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The Operation of Logging Trucks on Steep, Low-Volume Roads

PAUL T. ANDERSON, MARVIN R. PYLES, AND JOHN SESSIONS

The selection of a maximum grade for a road standard is a complex decision that involves design, construction, maintenance, vehicle, amount of use, and cost considerations. In the western United States, steep terrain, high construction costs, and the need to maintain slope stability make ridgetop instead of sidehill road locations attractive. Therefore, the gradability of steep (greater than 16 percent), low-volume roads primarily used by logging trucks and assisting vehicles is of major concern. Gradability is strongly influenced by the coefficient of traction, the most important variable, and by apparent truck grade and turning resistance around curves. The effect of grade on truck speed is also economically important. Truck safety depends on the road surfacing material and truck design, especially the truck braking system. As grades steepen, the amount of energy that the engine and service brakes must dissipate increases, and the rise in brake temperature can become critical. The road surfacing material has a major effect on truck performance. Gradation, particle shape, and in-place density of aggregate surfacing materials strongly influence the gradability of steep roads. Crushed-rock aggregate is preferred because it develops the greatest coefficient of traction under wet-season conditions, although some native soils develop higher coefficients of traction under dry-season conditions. Aggregate strength apparently increases as the fine-grained particle content increases under optimal moisture conditions. Careful planning can identify the conditions under which steep roads are most economical. Management alternatives include the use of assisting vehicles with logging trucks, surface stabilization to avoid erosion and added maintenance costs, and control of the season of use.

The selection of the maximum grade for a road standard is a complex decision that involves design, construction, maintenance, vehicle, amount of use, and cost considerations. Concerns over vehicle capability and operating costs have historically resulted in limited maximum road grades. More recently, however, the rise in road construction costs resulting from the need to maintain slope stability in steep terrain has prompted a review of recommended maximum grades and encouraged construction of roads at grades steeper than past maximums.

In the western United States, a combination of steep topography and erosive or unstable soils influences the range of physical options available. For example, approximately one-fifth of the roads constructed between 1972 and 1982 in the Mapleton District, Siuslaw National Forest, in the Oregon Coast Range were steeper than a 15 percent grade (*1*). Adverse (uphill) grades as steep as 26 percent for loaded logging trucks without an assisting vehicle and 30 to 35 percent for assisted logging trucks have been reported (*2*).

Road designers in the Oregon Coast Range currently prefer ridgetop instead of sidehill road locations to reduce overall road length and to avoid the cost of hauling and disposing of large volumes of excavated material. As the subgrade width and percent side-slope increase, the volume of excavated material increases dramatically (Figure 1). The USDA Forest Service estimates that ridgetop roads in the Coast Range cost an average of $100,000/mi, whereas sidehill roads cost from $250,000 to $600,000/mi. The disadvantages of ridgetop roads

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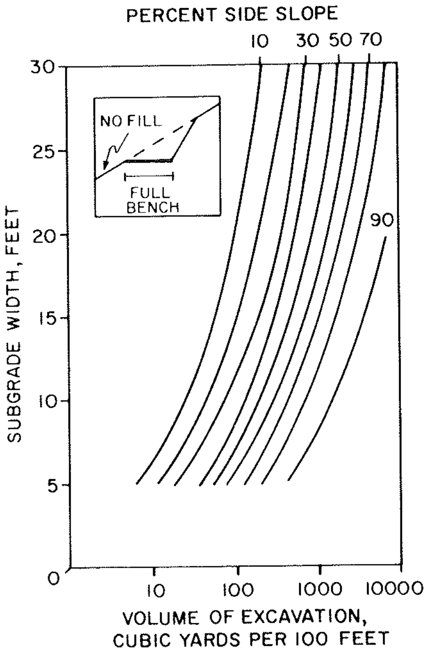


FIGURE 1 Excavation required for full-bench construction as a function of subgrade width and side slope.

are the need to use grades steeper than 20 percent (in some cases, steeper than 30 percent), higher direct operation costs (e.g., increased vehicle maintenance and the need for assisting vehicles), and increased potential for road surface erosion and therefore maintenance.

A summary is provided of the current knowledge of the design, construction, and maintenance of low-volume roads steeper than 16 percent that are primarily used by logging trucks in the western United States. In addition, the results are presented of an informal survey of engineers and road managers.

