# Factors Affecting Maximum Gradeability of a Log Truck Around a Curve

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Steep road grades provide managers with a way to reduce the economic and environmental costs of transportation systems. Available formulas for calculating log truck gradeability do not consider the performance of log trucks on horizontal curves. The maximum grade that a log truck can climb on a circular curve is less than that on a tangent for a number of reasons. These factors are discussed and some preliminary results obtained from a mathematical model are presented. Predictions from the mathematical model are compared with field observations collected from a survey of steep road operations from forest road managers throughout the USDA Forest Service.

During the last 20 years there has been increasing concern within the forest community about road-related landslides, impacts of roads on visual quality, and increased road construction costs. Permanent gravel-surfaced roads with grades up to 20 percent and temporary unsurfaced roads up to 26 percent have been negotiated successfully by loaded and unloaded log trucks under their own power. One critical element in evaluating feasibility of such steep, adverse grades is estimating the maximum grade that a loaded log truck-trailer combination can climb at a constant speed without losing traction. This maximum grade is referred to as the traction-limited gradeability for the vehicle, or often simply as the gradeability. Modern logging trucks often have engines of 350 to 400 hp with sufficient torque in low gear so that their grade-climbing ability is not limited by torque requirements. Formulas for evaluating the maximum traction-limited gradeability for loaded and unloaded log trucks on tangent road sections with no superelevation have been derived (*1*). These formulas consider rolling resistance, vehicle geometry, weight distribution between axles, and the coefficient of traction between the tires and the running surface.

The maximum grade that a log truck can climb on a circular curve is lower than that on a tangent due to a number of factors. Many road managers recognize that gradeability around a curve is lower and use various rules of thumb to reduce the maximum design grade around the curve relative to the tangent-limited grade. Factors that reduce gradeability around horizontal curves are discussed and predictions of a mathematical model are compared with results from a survey of steep grade operations taken from road managers throughout the USDA Forest Service.

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## FACTORS AFFECTING GRADEABILITY AROUND CURVES

Unlike log trucks on tangents, log trucks on horizontal curves are affected by six factors that do not exist on tangents:

1. Actual road grades (effective grades) for the tractor and trailer that differ from the centerline grade,
2. Tandem drag,
3. Resisting forces on the log load and trailer that do not act parallel to the truck-tractor,
4. Centrifugal force,
5. Superelevation, and
6. Torque requirements of the drive axle differential.

The vehicle referred to in this discussion is the typical truck-tractor and pole-steered trailer used throughout western North America (Figure 1). The trailer is steered by a telescoping pole that connects the trailer axles to the frame of the truck-tractor. The telescoping pole is not designed to be in tension and the trailer is pulled by the logs held by friction between the logs and the log bunks. The pole-steered trailer requires less road width than the conventional trailer steered by the fifth wheel (*2*).

### Effective Grades

As a loaded logging truck travels around a curve on a grade, the grade along the centerline of the truck and trailer is different from the grade along the centerline of the road because the truck and trailer tandem axle sets do not follow the path of the steering wheels around the curve. In effect, the trailer straddles the roadway. This straddling of the roadway creates a steeper grade (the effective grade) than the trailer would have experienced on a tangent (Figure 2), making the trailer drag due to gravity higher than would have otherwise occurred.

### Tandem Drag

As a tandem axle is pulled around a curve, drag forces are created because of the turning resistance of the tandem axles (*3*). This drag resistance is proportional to the normal load on the axles and inversely proportional to the curve radius. Tandem drag does not exist on a tangent and must be added both to the forces acting on the truck-tractor because of the drag of the tractor drive tandems and to the trailer if both units have tandem axles.

