Effects of Vehicle Type and Tire Pressure on Dry-Weather Road Maintenance

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In 1993 a structured test was conducted to measure the effects of different vehicle types on road maintenance for operation in a dry climate. Three different vehicle types were compared: high-tire-pressure logging truck, low-tire-pressure logging truck (both were 18-wheel, western U.S.–style logging trucks), and a mix of light, two-axle vehicles. The test track consisted of four different sections and three individual lanes. Comparisons were made for roadway roughness (washboarding, potholing), material loss, and rutting. Results are presented indicating that grade and alignment have substantial impacts on road maintenance ratios between light and heavy vehicles operating under dry conditions. Maintenance ratios between light and heavy vehicles are on the order of five to one for the dry operating conditions experienced.

A number of studies have been performed that have attempted to quantify the effects of different vehicles on paved surfaces. Gibby et al. (*1*) review the rationale for allocating maintenance costs among various users. Their study resulted in about a 1 to 95 damage ratio between light and heavy vehicles. Relatively little is known about the maintenance effects of different vehicles on unpaved low-volume roads. The World Bank's HDM-III model is perhaps one of the best and most commonly accepted models, but it does not specifically address road maintenance concerns for operation in a dry environment where roughness is dependent on the vehicle's characteristics (*2*). Paige-Green and Visser (*3*) use an algorithm to predict roughness, but vehicle type is not specifically handled.

In 1993, a test was conducted to determine the maintenance effects of vehicles in dry-weather conditions. The test was designed to examine failures that occur not from shear failure of the road surface but from the mechanistic failure that leads to road roughness in the form of roadway corrugations (washboarding), potholes, and surface material loss. This study was undertaken because the proponents felt that currently accepted ratios for maintenance of aggregate and native roadways do not always address these failure modes for dry-weather operation and place too much emphasis on the heavy vehicle as the major cause of road deterioration regardless of seasonal operating variables.

Objectives

The U.S. Department of Agriculture (USDA) Forest Service Commensurate Share Study was conducted at the Nevada Automotive Test Center (NATC) in Carson City, Nevada. It was designed to quantify and compare the effects on road deterioration from the operation of heavy and light vehicles in dry-weather conditions (*4*). The objective was to determine road-user maintenance

cost share ratios between logging truck traffic with high-pressure tires, logging truck traffic with low-pressure tires [Central Tire Inflation System (CTIS) operation], and light vehicle traffic. These ratios play an important part in determining the relative shares of responsibility for road maintenance where both the government and the private sector have traffic over the same road. Both aggregate and native road surfaces were evaluated in this study.

The tests were designed to achieve the following subsidiary objectives:

- Provide evaluation of vehicle weight and operating characteristics on road-user maintenance;
- Provide evaluation of the causes of maintenance; and
- Provide guidance for the planning and execution of subsequent field tests for local verification.

The test was designed to allow calculation of commensurate share ratios. These ratios are used by the USDA Forest Service to determine relative responsibilities for road maintenance, and they are based on the amounts of traffic attributable to each party. It is important to note that in this test design, all variables that could be controlled were identical for the three test track lanes. All lanes were constructed the same, maintained the same, and measured the same, and all traffic was applied in a similar manner (closely controlled speeds, loads, loaded and unloaded lap percentages, etc.). The number of laps to failure may be different based on local conditions and maintenance practices; however, the ratios should be approximately the same for dry-weather conditions.

Test Sections

Four test sections were constructed that were representative of typical Forest Service road design and aggregate material selection. The course shown in Figure 1 was constructed with 76 mm (3 in.) of 38-mm (1.5-in.) minus base material and 15.2 cm (6 in.) of 25-mm (1-in.) minus surfacing material. The native test section consisted of 15.2 cm (6 in.) of compacted native soil. In reference to Figure 1, the loaded vehicles traveled clockwise, and the unloaded vehicles traveled counterclockwise, resulting in a combination of adverse and favorable grades. The track geometry consisted of the following:

- 8 percent grade favorable: an 8 percent aggregate grade favorable to loaded logging truck traffic tangent (straight), 91.5 m (300 ft) long, 3.7 m (12 ft) wide;
- 3 percent grade (adverse): a 3 percent aggregate grade adverse to loaded logging truck traffic tangent (straight), 91.5 m (300 ft) long, 3.7 m (12 ft) wide;
- Curve: 27.5-m (90-ft) radius, 180-degree aggregate curve on a 2 to 3 percent grade with an apex in the middle of the curve equal radii, 86.3 m (283 ft) long, 4.3 to 4.9 m (14 to 16 ft) wide; and
- Native (3 percent adverse): a 3 percent grade with native surfacing material, adverse to loaded logging truck traffic tangent (straight), 91.5 m (300 ft) long, 3.7 m (12 ft) wide.