TRUCK OPERATION

Gradability

A major consideration in the operation of trucks on steep roads is vehicle gradability, which is defined here as the maximum grade that a vehicle or vehicle combination can climb or descend while maintaining adequate control.

A number of formulas for predicting logging truck gradability for straight road segments are available (*3-6*). These formulas, which are based on different sets of assumptions, describe gradability at different levels of detail. The most important variable is the coefficient of traction, which, unfortunately, has been quantified only generally. The wide variation in materials used for road surfacing and the degree of compaction apparently results in widely varying coefficients of traction. Caterpillar reports a 0.55 coefficient of traction for firm earth, Taborek reports 0.65 for dry earth (*7, 8*). This difference would change the maximum gradability of a loaded logging truck from approximately 23 to 28 percent.

In a study that related tire wear to slippage, Della-Moretta found that in cases in which tire slippage was less than 15 percent, the coefficients of traction for sand and gravel aggregate surfaces were less than 0.50 (*9*). If the coefficients of traction and truck geometry are known, gradability can then be calculated with the model presented by Sessions et al. (*6*). The developed slippage is related to the coefficient of traction in Table 1. Also shown is the gradability for a typical loaded logging truck in the western United States.

When traction is insufficient, an assisting vehicle is necessary to help a truck up the grade. For the purposes of this analysis, it is assumed that the vehicles can work together to produce the maximum thrust available from both vehicles. The basis of this assumption is that drive trains of the commonly used assisting vehicles (crawler tractors, rubber-tired skidders, and front-end loaders) can produce maximum thrust over the full range at a speed likely on a steep grade. For example, the gradability of a 76,000-lb loaded logging truck in combination with a 56,000-lb assisting vehicle would be approximately 38 percent if both the assisting vehicle and truck could develop a coefficient of traction of 0.55. The coefficient of traction of tracked vehicles is usually higher than that of wheeled vehicles on aggregate surfaces and unsurfaced roads (Figure 2).

TABLE 1 RELATIONSHIPS BETWEEN COEFFICIENT OF TRACTION, TIRE SLIPPAGE, AND GRADABILITY FOR A TYPICAL, LOADED LOGGING TRUCK IN THE WESTERN UNITED STATES

Coefficient of Traction	Slippage (%)	Gradability (%)
0.10	1.40	1.33
0.20	3.15	5.82
0.30	5.48	10.50
0.40	8.20	16.55
0.45	10.96	17.81
0.55	20.00	22.94

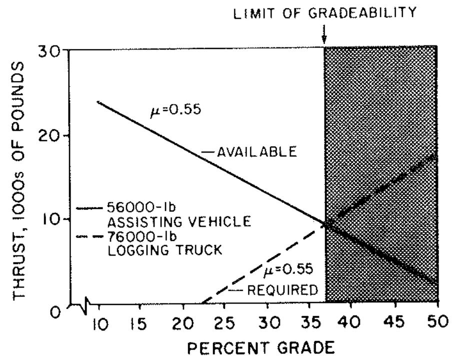


FIGURE 2 Thrust required by a loaded logging truck and that available from an assisting vehicle at various grades on a high-quality aggregate surface; μ = coefficient of traction. Shaded area indicates insufficient traction for the vehicle combination.

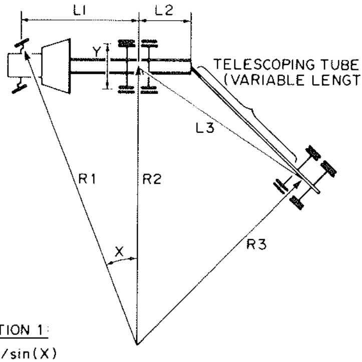
Gradability Around Horizontal Curves

The gradability of loaded logging trucks around horizontal curves is lower than that on straight road segments because of the additional resistance forces that arise from (a) off-tracking of the trailer, (b) the need to force the tandem axles around the curve, and (c) the inability of the tractor to apply thrust to the center of mass of the trailer along the direction of travel. Off-tracking is the difference in the path of the inside front wheel relative to that of the inside rear wheel as a vehicle or combination vehicle negotiates a curve (*10*). In addition, the available coefficient of friction to develop traction may have to provide lateral resistance to oppose centrifugal force on curves and thrust for forward movement.

