results of an FWD survey and analysis using the LOADRATE program for an entire county in Texas was presented to illustrate the use of the load rating procedure.

It was determined for Willacy County that an FWD survey of the FM roads at half-mile intervals would be sufficient to locate weak pavement sections. About 10 mi of road per hour could be tested at this rate. A complete survey and LOADRATE analysis of all the FM roads in a county that had about 200 mi of roads could take about 1 month, which means that the procedure described here is feasible, especially for managers of large highway networks. It is also shown that the information obtained from the LOADRATE procedure can help locate weak pavement sections and help manage pavement systems more efficiently. This information can also enable pavement engineers to evaluate overweight vehicle permit applications more efficiently, to decide which FM roads to load-zone, and to determine the level of effort required to lift load restrictions.

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The Use of Central Tire Inflation Systems on Low-Volume Roads

EDWARD STUART III, ED GILILLAND, AND LEONARD DELLA-MORETTA

A description is provided of a comprehensive program that was conducted by the U.S. Department of Agriculture, Forest Service, to evaluate the effectiveness of central tire inflation (CTI) systems in the transportation of forest products over unpaved low-volume roads. CTI is a mechanical component system for vehicles that allows the operator to adjust the inflation pressure of tires while the vehicle is in motion. The use of this system would allow tire pressure to be varied so that low-strength, low-speed roads could be negotiated with low tire pressures and higher-strength, higher-speed roads could be negotiated at higher tire pressures. A proof-of-concept test and a feasibility study indicated that the use of such systems on low-volume roads is technically and economically feasible. Such systems would provide considerable benefits to both the road agency and the road user in the form of lower costs for construction and maintenance, and lower operating costs and a reduction in driver fatigue, respectively. In 1986 the Forest Service initiated two controlled, quantitative tests on specifically designed and constructed test tracks to measure the effects of tire pressure on the road and the vehicle. A series of qualitative tests were simultaneously conducted on ongoing projects of logging operations and gravel hauling to ascertain and demonstrate the feasibility of using low tire pressures on low-volume roads.

E. Stuart, III, Pleasant Hill Engineering Center, USDA Forest Service, 2245 Morello Ave., Pleasant Hill, Calif. 94523. E. Gililland and L. Della-Moretta, Equipment Development Center, USDA Forest Service, 444 E. Bonita, San Dimas, Calif. 91773.

The USDA Forest Service has been investigating the relationship between tire pressure, road deterioration, and timber haul costs. The tires of commercial logging trucks are typically inflated to pressures above 100 psi. Central tire inflation (CTI) systems, which are now available on some types of trucks, allow

the tire pressure to be varied over a wide range while the vehicle is in motion. A driver can reduce tire pressure to an appropriate level to negotiate low-speed, low-volume roads, and then increase the pressure to a level more appropriate for high-speed highway haul.

It has been estimated that if these tire pressures can be reduced to a range of 20-45 psi on low-speed, low-volume roads, considerable construction and maintenance costs could be saved. These savings would result from reduced surfacing and road maintenance costs. The vehicles would not only cause less road deterioration, but they would actually aid road maintenance. It has been shown that low-pressure tires iron out washboards and smooth the road surface. In addition, less surfacing depth would be required to spread the loads to the subgrade because the tire footprint length is greatly increased and the load is applied over a substantially larger area. Additional benefits should also be realized from lower tire replacement costs (softer tires are damaged less often), reduced vehicle maintenance (softer tires have less of an impact on the vehicle as well as the road), and reduced operator fatigue (because of the softer ride).

PROOF-OF-CONCEPT TEST

A proof-of-concept test was conducted on a national forest in northern California during the summer of 1984. A fully loaded logging truck was operated on forest roads with cold tire pressures of 24 psi and 100 psi. The roads included unsurfaced (native soil) sections and cinder aggregate-surfaced sections. The test consisted of 300 passes of the vehicle with tires at the low pressure of 24 psi, followed by 300 passes at the higher pressure of 100 psi, and a final 300 passes at the low pressure of 24 psi. Truck speed was governed by operator comfort and control. Observations made during the test indicated that the high-pressure tires caused the road surface to deteriorate significantly in a form that included serious washboarding. The low-pressure tires caused no perceptible road damage; in fact, a significant improvement in the surface was noted at the completion of the final 300 passes. Other notable observations were made. During the high-pressure passes several parts were shaken off the truck; this did not occur during the low-pressure passes. Driver fatigue and discomfort were much greater during the high-pressure test. The time it took to complete a pass was longer during the high-pressure test and increased as the road deteriorated. Traction was much better with low-pressure tires, and less tire damage was noted during the low-pressure tests. There was no discernible difference in fuel consumption between the tests. The additional fuel that was consumed because of longer footprints was apparently offset by the factors of reduced road roughness and tire sinkage into the road surface.