The aggregate test sections consisted of 76 mm (3 in.) of 38-mm (1.5-in.) minus base material, design California bearing ratio (CBR) values of 20 to 25, and an actual average CBR value of 21.4; and 152 mm (6 in.) of 25-mm (1-in.) minus surfacing material, design CBR value of 60, and actual average CBR value of 40.5. The native test section contained 15.2 cm (6 in.) of compacted material.

Base Material

Although no requirements were specified for the subbase material, it was sampled with the following results. The gradation showed that the subbase material met a C grading according to Forest Service EM-7720-100LL, dated April 1985. The grading analysis (AASHTO T11, T27) was as follows: Atterberg Limits (AASHTO T89), plasticity index, 13; liquid limit, 36. Los Angeles abrasion (AASHTO T96), 500 rev, % loss, 14.7; durability index (AASHTO T210), course, 55; fine, 26.

Maintenance Blading

All maintenance for the test sections was performed with a John Deere 570 grader; the procedure was always the same between the test sections. After the test section failed due to one of the four failure criteria, it was bladed using a "tight blading" technique in which the material was cut with the blade angled (the cutting edge and the blade itself) and then carried and rolled within the blade width, remixing the fines and segregated rock. Before the blading, the moisture content was increased by running a water truck over the failed test section. The actual maintenance blading operation consisted of four to six alternating passes with a water truck and grader, followed by limited wheel compaction with the water truck. The surfacing material was worked back and forth across the lane width by running the grader in opposite directions through the test section.

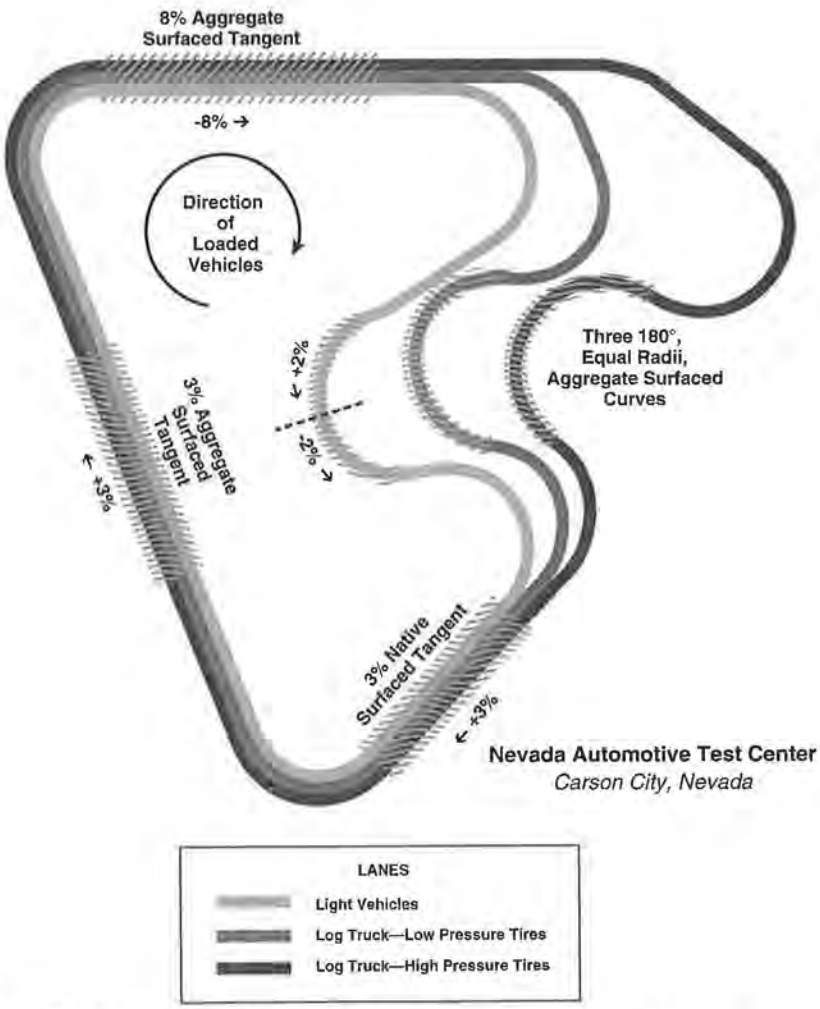

FIGURE 1 Diagram of NATC Test Track for dry-weather maintenance comparisons.