Grade Resistance on Curves

As a loaded logging truck travels around a curve on a grade, the grade along the center line of the truck and trailer is different from the center line grade of the road, because the tractor and trailer tandems do not follow the path of the steering wheels around the curve (*3*). The trailer tandems off-track from the tractor tandems. The amount of off-tracking depends on vehicle geometry, curve radius, and curve length. Off-tracking causes the vehicle's center of mass to travel along a grade that differs from the center line grade of the road. The apparent grade that the tractor and trailer have to overcome must be included in a rigorous calculation of gradability. That grade will be steepest when the tractor and trailer have reached an equilibrium geometry (maximum off-tracking, e.g., in a tight switchback curve) for the curve. However, the trailer tandems often do not develop maximum off-tracking but move into and out of the curve on a transition pattern. Computing gradability for the maximum off-tracking case provides a conservative upper limit of gradability around a curve.

Maximum off-tracking of a stinger-steered, tractor-trailer combination on a curve with no side-slope to the road surface can be calculated by Equation 1 in Figure 3 (*3*). Once the relative positions of the axles on the curve are known, the relative elevations of the tires can be calculated and gradability can be determined. A formula recently published by the USDA Forest Service can be used to estimate tire locations for situations in which the vehicle does not develop maximum off-tracking (*11*).



EQUATION 1:

$$R1 = L1/\sin(X)$$

$$R2 = L1/\tan(X) - Y/2$$

$$R3 = \frac{R2 \times \cos\left[\sin^{-1}\left\{(L3/R2) \times \cos\left[\tan^{-1}(L2/R2)\right]\right\} - \tan^{-1}(L2/R2)\right]}{\cos\left[\tan^{-1}(L2/R2)\right]}$$

R1 = radius to outside front wheel in ft,
L1 = tractor wheel base in ft,
X = cramp angle of outside front wheel in degrees,
R2 = radius to center of tractor axles in ft,
Y = tractor width in ft,
R3 = radius to center of trailer axles in ft,
L3 = distance between the centers of the tractor and trailer tandems in nonturning motion, and
L2 = length of stinger in ft.

FIGURE 3 Off-tracking of a loaded, stinger-steered logging truck.

Turning Resistance of Tandem Axle Sets

As a tandem axle is pulled around a curve, drag forces are created. Smith suggested that the drag (D, in lb) that results from the forces aligning the tandems can be calculated as follows:

$$D = (u\ Wt\ L)/(2\ Rc) \qquad (2)$$

where

u = 0.2 (lb/lb), a coefficient of friction associated with tandem cornering,
Wt = normal force on the tandem in lbs,
L = tandem spacing in ft, and
Rc = radius of curvature for the tandems in ft (*12*).

Effect of Axle Differentials on Gradability

Logging trucks are equipped with torque-balancing differentials on the powered axles. The effective thrust that can be developed is twice the thrust that can be developed by the most lightly loaded side of the tandems. It is therefore important to consider the normal forces on the driving tires. Both the angle of pull of the trailer on the tractor and centrifugal force can affect the distribution of normal forces. Because the trailer does not follow directly behind the tractor when going around a curve, the resisting force exerted on the tractor by the trailer is not directly in line with the thrust provided by the tractor tandems. The angle through which the force acts is the angle between the tangent to the arc that the tractor tandems describe and the tangent to the arc that the center of mass of the trailer describes. The resisting forces can be broken down into tangential and perpendicular components relative to the center line of the tractor. The perpendicular component acts toward the center of the curve and creates a moment that unloads the outside set of wheels. Centrifugal force can counteract this effect, but it is small at the low speeds reached on steep roads.

Effective Coefficient of Traction

The thrust produced by a moving vehicle depends on the coefficient of traction that can be developed on the road surface. That thrust must equal the magnitude and direction of the vector sum of the resisting forces. Because a major resisting force is not parallel to the direction of travel, the resultant of the coefficient of traction that must be developed also is not parallel to the direction of travel. This means that the effective coefficient of traction that can be developed parallel to the direction of travel is reduced to prevent the truck from sliding off the curve.

For a given coefficient of traction, μ, the gradability of a loaded logging truck on a curve can be determined by including in the calculations the resisting forces that result from cornering and climbing straight road segments. The grade-climbing ability of loaded logging trucks drops sharply on curves with radii less than 100 ft (Figure 4). The straight-segment gradability for a coefficient of traction of 0.45 is 17.8 percent; for a 50-ft curve radius, the maximum gradability is 13.7 percent.