FEASIBILITY STUDY

As a result of the proof-of-concept test, the Forest Service has accelerated a program to investigate the effects of tire pressure and the implementation of CTI systems on forestry-related vehicles. A feasibility study was conducted by an independent consulting firm under contract with the Forest Service to determine the benefits gained from variable tire pressure to the Government, road users, and vehicle and tire manufacturers based on available data. This study concluded that

> The use of such systems was technically and economically feasible. Significant savings in road construction and maintenance can result from the use of lower tire pressures on unsurfaced (earth or native surface) and aggregate-surfaced roads. User benefits that can be expected from the use of the lower tire pressures include:
>
> - Significant reduction in tire damage (bruises).
> - Significant reduction in impact-related spare-parts consumption.
> - Potential reduction in tire wear.
> - Potential reduction in fuel consumption.
> - Potential reduction in personnel injury due to road impacts.

Potential benefits to vehicle, system, and tire manufacturers are primarily in the form of additional sources of revenue that would result from new products and markets.

QUANTITATIVE TEST PROGRAM

Because a significant number of quantitative unknowns still exist as to the various effects of low-pressure tires on roads, vehicles, and drivers, the Forest Service initiated an aggressive test program. The first quantitative test was conducted under a contract with the Nevada Automotive Test Center (NATC) in Carson City, Nevada. This test consisted of building a special test track approximately κ mile long. The track consisted of sections that had native, aggregate, and paved (asphalt concrete and double-chip seal) surfaces of various thicknesses and sections that had a variety of obstacles such as half-buried rocks, washboards, and reinforced potholes. The primary purpose of this test was to quantitatively evaluate the effects of tire pressure on the vehicle including the tires and the vehicle operator. The secondary purpose of this particular test was to observe the effects of tire pressures on the various road surfaces.

Two identical logging trucks were used in this test. The tires on both trucks were new steel-belted, 14-ply rated, radials of a rib and lug tread design that were supplied by tire manufacturers. Each truck made a total of 2,000 passes over the course with a full load of logs (80,000-lb GVW) and a total of 2,000 passes with no load (30,000-lb GVW). The trucks travelled at identical speeds that were predetermined for each section of the course. The following measurements were made using a variety of state-of-the-art mechanical, electronic, and electromechanical measuring devices: tread depth, tire geometry, deflection of the suspension system, yaw and pitch, fuel consumption, fuel temperature, drive shaft torque, tire slip, seat air-chamber pressure (driver comfort), and vertical and lateral forces at selected locations on each truck. In addition to the test track evaluations, the logging trucks were run on paved roads with high tire pressures at highway speeds. This was done to ascertain whether or not driving these tires on unpaved roads at low pressures had any effect on the performance of the tires with high pressures at highway speeds. This test was initiated in August 1986 and was expected to be completed in March 1987. However, at this point in time, a number of definitive results have been obtained that are reported in a later section of this paper.

As previously mentioned, the effect of tire pressure on unsurfaced or aggregate-surfaced roads was a secondary objective of the NATC test effort and for the most part only qualitative evaluations were made. A second test track was under construction at the time this paper was prepared at the U.S. Army Corps of Engineers' Waterways Experiment Station (WES) in Vicksburg, Mississippi, to quantitatively determine these effects. The primary purpose of this test is to produce data that will be used to develop a formalized methodology to relate tire pressure to structural section design and road maintenance. This track, which is an approximately 0.6-mi loop, consists of two parallel lanes that have tight, 90-ft radius curves, flat tangents, and steep, 12 percent grades. Various types and thicknesses of surfaces are to be placed on the test track, and loaded and unloaded logging trucks are to be run over the test track at various tire pressures in the same way as the NATC test program. The following quantitative measurements are planned:

- Surface loss;
- Roughness of road surface, including washboarding, rutting, and shoving;
- Changes in density and moisture content;
- Maintenance requirements of the various road surfaces;
- Fuel consumption; and
- Vehicle speed.

All pertinent soil characteristics have been determined for both the native soil and surfacing materials. Road structural section requirements were predicted and will be compared with actual field results.

Qualitative evaluations are planned to be made of vehicle stability and handling, and driver comfort and physical well-being. Quantitative measurements will be made to determine tire wear and damage, and the effects on the trucks. Testing will commence in the fall of 1987 and will be completed by September 1988.

QUALITATIVE TEST PROGRAM

The test program just described was designed to control and quantify as many of the variables as possible in a relatively controlled environment. As an adjunct to these tests, a series of qualitative tests were and are to be conducted in an uncontrolled environment on ongoing projects. The first of these tests was performed during a logging operation in the Boise National Forest in Idaho during the fall of 1986. A total of approximately 1.7 million board feet of logs (about 400 truck loads) were driven over a series of native-surfaced logging roads.