Traffic Lanes

As shown in Figure 1, each test section was three lanes wide, each lane dedicated to a specific vehicle class, and no mixed-vehicle running was conducted. The following were the vehicle classes to which each lane was dedicated:

- Inside lane: light vehicle traffic,
- Middle lane: logging truck traffic with low tire inflation pressures,
- Outside lane: logging truck traffic with high tire inflation pressures.

Vehicle Selection

Four light vehicles (Figure 2) were selected to represent typical traffic using Forest Service roads. Before the start of the test, the vehicles were inspected, serviced, and aligned to factory specifications. The shock absorbers were verified in good condition. New tires were installed, and tire pressures were set to the manufacturer's recommendations for highways. Scheduled services, tire and shock inspections, and maintenance of the vehicles were performed throughout the test.

The target percentage of the total running for the light-vehicle lane was as follows:

Type of Vehicle	*Loaded or Unloaded*	*Percentage of Total Running*	*Direction on 8 Percent Grade*
680 kg (3/4 ton) pickup truck	Loaded	40	Down
680 kg (3/4 ton) pickup truck	Unloaded	40	Up
Light pickup	Unloaded	10	Either
Utility vehicle	Unloaded	10	Either

FIGURE 2 Light vehicles used for comparison testing.

The test design required that the loaded and unloaded 680-kg (3/4-ton) pickups travel in opposite directions around the course. Also, the 680-kg (3/4-ton) pickup traffic represented 80 percent of the total laps in the light-vehicle lane. Given that the unloaded pickups produced rapid road deterioration on the 8 percent grade, these vehicles were run either one for one (i.e., passing in the transition areas) or on an hour rotation between the two trucks (approximately 37 passes per hour).

Logging Trucks

Two nearly identical Class 8 western U.S.–style logging trucks were selected to meet the contract requirements for two heavy logging trucks (Figure 3). These vehicles had five axles—one steering axle, two drive axles, and two trailer axles—in the loaded configuration, and one steering and two drive axles in the unloaded configuration (trailer carried on top of vehicle for return trip). Before the start of the test, the vehicles were inspected, serviced, and aligned to factory specifications. Previous road testing confirmed the performance equivalency of both trucks. The tandem torsion bar suspension of the two trucks was adjusted to provide equivalent ride height and, hence, equivalent nominal spring rates.

FIGURE 3 Heavy vehicle operating on test course.

Definition of Failure Modes

For this test, four failure modes were defined, and equal levels of these failure modes were reached before road maintenance was performed. Road maintenance consisted of blading using four to six passes with a water truck and grader, followed by limited wheel compaction with the water truck. Table 1 shows the four failure modes defined for this test and the resulting modes of failure for the four test sections.

NATC's dynamic force measurement vehicle (Figure 4) was used to perform longitudinal profiles of the road roughness (*5*). An initial "trigger" level was set by having maintenance personnel view and drive the test track. A spectral analysis of the washboard energy was then used to determine when subsequent washboarding had reached the "trigger" level for road maintenance, thus ensuring that all test sections were maintained at an equal level of washboard amplitude.

Summary of Test Results

Blading Ratios

The primary objective was to determine blading maintenance ratios between light-vehicle traffic and logging-truck traffic with both high- and low-pressure tires. The units in Tables 2 and 3 are the number of vehicle laps for an equivalent amount of road damage given the four failure modes. The lap totals are the averages from the individual failure data shown in Table 2. Given the 50-50 split between loaded and unloaded logging-truck traffic, a 1,000-pass reference in Table 2 is the same as 500 round-trips to the sawmill. In Table 2, a ratio greater than 1 means that the logging truck does more damage, whereas a ratio less than 1 means that the light vehicle does more damage. For example, a value of 5.0 means that five passes of a light vehicle are equal in road damage to one pass of a logging truck.