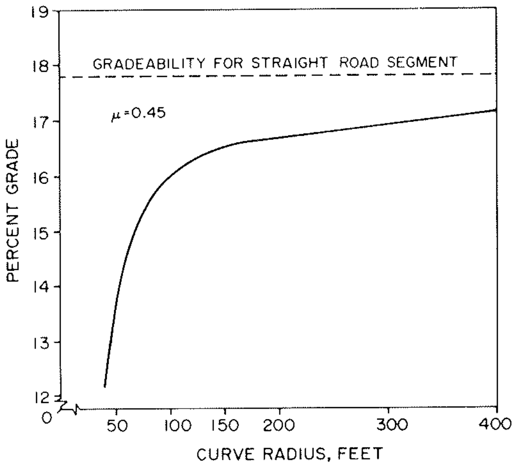


FIGURE 4 **Grade-climbing ability around a curve for a typical loaded logging truck in the western United States; μ = coefficient of traction.**

Horsepower-Limited Speeds on Aggregate Surfaces

Although truck performance on steep, adverse grades is ultimately limited by available traction, the effect of the grade on truck speed is economically important because a slower speed increases hauling costs. On steep, adverse grades for which truck speed (V, in mph) is limited by available horsepower, not road alignment, McNally suggests the following formula:

$$V = (NHP \times E \times 375)/(RR + GR + AR) \qquad (3)$$

where

NHP = net engine power in hp,
E = drive-train efficiency as a decimal,
RR = rolling resistance in lbs,
GR = grade resistance in lbs, and
AR = air resistance in lbs (*4*).

Air resistance can be ignored for speeds less than 30 mph. For steep grades that require the development of large thrusts, McNally's equation should be modified to include tire slippage as follows:

$$V = [NHP \times E \times 375 \times (1 - slip)]/(RR + GR + AR) \qquad (4)$$

For instance, on adverse grades steeper than 15 percent, a loaded truck with 450 hp will be limited to a speed less than 9 mph (Figure 5) and may be even further constrained by gearing combinations (Table 1).

Superelevation

Superelevation exists any time a road has a cross-slope downward to the inside of a curve. The road surface may have been superelevated to produce a cross-slope for drainage or to counteract the vehicle side thrust that results from centrifugal force as a vehicle negotiates a curve. The superelevation required to counteract side thrust is a function of vehicle speed and road geometry. If the design speed for a given superelevation cannot be maintained around a curve, then the tractor could lean into the curve, which would reduce the normal force on the outside tractor tandems and, as a result, the available thrust due to the action of the drive axle differential.

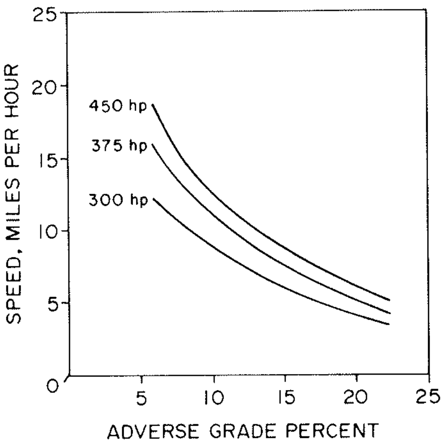


FIGURE 5 **Horsepower-limited speed on adverse grades in which the effect of slip is taken into account (*4*).**

Even the most powerful trucks commonly in service cannot travel fast enough on a steep, adverse grade to require significant superelevation. Log hauling contractors who were contacted in the informal survey reported that the use of superelevation on adverse grades steeper than 15 percent is not desirable.

Safety

Braking

The typical braking system on logging trucks in the western United States consists of an engine brake and air-operated service brakes. The Jacobs engine brake, a major improvement in logging truck brakes that was developed in the early 1960s, has become the industry standard. The braking force from the engine brake is applied to the road surface through the wheels of the tractor tandems. The maximum braking horsepower developed by an engine brake depends on the displacement, compression, and injection timing of the engine; the model of engine brake used; and engine speed. As road grades become steeper, the amount of energy the brakes must dissipate increases. For example, an 80,000-lb logging truck traveling at 10 mph while descending a 10 percent grade does not require the assistance of service brakes to maintain a constant velocity if the truck's engine brake and drive line friction can dissipate 285 hp. At a 15 percent grade, the service brakes must handle 9 percent of the braking load (dissipate 27 hp); at 20 percent grade they must handle 31 percent of the braking load (dissipate 129 hp).