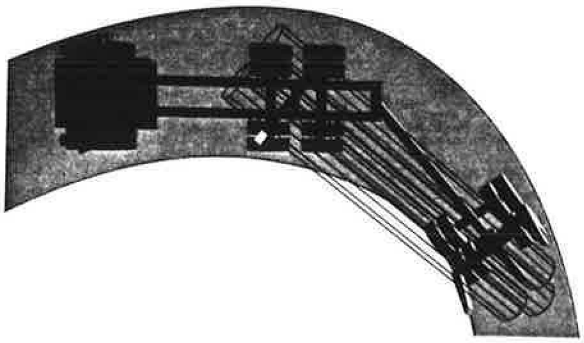

**FIGURE 1 Perspective view looking down on a loaded log truck-tractor with pole-steered trailer climbing around a steep curve.**

### Nonparallel Forces

Because of the turning action of the truck and trailer on a curve, the pull of the log load transmitted by the logs to the front bunks is not on a line parallel to the truck-tractor (Figure 3). This creates a moment about the drive axles that redistributes the wheel loading from what would have occurred on a tangent. The normal load on the outside wheels is reduced and the loading on the inside wheel is increased.

### Centrifugal Force

Centrifugal force arises from acceleration due to the changing direction around the curve. Centrifugal force acts through the center of mass and is proportional to the square of the velocity and inversely proportional to the curve radius. The effect of centrifugal force is to unload the inside wheels and load the outside wheels.

### Superelevation

Superelevation creates a redistribution of the wheel loadings by introducing a gradient perpendicular to the centerline gradient. Superelevation can either load or unload the inside (or outside) wheels depending upon the direction of the superelevation. If the road is sloped inward toward the curve center (positive superelevation), the normal force on the inside wheels is increased and that on the outside wheels is reduced. Higher-speed roads normally have positive superelevation to counteract the overturning or sliding effects of centrifugal force. Superelevation also affects the effective grades of the tractor and trailer straddling the curve.

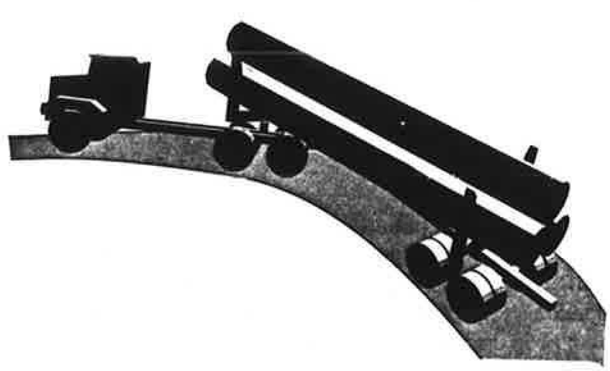

**FIGURE 2 Inside-of-curve perspective view of a loaded log truck climbing around a steep curve.**

**FIGURE 3 Outside-of-curve perspective view of a loaded log truck climbing around a steep curve.**

### Axle Differential

Logging trucks are equipped with differentials between the drive axle shafts to permit the inside wheels to turn at a slower speed than the outside wheels as the truck goes around a curve. While the differential gears are operating (unlocked), the torque transmitted to each axle by the drive shaft is the same. Effectively, this means that the maximum thrust for the axle (left and right wheel sets combined) is equal to two times the most lightly loaded side.

If the traction coefficients under each wheel set are the same and the tire radii are equal, the greatest combined thrust can only occur when the normal forces on the left and right wheel sets are equal. If wheel loading is unequal and torque requirements are high, the lightly loaded wheel cannot absorb the same torque as the more heavily loaded wheel and will begin to spin. Because of differential action, as the lightly loaded wheel increases its revolutions per minute, the revolutions per minute of the opposite wheel are reduced and eventually stop. Limited slip differential devices can maintain torque to the more heavily loaded wheel set, but gradeability is still less than that on tangents because of the lower ratio of normal force on the driving wheels to gross vehicle weight.