Before the start of this test, estimated blading maintenance ratios between light and heavy vehicles ranged from 3:1 to 96:1 for dry-weather operation depending on the method of calculation and study cited. The data from this test indicate that the blading maintenance ratio ranges between 10:1 to 0.5:1 and varies significantly by grade and alignment. Figure 5 shows the maintenance trends determined from this test. It is important to note that the plane drawn to show the relationship between the blading maintenance ratio and percentage

TABLE 1 Modes of Failure for NATC Test Sections

Failure Mode #1 —	Washboard
Failure Mode #2 —	Four-inch rut depth with limited washboard (from the original ground-line)
Failure Mode #3 —	Material push to the outside of the curve, which tended to super-elevate the curve
Failure Mode #4 —	Combination of potholes/washboard and limited rut depth (worn rut)

Test Section	Light Vehicles	High Pressure Logging Truck	Low Pressure Logging Truck
8% Grade	Washboard	Washboard	Washboard
Curve (ruts)	Ruts	Ruts	Ruts
Curve (out track)	Washboard	Material Push	Material Push
3% Grade	Pothole/Washboard	Pothole/Washboard	Washboard
Natural	Ruts	Ruts	Ruts

grade was drawn from the limited number of data values determined from the test parameters (aggregate gradation, surface thickness, etc.).

Moisture content was approximately 5 percent for the duration of the test, and the subbase was not considered to be a test variable. Whereas a loaded vehicle potentially does more damage to an aggregate road in wet conditions (i.e., ruts, depressions, subgrade damage) (*6*) the unloaded vehicle—whether a light vehicle or logging truck—does more damage to a road with grade in dry-weather conditions. Therefore, in Figure 5, the empty vehicle was referenced because of the greater potential for washboard damage. In dry weather, the road manager should be aware that the mix of unloaded traffic will have the most damaging effect.

In Table 2, the loaded logging trucks were responsible for the majority of the rut depth and material push in the 27.5-m (90-ft) radius curves, and the higher ratio (9.5:1) reflects this result.

The trend showed that the empty light vehicles ascending the 8 percent grade produced more road deterioration than the empty logging truck according to the results in Table 2. Likewise, the empty light vehicle descending the 3 percent grade resulted in less damage than the logging trucks. The level of washboard damage is a direct function of the wheel torque required to climb the grade and the resulting high wheel slip and tractive hop. In addition, loose (unbound) and unconsolidated material reduces tractive efficiency and increases the energy investment in shear displacement at the tire-ground interface. Washboarding is initiated by this shear displacement. Excessive shear displacement results in cyclical oscillation of the tire and suspension, which further develops the washboard pattern. If traction demand remains constant (i.e., climbing the 8 percent grade), the cyclical change in vertical load (loading and unloading) produces the tractive hop and high wheel slip. Because slip is a function of vertical load, the lighter the axle load under torque, the greater the potential for the mechanisms of washboard formation to start and amplify (*7*).

In contrast, the unloaded vehicles descending the 3 percent grade required very little torque; therefore, the phenomenon of high wheel slip and tractive hop was

FIGURE 4 Dynamic force measurement vehicle used to determine when maintenance should occur.

TABLE 2 Summary of Blading Maintenance Ratios

INITIAL FAILURE

Test Section	Light Vehicle / High pressure logging truck	Light Vehicle / Low pressure logging truck
8% Grade (favorable)	1262 / 1666 = 0.8	1262 / 3588 = 0.4
3% Grade (adverse)	23978 / 4170 = 5.8	23978 / 8420 = 2.8
Curve (in wheel tracks)	8827 / 921 = 9.6	8827 / 930 = 9.5
Curve (out tracking)	13368 / 3117 = 4.3	13368 / 3663 = 3.6
Native (3% adverse)	(23978) / (4958) = 4.8	(23978) / (8643) = 2.8

SUBSEQUENT FAILURES

Test Section	Light Vehicle / High pressure logging truck	Light Vehicle / Low pressure logging truck
8% Grade (favorable)	561 / 1218 = 0.5	561 / 2746 = 0.2

NOTE: *Lap totals in parentheses represent the passes completed to date but the roughness did not reach the failure criteria.*

never initiated to a level to generate "maintenance level" washboarding. Without cyclical load changes, continuous displacement of road material developed worn ruts rather than washboarding. Worn ruts and limited washboarding were the failure modes on the 3 percent grades (native and aggregate).