Tests by Kenworth Motor Truck Company and Rockwell International Corporation on trucks with braking systems similar to those on logging trucks showed that the tractor-tandem service brakes often do relatively more work than the other service brakes (*13*). Because the engine brake also acts through the tractor tandems, the tractor tandems could lock up when trucks descend steep grades. One way to approach this problem is not to use the engine brake during steep descents; another way is to use only the trailer service brakes and the engine brake.

The percentage of the braking that each axle performs may not be proportionate to the static load it carries. Kenworth Motor Truck Company and Rockwell International Corporation performed tests of brake performance on tractor-trailer combinations (equivalent to loaded logging trucks) to determine the amount of braking performed by each axle (*13*). These tests showed that the tractor tandem does about 52 percent of the braking and carries 44 percent of the static load; the trailer tandem does about 41 percent of the braking and carries 44 percent of the static load; and the front axle does about 7 percent of the braking and carries about 12 percent of the static load. Because the tractor tandem brakes absorb a higher percentage of the energy used to stop the loaded vehicle, they would be expected to reach critical temperature first. Truck brakes normally operate at about 200°F and begin to fade substantially at about 650°F. Newcomb and Spurr developed the following equations to represent the temperature rise at the point of contact between the brake shoe and brake drum as the vehicle descends a grade and the brake is steadily applied to maintain a constant speed:

$$T = (2a^{0.5} \times t^{0.5} \times N)/(k \times 3.1416^{0.5}) \quad \text{when } L \geq 1.21 \qquad (6a)$$

$$T = (a \times N) \times (t + d/3a)/(k \times d) \quad \text{when } L < 1.21 \qquad (6b)$$

where

T = temperature rise in °C,
a = k/p in ft^2/sec,
k = thermal conductivity of brake drum in chu/ft/sec/°C,
p = density of brake drum in lb/ft^3,
t = time of brake application in sec,
N = energy input to brake drum in ft-lb/sec,
L = $[d/(a \times t)]^{0.5}$, and
d = thickness of brake drum in ft (*14*).

These equations do not account for cooling of the outer surface of the brake drum.

The amount of energy that must be dissipated can be readily calculated for a given speed and grade. The temperature rise in the wheel brakes can then be computed with Equation 6a or 6b. The results of these computations using the braking percentages from the Kenworth and Rockwell tests are shown in Figure 6 for three rates of energy dissipation of the service brakes (*13*). The distance that a loaded logging truck can travel at 10 mph before temperature rise becomes critical (650°F) in one set of tandems is shown in Figure 7. The distance was predicted by solving Newcomb and Spurr's equations for the time of braking application (*14*). The engine brake is assumed to dissipate 275 hp. When the engine brake and all the service brakes are being used, the critical brakes are in the tractor tandem axles. When the engine brake and only the trailer service brakes are being used, the critical brakes are the trailer brakes.

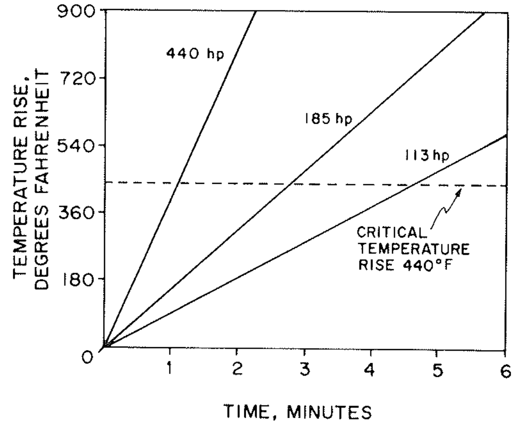


FIGURE 6 Temperature rise in the tractor tandem brakes as a function of energy dissipated by the total braking system.

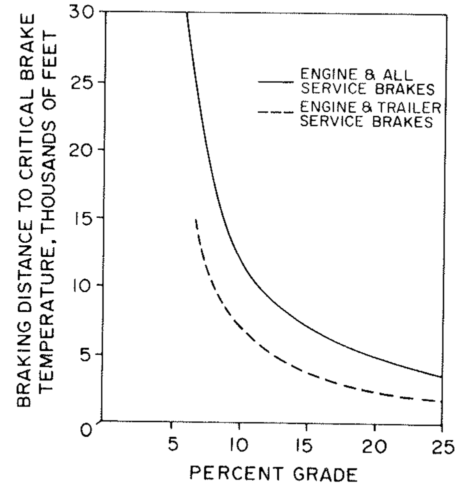


FIGURE 7 Braking distance traveled by a loaded logging truck at 10 mph before the rise in brake temperature becomes critical (650°F) in the tractor and trailer tandems. Engine brake is assumed to dissipate 275 hp.