## MODELING GRADEABILITY AROUND CURVES

A model has been developed to calculate the maximum grade that a log truck could climb around a curve, considering the six factors discussed previously. Using an iterative algebraic procedure, the procedure begins with guessing a maximum centerline grade and comparing the available thrust at the driving wheels with the thrust required to balance the resisting forces. The algorithm is terminated when the grade is identified at which the maximum available thrust at the driving wheels equals the required thrust to negotiate the grade. The nine steps in the algorithm are as follows:

Step 1: Establish the location of the truck and trailer wheels on the curve. For trucks on long curves, the equation from Anderson et al. (*4*) can be used. For trucks on short curves where full offtracking of the trailer wheels is not developed, the procedures outlined by Erkert et al. (*2*) can be used.

Step 2: Calculate the effective grades for the truck-tractor and the loaded trailer given the wheel locations calculated in Step 1.

Step 3: Solve for the normal force on the trailer axle and the reactions at the front log bunk pin (similar to fifth-wheel location) created by the loaded trailer. These are calculated by summing forces parallel and perpendicular to the effective grade of the trailer calculated in Step 2 and a moment balance around the midpoint of the trailer axles.

Step 4: Resolve the reactions at the front bunk calculated from Step 3 perpendicular and parallel to the effective grade of the truck-tractor that was calculated in Step 2.

Step 5: Calculate the centrifugal force on the driving wheels for an assumed truck velocity.

Step 6: Calculate the normal force on the combined left and right driving wheels considering the forces acting from the trailer (Step 4), the center of gravity of the truck-tractor, and rolling resistance of the truck-tractor.

Step 7: Calculate the normal force on the inside and outside wheel sets considering the trailer reactions on the front bunk (Step 4), centrifugal force on the driving wheels (Step 5), and the normal force on the combined left and right driving axles (Step 6).

Step 8: Compare the thrust available at the driving wheels with the vector sum of the thrust required to oppose the forces parallel and perpendicular to the driving wheels. The traction-limited thrust available at the driving wheels is equal to two times the normal force on the most lightly loaded side multiplied by the coefficient of traction.

Step 9: If the thrust available at the driving wheels exceeds the thrust required to overcome the resisting forces, increase the centerline grade and return to Step 1. If the available thrust is less than the sum of the resisting forces, reduce the centerline grade and return to Step 1. A numerical method such as binary search or the secant method can be used to identify the maximum centerline grade within a few iterations.

## AN EXAMPLE

Using the gradeability algorithm, specifications for a typical loaded log truck with pole-steered trailer, a truck speed of 3.5 mph, and a coefficient of traction of 0.45, the gradeability was calculated for various curve radii and superelevation rates. A speed of 3.5 mph was chosen as being representative of the maximum speed in low gear. The net engine power requirement is on the order of 220 to 300 hp depending upon the final gradeability. The coefficient of traction of 0.45 was chosen as representative of the lower limit for firm native soil or medium-packed gravel (*1,5*). In order to simplify the presentation, the log truck was assumed to be in a deep curve, that is, a curve long enough for maximum offtracking to have been developed. This approach is a conservative one that provides the lowest estimate of gradeability.

Superelevation was varied from −6 to +6 percent (Figure 4). Log truck gradeability increases with curve radius. At positive superelevation, gradeability was reduced as compared with no superelevation because of the low centrifugal forces generated at the assumed truck speed of 3.5 mph. Higher truck speeds (up to a point) would have permitted higher gradeability, but it was believed that assuming higher speeds on steep grades was a less conservative approach.

With negative superelevation, log truck gradeability increased when compared with no superelevation. With a −6 percent superelevation, maximum gradeability increased until the curve radius became larger than 100 ft and then decreased. This decrease in gradeability is due to an excessive amount of negative superelevation. At larger curve radii, the trailer tracks