For the grade lengths in this test, steady-state torque was required to climb the grade and vehicle momentum was minimized. It should be noted that for grades that are extremely short in length, vehicle momentum is often used to "shotgun" over the shorter grades. Since wheel torque is not applied in a steady-state format given short grade lengths, the results for shorter slopes may differ. When using these ratios and establishing local validation tests, it is recommended that the road network be examined based on 300-ft (91.5-m) sections as the minimum length.

As shown in Tables 2 and 3, the damage ratio relationship decreases as logging truck tire pressures decrease. This is due to the reduced road damage with the use of reduced tire inflation pressures on logging trucks. Table 3 shows the damage ratios between the logging truck with high-pressure tires and the logging truck with low-pressure tires. Table 3 shows that on the straight test sections, the low-pressure logging truck could travel twice the number of passes between maintenance bladings. On the 27.5-m (90-ft), 180-degree curve, the damage was approximately equal.

The trend indicates that the initial "washboard-generated" failure takes longer than subsequent failures. This is potentially because a pattern or reflection is established in the subbase during the initial running that is not removed during subsequent maintenance blading. The pattern accelerates the rate at which the washboard pattern returns. Limited measurements and observations on the high-amplitude washboard cycles showed that the washboarding developed in exactly the same location (longitudinally) with subsequent running after maintenance.

For this test, the maintenance blading restructured the top 7.6 to 10.2 cm (3 to 4 in.) of material given a 15.2-cm (6-in.) aggregate surface. The base material was not disturbed during maintenance blading, and the remaining pattern or reflection of the washboarding helped generate such damage much more quickly with continued running.

TABLE 3 Summary of Blading Maintenance Ratios Between High- and Low-Pressure Logging Trucks

Test Section	High pressure logging truck / Low pressure logging truck
8% Grade (favorable)	1666 / 3588 = 0.5
3% Grade (adverse)	4170 / 8420 = 0.5
Curve (in wheel tracks)	921 / 930 = 1.0
Curve (out tracking)	3117 / 3663 = 0.9
Native (3% adverse)	(4958) / (8643) = 0.6

SUBSEQUENT FAILURES

Test Section	High pressure logging truck / Low pressure logging truck
8% Grade (favorable)	1218 / 2371 = 0.5

NOTE: Lap totals in parentheses represent the passes completed to date but the roughness did not reach the failure criteria.

For dry-weather road conditions, the unloaded vehicle did a majority of the washboard-generated damage, especially on the 8 percent grade. This was true for all lanes. Observations on the 8 percent grade showed that the unloaded light vehicles could cause "maintenance-level" washboarding in as few as 74 passes (observed on the sixth and later unofficial failures). The high-pressure logging truck could cause maintenance-level washboarding in as few as 152 unloaded passes (observed on the fifth unofficial failure). This trend indicates that as the road ages from operation in dry-weather conditions, the maintenance cycles will become more frequent. It should be noted that no new aggregate was placed on the test sections during testing (even after the required number of failures); therefore, this trend was noted given the increasingly frequent blading cycles required on the 8 percent grade.

Although no attempt has been made to quantify the ratios given for exclusively unloaded (empty) traffic, the laps to failure would have certainly been significantly fewer for all vehicle types. The loaded vehicles had a tendency to smooth or iron out the washboarding. There is a point, however (especially on the 8 percent grade), where the washboard amplitude reaches a level that the loaded vehicle can no longer smooth out, and washboard failure occurs within the next series of vehicle passes regardless of vehicle load.

On the 8 percent grade, the unloaded vehicles ascended the grade. On the two 3 percent grades, the unloaded vehicles descended the grade. Given that unloaded vehicle traffic ascending a grade caused the majority of the washboarding, the 8 percent grade was at a disadvantage and the 3 percent grades had the advantage from the standpoint of washboard generation. However, for grade operation, the data indicate that there would be a crossover grade where the light vehicle did less damage than the heavy vehicle for an adverse grade, as shown in Figure 5.