Other Safety Concerns

The basic design of the stinger-steered logging truck (Figure 3) presents some safety problems on steep grades. Under normal operation the only positive connections between the tractor and trailer are the logs. How tightly the logs fit into the bunks dictates how much assisting force can be applied toward pulling the tractor or pushing the trailer or logs. Assisting vehicles have been known to push logs into the truck cab or pull the tractor out from under the load.

A road surfacing material that could lose surface traction rapidly also could be a safety hazard. For example, when asphalt concrete is clean and dry it may have a coefficient of traction of 0.8 or 0.9, but when it is contaminated with loose particles, it may have a coefficient of traction of only 0.3.

STEEP ROAD SURFACING

Surfacing Material

Crushed-rock aggregate is the major surfacing material used on all-weather, low-volume roads. The crushed rock should be thick enough to distribute surface wheel loads to the subgrade during critical wet-season months so that bearing capacity failure and associated rutting do not occur. On steep roads, subgrade support during the design life of the road is important; however, of equal and more immediate importance is the coefficient of traction of the road surface. Proper planning and management of steep roads require knowledge of the coefficients of traction of both aggregate- and soil-surfaced roads under various moisture conditions.

Gradation, particle shape, and in-place density of aggregate surfacing materials strongly influence gradability on steep roads. Crushed-rock aggregate is preferred for unpaved, all-weather roads because it develops the greatest coefficient of traction under wet-season road conditions. Under dry-season conditions, however, some native soils develop greater coefficients of traction. In fact, the highest coefficients of traction have been recorded on moist, fine-grained soils. The maximum, unassisted adverse climb observed was on a 26.4 percent grade in dry weather on a straight road segment composed of moist, nonplastic sandy silt. Published coefficients of traction for rubber tires on loose earth, firm earth, and clay loam range from 0.45 to 0.55, whereas the coefficient of traction for gravel is 0.36 (*7*).

Adverse gradability of loaded logging trucks could be limited to 16 percent when they are operating on pit-run aggregates that are loose and poorly graded (Unified Soil Classification System). If the gradation is improved, traction on pit-run aggregates could be improved; however, most engineers surveyed for this paper believe it is harder to produce a well-graded, 3- to 4-in minus aggregate than a well-graded, 1- to 1.5-in minus aggregate. A well-graded aggregate with a small maximum particle size appears to provide a higher coefficient of friction than large, open-graded aggregates. Trucks can often climb 18 to 20 percent grades without an assisting vehicle on well-graded, 1- to 3/4-in minus crushed rock.

A case history from the Sierra Nevada mountains in California illustrates some of the problems that can develop from using rock aggregate on steep road segments. Loaded logging trucks were unable to climb a 19.5 percent grade on a 185-ft-radius curve without an assisting vehicle after the road was surfaced with poorly graded 1-in minus crushed-rock aggregate and oiled. After clay from the cut bank was added to the oiled aggregate mixture on the steep section, which increased the fine-grained fraction of the mixture from 7 to 17 percent by weight (Figure 8), the trucks could climb the grade unassisted.

Casual field observations from the survey indicate that the preferred surfacing material for steep roads is crushed rock, but no quantitative guidelines were provided. Specific data relating coefficient of traction to aggregate gradation, particle shape, or in-place density are lacking. However, the available published data suggest the likely mechanism by which the traction limit of a rubber tire is exceeded on steep roads with aggregate surfaces. Although published coefficients of traction for rubber tires on a given surface vary, the coefficient of traction of a hard rock-like surface is consistently twice that of a rock aggregate surface (*7-9*). The characteristics of the individual particles within the aggregate surface probably explain much of this difference. If the coefficient of traction between rubber tires and the surface particles of an aggregate surface road approaches the published value between rubber and a rock surface, then traction failure on an aggregate surface must involve movement of the particles within that surface relative to one another. Particles probably both slide and roll within the surface; they also probably roll under the rubber tires. The coefficient of traction on a given aggregate surface is therefore limited by the stability of the individual particles that compose the surface layer. We have chosen to call this individual particle stability "matrix stability" to indicate all the particles of the surfacing material.