Approximately 230 of these passes were operated at low tire pressures (45 psi loaded and 20-25 psi empty) and the remaining 170 passes were operated at more commonly used tire pressures (90-110 psi). The four trucks were all equipped with new radial truck tires (11R 24.5) immediately before the tests and were not driven anywhere but at the test site. The tire pressures were manually adjusted to the level appropriate for each phase of testing. Road deterioration, haul cost effects, speed, driver comfort, vehicle handling characteristics, and the effects on the vehicle were evaluated. Road deterioration was determined by making qualitative evaluations of roughness and soil and aggregate shoving on five test sections that were approximately 300 ft long. Haul costs were determined by maintaining records of fuel consumption, round trip times, tire wear and damage, and vehicle maintenance. The speed of the vehicles was not controlled but was measured at critical locations (curves, grades, and tangents) with a radar gun. Driver comfort was qualitatively determined by interviewing the drivers and was quantitatively determined by a ridemeter that was developed by the U.S. Army Corps of Engineers at WES. Vehicle handling characteristics and the effects on the vehicle were determined by means of observation and interview. All tires were removed from the trucks at the conclusion of the test and a sample of 10 tires was tested and evaluated to ascertain the effects of low-pressure operations.

Another test was conducted in Alabama during the fall of 1986. Two new, 10-wheel pulp trucks were furnished for this test by Mack Trucks, Inc.; they were equipped with prototype central tire inflation systems. These trucks were evaluated for system performance on a native-surfaced logging road that was closed to all other vehicles. The road was divided into three segments. One segment was travelled with high tire pressures (70-100 psi), the second at low pressures (25-65 psi), and the third at extremely low pressures (10-20 psi). Observations and measurements similar to the Idaho unstructured test were made on the trucks and the road.

A third test is currently being conducted at the Olympic National Forest in the state of Washington. This test will evaluate the effects of tire pressure on six 10-yard dump trucks during a gravel haul over aggregate-surfaced roads. One truck is equipped with a prototype CTI system. The tires on the other five trucks are being adjusted manually. Approximately 1,500 loads are scheduled to travel over 7 miles of the road from the quarry to the construction site. Measurements and observations similar to those made in Idaho are also being made for this test. Additional qualitative tests on ongoing timber sales will be conducted during the summer of 1987 at locations throughout the United States.

RESULTS

Quantitative Test Program: NATC Site

As was previously discussed, the NATC test was not completed at the time this paper was written. However, preliminary results have been obtained and are shown below and in Table 1.

Vertical G-Force Measured at the Axle End of the Loaded Trucks in the Washboard Section

Axle	*High Pressure*	*Low Pressure*
Steering	1.50	0.78
1st drive	0.99	0.85
2nd drive	1.40	1.02
1st trailer	1.10	0.81
2nd trailer	1.44	0.72

The percentage of average tire wear during the loaded phase of the test at a high pressure was 15.4 and at a low pressure was 13.1. Fuel consumption (ton mile/gal) during the loaded phase of the test at a high tire pressure was 84.1 and at a low tire pressure was 83.0.

All operators and visitors riding in the truck shared the opinion that the ride quality significantly improved when low

TABLE 1 REPAIRS AND ADJUSTMENTS OF TRUCKS DURING THE LOADED PHASE OF THE TEST

	High Pressure	Low Pressure
Man-hours for repair	37.5	15.6
Number of load chain adjustments	15	3
Nuts required tightening	Yes	No
Replaced engine cross member	Yes	No
Coolant leaks	Yes	No
Replace king pin bushing	Yes	No
Exhaust bracket loose	Yes	Yes
Door latch broken	Yes	No
Belts loosened	Yes	Yes
Fuel tank strap broken	Yes	No

tire pressures were used. During the test, the speed of the high-pressure truck had to be reduced in the washboard section because of the damage to the truck. All tests and evaluations performed on the tires to date indicate that there were no adverse effects from operating them at low pressures.

The original washboard sections were constructed identically for both the high- and low-pressure lanes. However, during the test, the high-pressure lane showed a significant increase in the magnitude of washboards, whereas the low-pressure lane showed a significant reduction in the severity of the surface.

Qualitative Test Program: Boise National Forest

It was evident to both the logging truck drivers and the Forest Service that changing tire pressures improved the condition of road surfaces and decreased the overall road maintenance requirements. This situation was dramatically different from that of the previous haul year, in which the road had required continual maintenance. The roads in this area became greasy when wet. During this test, the first pass of low-pressure tires had made the road surface so hard and smooth that only in areas of excessive subsurface water did the road surface break down under the high-pressure trucks.