For future testing, of limited test time is available, it is recommended that only empty vehicles be used since they tend to cause a majority of the washboarding in dry-weather conditions. Additionally, it is recommended that the unloaded vehicles always ascend the grade.

In a previous Forest Service test conducted by NATC (*8*), the driving scenario required that the logging trucks accelerate on the gravel after coming off the asphalt.

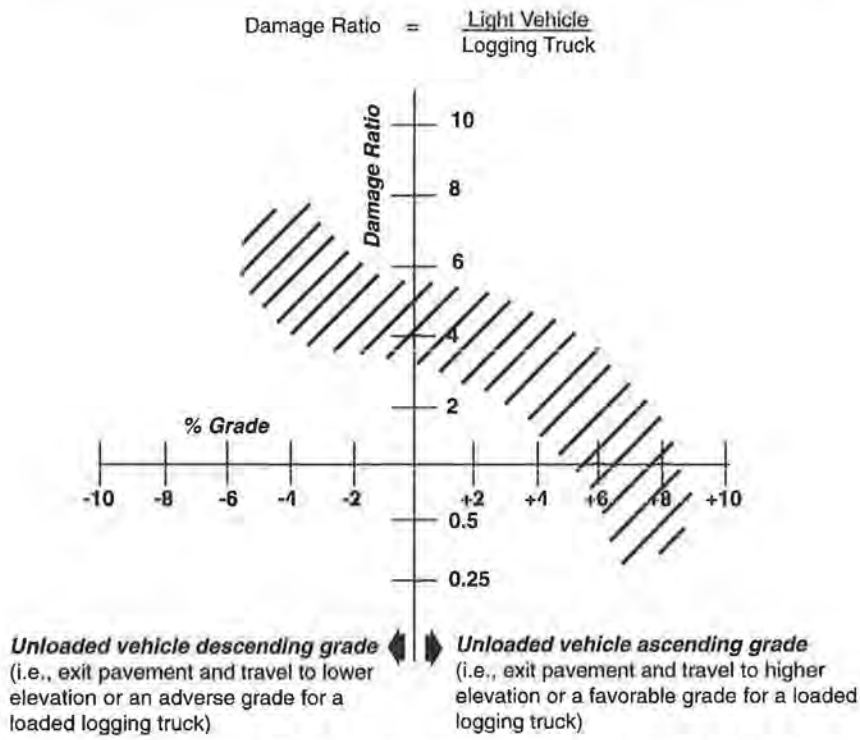

FIGURE 5 Graphical display of maintenance trends for dry-weather vehicle comparisons.

This acceleration generated washboarding quickly because it involved the same energy as climbing a grade. For road geometry that has frequent stops or areas of significant acceleration and deceleration, it is recommended that the ratios measured for the 8 percent grade be used.

It is also important to note that for this test, the vehicle held a constant speed through the curves, and the line of sight around the curves was unrestricted. Sight limitations on curves often dictate that a driver slow down entering the curve and then accelerate exiting it. This driving technique on a blind curve requires wheel torque changes that may reduce the lap totals shown in Table 1.

Finally, it is important to note that the decision to perform maintenance on a road network under actual road conditions may be driven by the highest maintenance area. For example, if the entire road network had grades of less than 3 percent, the ratio would be on the order of 5.8:1 and could involve a high volume of vehicle traffic. Likewise, if the road network had a high percentage of 8 percent grades, the ratio would be on the order of 0.8:1 and a high level of road maintenance would be required to control the roughness on the grades. These relationships need to be tailored based on the local road networks.

Material Loss Ratios

A second objective was to determine volume loss ratios between light-vehicle traffic and logging-truck traffic. Volume loss was a combination of many variables, such as dust, material separation (loss of fines), stone throw, material push to the outside of the curve, unrecoverable material lost due to blading, and so forth. Tables 4 and 5 show the volume loss ratios in cubic feet of material displaced as a result of the laps in Table 2. A negative value means that an overall material loss was measured. A positive value means that an overall material gain was measured. A material gain occurred when compacted material was displaced due to vehicle traffic and the uncompacted material consumed more volume in its berm form. This occurred predominantly in the curved test sections. For the straight test sections, the material loss or gain was that measured over the center 100 ft of the test section. For the curved sections, the material loss or gain was that measured over the entire 180-degree curve or 283 ft. For this analysis, transverse profiles measured from the 24 temporary benchmarks (TBMs) were averaged into a single plot to represent the entire test section.

