact of the tire to an unpaved road only a percentage of this energy is transferred to movement; much of it is lost in tire slip and soil shear. This slip excites the road/tire/suspension system and washboarding is a result (12).

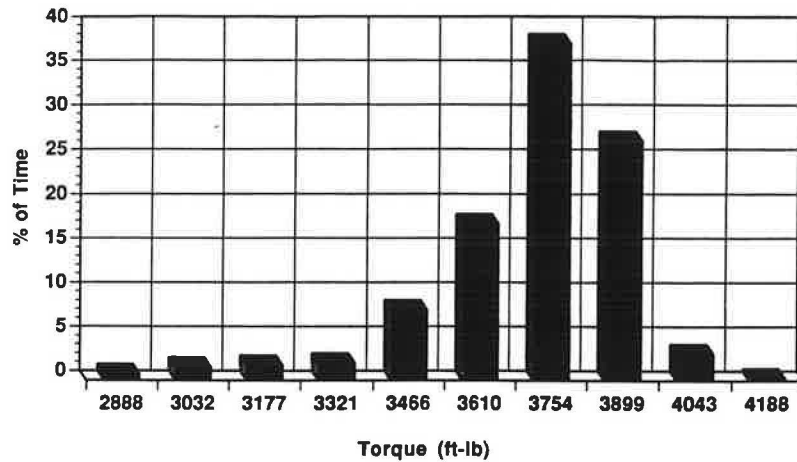


FIGURE 2 Drive shaft torque 10 percent adverse, 10 percent deflection.

On a given road surface with a given tire, CTI introduces the ability to increase the tire-soil contact area reducing the unit shear stress seen by the road surface. When the road surface is able to withstand this reduced shear, less energy is lost to slip and less road damage occurs. At the same time, the damping of any cyclic bearing loads is increased by the softening of the sidewall and lengthening of the tire contact patch. These factors are the main premises behind promoting the use of CTI systems on unpaved forest roads.

On steeper roads, the torque necessary to be transferred by the tires into forward movement is increased because of the increasing effects of gravity. The additional torque required for this task is not usually the limiting factor in today's vehicles, but the failure (i.e., tire slip and soil shear) at the tire-soil interfaces.

Some slip is inherent in the design of today's elastic pneumatic tires. Even before the visual failure of a spinout, the tire slips, the road surface shears, and consequently the tire sinks deeper. This sinkage continues causing increased contact area until the slip stops. As the tire is slipping, the tire is rotating faster and less torque is being transmitted. When the slip stops, the tire grabs and the torque requirement to continue moving forward is instantaneously increased.

As tire deflection and the contact area is increased, soil shear is reduced. When the tire does slip, the sinkage required to stop the slip, and therefore the elapsed time slipping, is also reduced. The rotational velocity attained by the slipping tire is less because there is less elapsed time for it to accelerate, and so the instantaneous peak torque required to arrest the spinning tire is also reduced. This concept was demonstrated in the field testing and is illustrated in the following charts of torque distributions as measured on the test vehicle.

TEST RESULTS

Drive shaft torque for each tire pressure on each grade is plotted in a histogram (Figures 2-7). These histograms provide a simple visual method of discerning the difference in peak and average torques for given conditions. Note that each stack in the histograms is labeled on the horizontal axis with the low torque of each interval. The vertical axis shows the percent of time on the constant grade that drive shaft was operating within the given torque range. The sum of the stacks in each histogram is 100 percent.

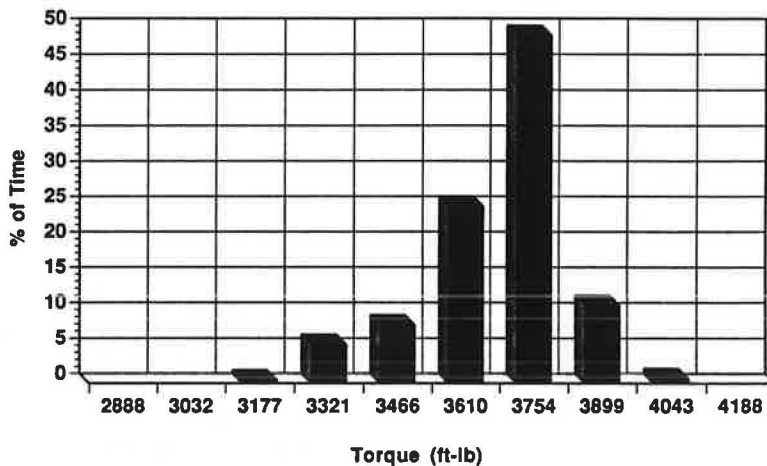


FIGURE 3 Drive shaft torque 10 percent adverse, 15 percent deflection.