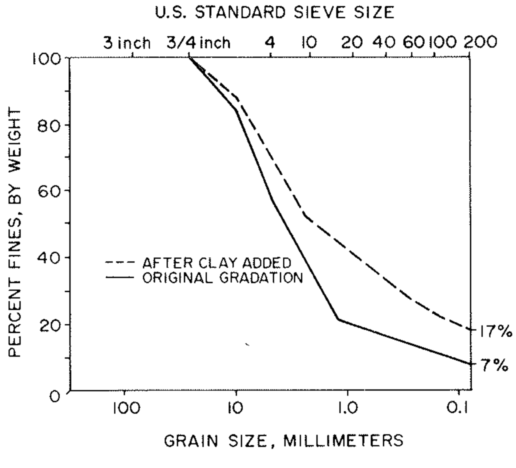


FIGURE 8 Effect on gradation of adding clay to an oiled, crushed-rock aggregate mixture on a steep road in the Sierra Nevada mountains.

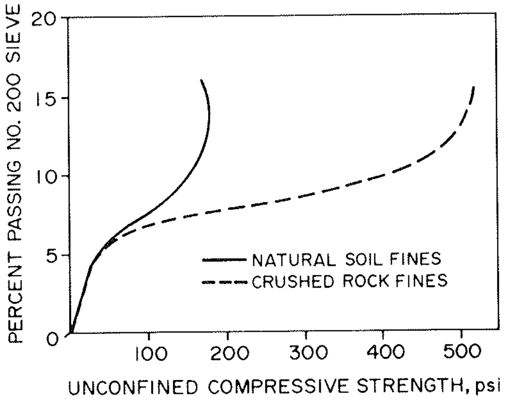


FIGURE 9 Unconfined compressive strength of aggregates as a function of fine-grained particle content (*16*).

Matrix stability of an aggregate surface is believed to be related to the gradation of the aggregate and the plasticity of the fine-grained fraction. Ames and Vischer have reported some attributes of well-graded aggregate that correlate with acceptable performance relative to traction and maintenance (*15*, *16*). Their measurements and observations of acceptable performance are interpreted to be an indication of matrix stability.

In a study of surface aggregate from roads with grades up to 16 percent, Vischer found that the oven-dried unconfined compressive strength of aggregates increased as a function of fine-grained particle content (Figure 9) (*16*). Tests were performed on samples compacted to maximum density by AASHTO T-99 and cured at 140°F for 48 hrs. Acceptable surface aggregate performance correlated with a minimum, oven-dried, unconfined compressive strength of 75 psi. When recommending gradations for road surfacing aggregate, Vischer limited the amount of allowable fines in an attempt to eliminate gradations that would lose strength under wet conditions (*16*). Although the unconfined compression test may not be the most appropriate test for evaluating road surfacing materials, Vischer's work indicates that it is a reasonable index of performance. Vischer's recommended surface aggregate gradations are shown in the following table (*16*).

U.S. Standard Sieve Designation	*Percent, by Weight, Passing Through Sieve*
1 in	100
1/2 in	68-80
No. 4	42-54
No. 10	26-38
No. 40	12-23
No. 200	7-12

Ames identified aggregate gradations that provided acceptable traction on grades from 14 to 20 percent (*15*). In order to assess aggregate strength, Ames recorded the length of sample that was self-supporting when extruded horizontally from a sample mold for aggregates compacted and cured at room temperature for 2 hrs. The tensile bending strength from Ames' results was computed, assuming the neutral axis of the sample was located at the center of the sample cross-section. Tensile strength increased as the percent, by weight, of the sample passing the No. 200 sieve increased (Figure 10).

Specifications relating to the plasticity index and amount of permissible fines do not apply to poorly graded aggregates as they do to well-graded aggregates (*15-17*). The void ratio is likely to be higher for poorly graded aggregates, which results in a lower strength, and, therefore, a lower matrix stability. Vischer recommended a narrow gradation band to ensure that only well-graded aggregates could meet specifications (*16*). If poorly graded aggregates are considered for use, their strength should be tested relative to available well-graded aggregates, because large differences in strength are likely to produce similar differences in the matrix stability, and, therefore, the coefficient of traction.

Both Vischer and Ames found that aggregate strength increased as fine-grained particle content increased (*15, 16*). It is currently inferred that the matrix stability and coefficient of traction are directly related to aggregate strength; however, further study is required to clarify this relationship.