Note that in this volume loss ratio analysis, the results are inverted from the maintenance blading ratios.

TABLE 4 Summary of Volume Loss Ratios

Test Section	Light Vehicle / High pressure logging truck	Light Vehicle / Low pressure logging truck
	Ratio Units are Volume Loss (M^3) per Pass X 1000	
8% Grade (favorable)	0.493 / 0.719 = 0.7	0.493 / 0.716 = 0.7
3% Grade (adverse)	0.079 / 0.261 = 0.3	0.079 / 0.346 = 0.2
Curve (in wheel tracks and outtracking)	0.201 / 1.731 = 0.1	0.201 / 2.450 = 0.08
Native (3% adverse)*	0.045 / 0.235 = 0.2	0.045 / 0.119 = 0.4

* *Measured at 4958, 5523 and 15,001 passes for the high pressure, low pressure and light vehicle lanes, respectively.*

For the volume loss ratios, a value less than 1 means that the logging-truck traffic has a higher amount of volume loss per pass. For the straight test sections, the trend is similar to the maintenance blading ratios shown in Table 2 and ranged from 0.2 to 0.7, depending on the grade and alignment (indicating that a logging truck produces 1.5 to 5 times more volume loss per pass than a light vehicle). Similar to the maintenance blading ratios, the pickup and logging-truck ratios are closer to unity when the unloaded vehicles ascend the 8 percent grade.

In Table 4, the loaded logging trucks were responsible for the majority of the rut depth and material push road damage in the 27.5-m (90-ft) radius curves, which resulted in higher volume lost per pass. As a result, the ratios are higher for the curves than those shown in Table 2.

The material loss data from the curved test sections were inconclusive on an individual failure basis. The material loss data for the test scenario where the trucks stayed in their wheel paths showed a net gain in material for the first failure and a net loss for the second failure. It is hypothesized that the material gain came from removal of compacted material in the curves (due to the ruts or material push) and creation of berms of uncompacted material by the trucks. The uncompacted material had more volume, thus the overall gain of material. This volume gain trend was also measured for the test scenario where the trucks out-tracked with each vehicle pass. The trend showed that the logging trucks pushed more material in the curves than the light vehicles. The trend also showed that the low-pressure logging truck pushed more material than the high-pressure logging truck when the vehicle out-tracked with each vehicle pass. These volume loss ratios were 0.16 and 0.05 for the ratio between the light vehicle and the high- and low-pressure logging trucks, respectively. This means that the high-pressure logging truck has 6.3 times more volume loss than the light vehicles in the curves, and the low-pressure logging truck had 20 times more volume loss. This increased material push with the low-pressure logging truck was attributed to the longer footprint of the low-pressure tires.

TABLE 5 Summary of Volume Loss Ratios Between High- and Low-Pressure Logging Trucks

Test Section	High pressure logging truck / Low pressure logging truck
8% Grade (favorable)	0.719 / 0.716 = 1.0
3% Grade (adverse)	0.261 / 0.346 = 0.8
Curve (in wheel tracks and outtracking)	1.731 / 2.450 = 0.7
Native (3% adverse)	(0.235) / (0.119) = 2.0

NOTE: *Lap totals in parentheses represent the passes completed to date but the roughness did not reach the failure criteria.*

After two material push (out-tracking) road failures, the low-pressure logging truck lane was significantly superelevated, and little material remained on the inside of the curve (the subgrade material was exposed). The curve for the low-pressure logging truck would have required material replacement if additional running was to be conducted. Given 126.7 m^3 (4,525 ft^3) of material placed in each curve test section at the time of construction, the total volume lost for the low-pressure logging truck equaled 25 percent of the total volume.

The curves were the only test sections that experienced unrecoverable material loss due to blading. The superelevated material was pushed beyond the TBMs established for the transverse profile measurements. It should be noted that the straight test sections had 5 ft of additional road surface beyond the outside of the lanes; therefore, material lost in the ditch due to blading was not a factor in this test.