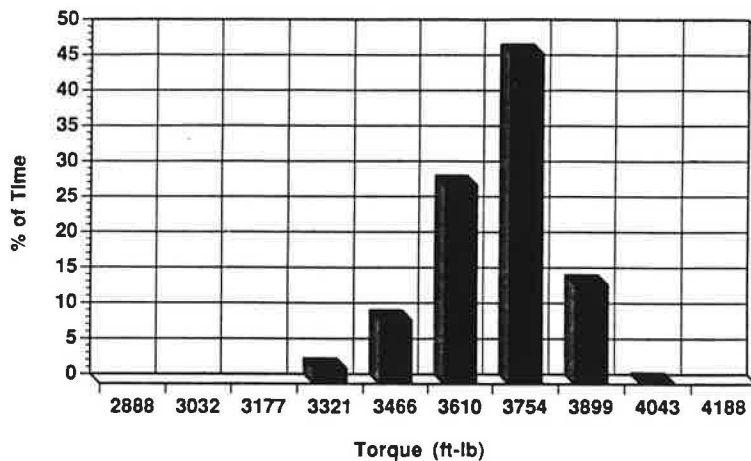


FIGURE 4 Drive shaft torque 20 percent adverse, 20 percent deflection.

It can be seen in Figure 2, with 10 percent tire deflection, the distribution of torques is wider than in Figure 4, with 20 percent deflection. Peak torques are higher at lesser deflection, and because the tire is slipping more often the torque drops more often.

Before testing, it was expected that the average torque would increase with greater deflection, because of the additional work used in flexing the tire on the compacted test sections. Rolling resistance is the sum of work to compress and deflect the road surface, flex the tire, overcome rolling friction (as in the bearings), and to overcome air frictions about the tire. The average drive shaft torque required to climb the grade did not significantly change, ranging from a low of 3,766 ft-lb at 15 percent tire deflection to a high of 3,780 ft-lb at 10 percent tire deflection (3,775 ft-lb at 20 percent). This would indicate that the additional rolling resistance of the tire expected with greater tire deflection is not a detectable amount, or is negated by the reduced work going into deflecting the road surface. The character of the road surface, where measurements were recorded, did not visibly change during the testing.

Operating the test vehicle on a 25 percent adverse grade demonstrates the results once again as shown in Figures 5-7. Peak torques are higher at lesser tire deflection, and the distribution of torques is wider. In Figure 5, besides a peak in the distribution of torques about the average, a lesser peak of values occurs at the 3,047 to 3,482 ft-lb range. This agrees with visual observations of the test vehicle experiencing significant additional slip at the 10 percent tire deflection on this steep grade.

Here again the average torques do not seem to reflect any logical pattern from the expected increase in rolling resistance caused by additional tire deflection. Average torque required to climb the 25 percent grade was 4,770 ft-lb.

CONCLUSIONS

With the gear ratio of 7.60:1 in the test vehicle differential, the average torque in the drive axles is 7.6 times that measured in the drive shaft less the loss to the inefficiency of the rear end. Drive train efficiency (Dte) is estimated by $Dte =$