The restorative effect of low-pressure tire passes became apparent early in the test program. During the first phase, rain storms had saturated the road to the point that logging operations were temporarily shut down. During this time, other traffic that used high-pressure tires seriously damaged the road. After the road surface had dried out enough to resume hauling, the first high tire pressure phase of the test was planned to begin. However, the logging contractor and truck drivers suggested that trucks with low tire pressures should haul over the road for 2 days in lieu of grading the road surface. The low tire pressures smoothed the road surface and grader maintenance was not required. Photographs that documented road conditions of this same haul road a year earlier, when normal tire pressures had been used on it, showed ruts as deep as 16 in. Road maintenance had been continual. This same haul road was never maintained throughout the course of this test program. On steep grades, truck traction was improved by the use of a low tire pressure. In the case of an adverse haul over a wet road surface, the use of a low tire pressure prolonged the haul and delayed a temporary shut down.

Condition surveys of the vehicles prior to and at the conclusion of the test indicated that no additional maintenance or repair was required on the vehicles. The truck drivers agreed that over an extended period of time overall truck maintenance and repair would be decreased by the use of low tire pressures. They believed that over a period of time, both the frequency and degree of truck repair would decrease.

Fuel use increased by approximately 10 percent during low-pressure operations. However, differences in road and weather conditions made the comparisons questionable. No tire damage was observed during the low-pressure operations. It is very unusual for logging trucks that operate on these types of roads to haul this amount of timber without any tire damage. One tire did blow out during the high-pressure operations. Upon completion of the test program, the trademark manufacturer designs that were molded in the tire tread were still evident, which indicated limited tire wear. However, during the course of this test program, each of the four logging trucks traveled less than 2,000 mi. Based on this limited mileage, no reasonable conclusions can be drawn from this test as to whether or not tread wear can be affected by changing tire pressures. The drivers noticed that their trucks bounced and rattled less and they were much less uncomfortable during the low-pressure operations.

Alabama Test

The road segment operated at a high tire pressure showed an increase in roughness (ruts and potholes) and finally became impassable after about 360 passes. At that point, the tire pressures were reduced to extremely low pressures to negotiate the damaged section. This section was gradually improved during the subsequent operations in which tire pressures were extremely low. The low-pressure segment showed minor roughness at the end of 360 passes, but was still considered to be in good condition. The section that was operated at extremely low pressures showed no deterioration during the test. No road maintenance was performed on any of the test segments.

As the tire pressures were varied for each segment of the road, it was not possible to discern relative tire wear for the various pressures; however, no major tire damage was noted during the test.

Fuel consumption was decreased on the sections in which low and extremely low pressures were used, which was attributed to the following statement of one operator.

> On the bad part of the road, with full tire pressure, I have to ease along in second gear using a lot of fuel . . . On the (low-pressure segments) I can drive with ease in fourth gear, and am using far less fuel. The truck is rolling easier, and smoother.

Washington State Test

Although this test was still underway at the time this paper was written, some preliminary results have already been obtained. After 3 weeks of hauling on low-pressure tires, the field personnel indicated that the haul road deteriorated much less than would normally be experienced at this time of year. No flat or damaged tires have been reported during this period. One can normally expect 12 flat or damaged tires in this time period.

All of the drivers have stated that they have experienced much more comfortable rides with low-pressure tires and have expressed a strong desire to continue to operate with them.

CONCLUSIONS

The following general conclusions are based on the results of the quantitative and qualitative test programs:

- Damage to native- and aggregate-surfaced roads significantly decreased when tire pressures were lowered.
- Low-pressure tires have a definite healing effect on the road surface. Improvements include the densification and smoothing of ruts and washboards.
- The thickness of the structural section of aggregate-surfaced roads can be reduced for trucks that use low tire pressures. The quantitative amount of this reduction is still to be determined.
- Vehicles with low-pressure tires can be operated in wet conditions that would normally prohibit truck travel because of the potential damage to the road and the inability of the trucks to negotiate the roads.
- The damage to tires when they are operated at low pressures is significantly less than would normally be expected if they were operated at high pressures. Preliminary results indicate a slight reduction in tire wear for low-pressure tires operated on gravel- or native-surfaces.
- The impacts on trucks and cargo are significantly reduced when low-pressure tires are used, which results in lower truck maintenance and repair costs.
- Fuel consumption data showed very little difference between low- and high-pressure operations on aggregate- and native-surfaced roads.
- Vehicle speed increases when an appropriate tire pressure is used for certain road surface conditions (i.e., low pressure for rough roads).
- Driver comfort and the control of the vehicle are greatly improved when low-pressure tires are used.

Although tests are still currently being conducted, it is evident that the variance of tire pressures on low-volume, unpaved roads has tremendous economic benefits. Annual savings to the Forest Service in road construction and maintenance alone will be in the millions of dollars. If the added benefits of extending the operating season, reducing haul costs, reducing driver injuries, and decreasing cargo damage are considered, it is apparent that this concept is the beginning of a new era in low-volume road transportation.

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