Rut-Depth Ratios

A third objective was to determine rut-depth ratios between light vehicle traffic and high- and low-pressure logging truck traffic. Tables 6 and 7 show the rut-depth ratios in average maximum rut depth in inches as a result of the laps in Table 2. For this analysis, 24 transverse profiles were averaged into a single plot to represent the entire test section. The rut-depth value reported was the maximum difference between the repaired profile before vehicle traffic and the damaged profile after vehicle traffic. In the case of the material push, where no dominant ruts developed, the rut depth reported was the maximum difference between the repaired and damaged profiles.

Note that in this rut-depth ratio analysis, the results are also inverted from the maintenance blading ratios. A value less than one means that the logging truck traffic has a greater rut depth per pass. For the straight test sections, the trend is similar to the maintenance blading ratios in Figure 5 and ranged from 0.2 to 0.8, depending on grade and alignment (indicating a logging truck produces 1.3 to 5 times more rut depth per pass than a light vehicle). Similar to the maintenance blading ratios, the light-vehicle and logging-truck ratios are closer to unity when the unloaded vehicles ascend the 8 percent grade.

Conclusions

This test indicated that many variables come into play regarding determination of road damage ratios by vehicle type. For the dry-weather conditions encountered, the light vehicle ascending a grade causes increasing damage as the road steepens. Additionally, for heavy-vehicle operations, the use of reduced tire pressure almost always results in a decrease in road damage.

TABLE 6 Summary of Rut Depth Ratios

Test Section	Light Vehicle / High pressure logging truck	Light Vehicle / Low pressure logging truck
	Ratio units are maximum average rut depth (mm) per pass X 1000	
8% Grade (favorable)	38.1 / 45.7 = 0.8	38.10 / 20.32 = 1.9
3% Grade (adverse)	2.54 / 11.68 = 0.2	2.54 / 5.84 = 0.4
Curve (in wheel tracks)	7.62 / 99.06 = 0.08	7.62 / 93.98 = 0.08
Curve (out tracking)	4.06 / 33.02 = 0.12	4.06 / 30.48 = 0.13
Native (3% adverse)*	(2.29) / (8.64) = 0.3	(2.29) / (3.56) = 0.6

* *Measured at 4958, 5523 and 15,001 passes for the high pressure, low pressure and light vehicle lanes, respectively.*

NOTE: *Lap totals in parentheses represent the passes completed to date but the roughness did not reach the failure criteria.*

TABLE 7 Summary of Rut Depth Ratios Between High- and Low-Pressure Logging Trucks

Test Section	High pressure logging truck / Low pressure logging truck
8% Grade (favorable)	45.7 / 20.32 = 2.3
3% Grade (adverse)	11.68 / 5.84 = 2.0
Curve (in wheel tracks)	99.06 / 93.98 = 1.1
Curve (out tracking)	33.02 / 30.48 = 1.1
Native (3% adverse)	(8.64) / (3.56) = 2.4

NOTE: Lap totals in parentheses represent the passes completed to date but the roughness did not reach the failure criteria.

Four modes of road deterioration were defined for dry-weather operation: washboarding, worn ruts, material push, and potholes.

Before the start of this test, estimated blading maintenance ratios between light and heavy vehicles ranged from 3:1 to 96:1 for dry-weather operation, depending on the method of calculation. The data from this test indicate that the blading maintenance ratio ranges between 10:1 to 0.5:1 and varies by grade and alignment.

On the 8 percent grade test sections, the empty vehicles ascending the grade caused the majority of the washboard damage, and the light vehicles did more damage than the logging trucks (0.5:1 ratio).

On the curved test sections, the loaded logging trucks did the majority of the damage, resulting in light- to heavy-vehicle maintenance ratios between 4:1 to 10:1, depending on the width of the road.

On tangent test sections, the blading maintenance ratio showed that a low-pressure logging truck would require half the road maintenance of a high-pressure logging truck. On curved test sections, the blading maintenance ratio was approximately equal. The same was true of the ratios for average rut depth per pass.

In dry-weather conditions, the primary trigger for road maintenance was washboarding. The data showed that the initial maintenance cycle required a higher number of passes to achieve the same level of washboarding than did the subsequent failures. The subsequent washboard-generated maintenance cycles occurred much more frequently due to the washboard pattern remaining in the road material below the depth of blading. Under continuous dry-weather conditions, the laps between subsequent maintenance cycles decreased.

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