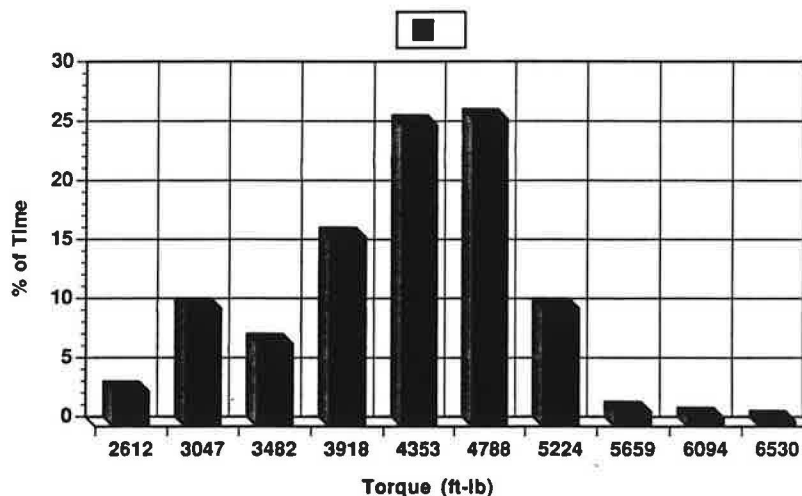


FIGURE 5 Drive shaft torque 25 percent adverse, 10 percent deflection.

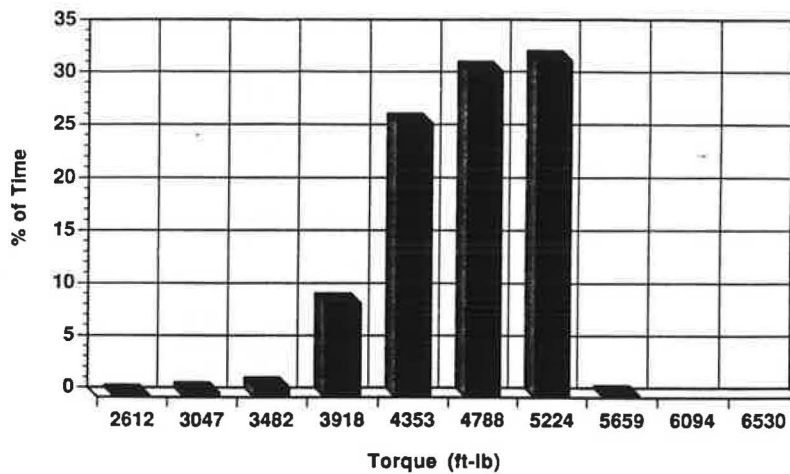


FIGURE 6 Drive shaft torque 25 percent adverse, 15 percent deflection.

($1 - 0.05N$), where N is the number of components in the drive train (13). In this case, torque was measured in the drive shaft and only one component, the rear end transmission, lies between the shaft and the drive axle. Efficiency is then estimated at 95 percent.

Average drive shaft torques measured to pull the 20 and 25 percent grades were 3,775 and 4,770 ft-lb, respectively. These amounts yield drive axle torques in the range of 27,200 and 34,400 ft-lb.

Tire deflection did not affect the most practical consideration of traction, gradeability. The test vehicle, operated at a slow and steady speed, climbed the 20 percent grade independent of tire deflection. On the 25 percent grade, the vehicle could not sustain the climb, again independent of tire deflection. The greater the tire deflection, the farther the vehicle traveled before totally losing its traction. Most likely, the greater tire deflection required a slightly larger bump, or a slightly weaker spot in the road surface before finally losing traction. This slight difference in tractive capability on a packed road surface, as is typical in the Northwest, is not sufficient reason on its own to operate at any particular deflection.

These test roads had near-ideal moisture contents and compactions. On unsurfaced spurs and landings, the difference in tractive capability would be expected to be greater, as seen in other testing (14).

At increased tire deflection, the data do point to less tire slip, fewer peak torques (instantaneous tire grabbing), and therefore more torque efficiently applied to moving the vehicle up the grade. Even in the situation on the 25 percent grade in which an assist vehicle would still be necessary, increased tire deflection would translate the power of the engine where it is needed rather than wasting it in road damage (tire slip) and additional gear train wear (torque spikes).

On the subject of drive train life, there are two factors to consider. Gear bending stresses vary linearly with torque. Contact stresses that include gear pitting and bearing fatigue are logarithmically dependent on stress (the square root of torque) (B. Hicks, unpublished data).