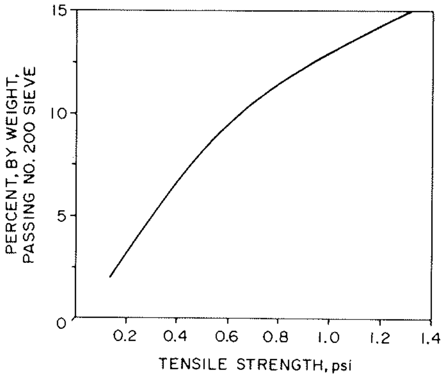


FIGURE 10 Tensile bending strength as a function of the fine-grained particle fraction (*15*).

Maintenance

Maintenance is often cited as one of the reasons steep roads are impractical, especially when maintenance problems are compounded by less than ideal weather and materials (*18*). As the road grade increases, both the road surface and ditch line require more maintenance.

In the Oregon Coast Range, because of unstable or erosive soils and high-intensity rainfall, most roads that are intended to be kept open must be surfaced whether or not they are intended for all-weather use. Maintaining these surfaces on steep roads is a problem. Graders must blade up the surface, reblend it, and spread it back out over the road. Some maintenance managers

TABLE 2 EFFECT OF ROAD GRADE ON DESIGN, CONSTRUCTION, MAINTENANCE, AND USE CONSIDERATIONS FOR STEEP, LOW-VOLUME ROADS

	As Road Grade Increases	
Consideration	Price per Unit	Quantity
Excavation	Stays roughly the same	Amount of excavated material decreases rapidly for ridgetop roads
End haul	Could increase or decrease	Would vary with excavation volume
Rocking costs	Increase slightly	Decrease if road length decreases sufficiently
Culverts	Stay the same	Increase
Maintenance		
Blading	Increases on roads steeper than 16 percent	Decreases; less length to maintain
Ditching	Increases	Decreases; fewer sidehill roads
Surface treatments to improve traction	Stay the same	Increase
Log haul		
Unassisted	Increases slightly	Stays the same
Assisted	Stays the same	Increases
Design and administration	Costs increase 20-40 percent	Stay the same
Clearing and grubbing	Decrease for ridgetop roads	Decrease for ridgetop roads

surveyed suggest that the minimum depth of rock aggregate that needs to be reblended is twice the diameter of the largest aggregate particle. Therefore, if the maximum particle size is large, more material must be bladed and reblended, which reduces the productivity of the grader and limits the grade on which it can effectively work. On steep, adverse grades, other maintenance managers simply blade to a lesser depth and deposit the oversized material along the road sides, which effectively changes the surface gradation. As road grades become steeper than 16 percent, some managers surveyed have reduced the maximum particle size specified in their aggregate mixes from 1.5 in to 1 in or even 0.75 in to facilitate grader maintenance. Although maintenance costs on these steep roads are higher, they apparently have not been high enough to outweigh the advantages associated with building steeper low-volume roads.

Roads constructed at grades steeper than 20 percent are generally intended for temporary use only. These roads are meant to provide access to a limited area during the dry season, serve their function, and be closed. Closure involves relatively maintenance-free out-sloping of the road section, removing stream-crossing culverts, and replacing cross-drain culverts with water bars or rolling grades. As a result, the general consensus among engineers surveyed is that such roads have not had extraordinary long-term maintenance problems.

COMPARISON OF STEEP, LOW-VOLUME ROAD OPTIONS

Road designers who are considering building steep, low-volume roads should take into account construction, hauling, and maintenance costs and intended use. All other things being equal, they will choose the alternative with the lowest cost. However, the effect of road grade on excavation, surfacing, drainage, hauling, and maintenance must be quantified for each situation. The sensitivity of these factors to road grade in the Oregon Coast Range, in which steep ridgetops are often preferred to sidehill locations, is shown in Table 2.

Steep grades have proved to be a viable alternative for low-volume roads in the mountainous western United States. Designers and managers have decided to use steep grades after considering the economics, environmental constraints, topography, and physical limits of equipment. However, they still need to better understand how rock gradation affects the surface aggregate strength and coefficient of traction; how to reliably estimate the erosion hazard from steep grades; and how to handle safety concerns about vehicle operation. Despite these gaps in the present knowledge, steep grades are being built, and will continue to be built. Only through careful consideration of each situation can reasonable and appropriate choices be made.

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