Average torque was not affected by tire deflection yet peak torques were reduced 14 percent while operating on a sustained 20 percent adverse grade, and reduced 9.6 percent on the 25 percent adverse. These results were accomplished by

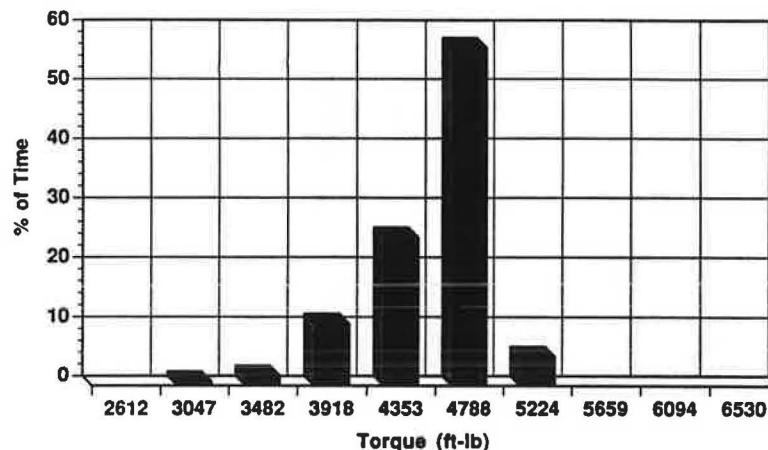


FIGURE 7 Drive shaft torque 25 percent adverse, 20 percent deflection.

increasing tire deflection from the typical 10 percent to the 20 percent approved in the interim standard issued by the Tire and Rim Association (8,9).

Peak axle torques on the 20 percent adverse grade ranged from 29,300 to 29,500 ft-lb at 15 and 20 percent deflection, respectively. Operating at the common tire deflection of 10 percent produced peak torques up to 34,200 ft-lb. Climbing the 25 percent grade produced peaks in the 38,500 to 42,500 ft-lb range.

Increasing tire deflection then does not have an adverse impact on drive train life on steep grades. The results of this test would indicate that it may increase the mean time to failure.

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance of the San Dimas shop crew and technician support, which put in many long hours; the road crew and engineering staff of the Siuslaw National Forest, Mapleton District, who jumped to assist, often late at night or on their days off; and a special thanks to LaMoure Besse for his continual assistance through all phases of this test.

REFERENCES

1. D. R. Freitag. *A Dimensional Analysis of the Performance of Pneumatic Tires On Soft Soils*. Technical Report 3-688. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 1965.
2. L. Della-Moretta. *Proof of Concept Tests for Central Tire Inflation*. U.S. Department of Agriculture, Forest Service, San Dimas, Calif., 1984.
3. P. Anderson. *A Survey of Design, Construction, and Operation Practices for Steep Roads in the Oregon Coast Range*. M.F. thesis, Oregon State University, Corvallis, 1985.
4. M. Rebar and H. Richard. *National Central Tire Inflation Program Mapleton Ranger District Field Operational Demonstration Prong Flight Timber Sale CTI*. Siuslaw National Forest, Corvallis, Oreg., 1988.
5. *Drive Traction Characteristics of Trucks and Truck Combinations*. Western Highway Institute, San Francisco, Calif., 1976.
6. E. A. Stryker. *Gradeability of Log Trucks*. M.F. thesis, Oregon State University, Corvallis, Oreg., 1977.
7. E. Gililand and W. Ryburn. Reduce Tire Pressure On Forest Service Roads Through Central Tire Inflation Systems. *Proc., Council on Forest Engineering*, Sept. 1986, Mobile, Ala., 1986.
8. *Engineering Design Information*. Tire and Rim Association, Inc., Akron, Ohio, 1987.
9. *Tire and Rim Association Yearbook*. Tire and Rim Association, Inc., Akron, Ohio, 1987.
10. A. E. Cohn. *Application of CTI/VTP Technology*. Goodyear Tire and Rubber Company, Akron, Ohio, 1989.
11. J. J. Taborek. *Mechanics of Vehicles: Machine Design*. Penton Publishing, Cleveland, Ohio, 1957.
12. L. Della-Moretta and H. Hodges. *Off-Highway Tire/Road Damage and Healing Mechanisms*. ASAE Paper 86-1060, American Society of Agricultural Engineers, St. Joseph, Mich., 1986.
13. P. S. Meyers. *The Diesel Engine for Truck Application*. SAE-SP-391, SAE, Warrendale, Pa., 1975.
14. C. Ashmore and D. Sirois. *Influences of the Central Tire Inflation System on Log Truck Performance and Road Surfaces*. ASAE Paper 87-1057, American Society of Agricultural Engineers, St. Joseph, Mich., 1987.