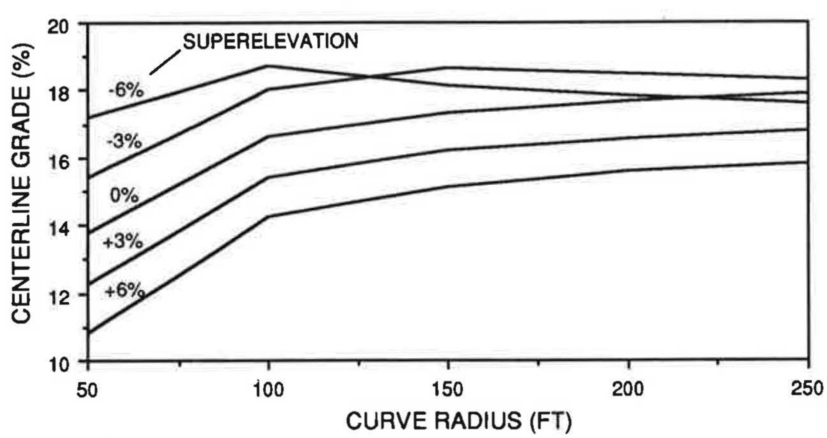


**FIGURE 4 Gradeability as a function of curve radius and superelevation for a coefficient of traction of 0.45.**

more closely with the truck-tractor, reducing the angle of pull of the trailer. The reduced angle of pull reduces the inward force that the combined effects of centrifugal force plus negative superelevation counteract.

## COMPARISON OF THEORETICAL WITH REPORTED PERFORMANCE

To identify the experience of road managers with operation of roads in steep terrain, a survey of USDA Forest Service road managers was conducted during 1988 on all national forests in the western United States. Road managers were asked to document specific road projects with steep roads, citing location, surface type, grade in direction of loaded haul, curve radius, and superelevation. Responses totaled 107 ranging from successfully negotiated favorable grades of −35 percent to successfully negotiated adverse grades of +26 percent. Of the 37 reports of adverse grade operations on curves with no superelevation, 30 were negotiated successfully and 7 were not. Successes ranged from a 26 percent grade on a 285-ft-radius curve on a native material surface to a 12 percent grade on a 50-ft-radius curve, also on native material. The highest of the reported successful steep road operations on roads with no superelevation are plotted in Figure 5. Several reports were available for trucks operating on steep grades with horizontal curves and negative superelevation. The reports for a 50-ft radius and a 250-ft radius were for a −3 percent superelevation and the 100-ft radius was for a −4 percent superelevation (Figure 6). All three reports were for operating on native surface.

## SUMMARY

Theoretical analysis and operational experience suggest that the gradeability of a log truck around a curve is less than that on a tangent section. A necessary condition for maximum gradeability of a log truck with trailer is to have equal normal force on the left and right wheel sets of the driving wheels. Road designers recognizing this principle can adjust road designs to achieve this force balance. Four design factors are within

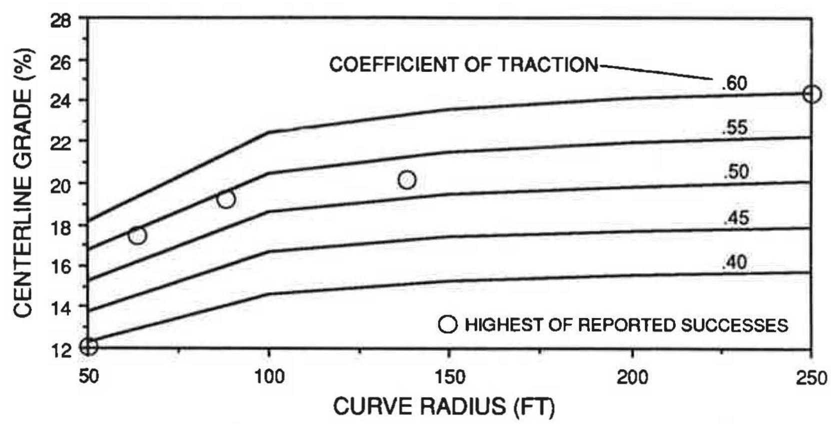


**FIGURE 5 Gradeability as a function of traction coefficient, curve radius, and zero superelevation. Points of highest reported successful operations are identified.**

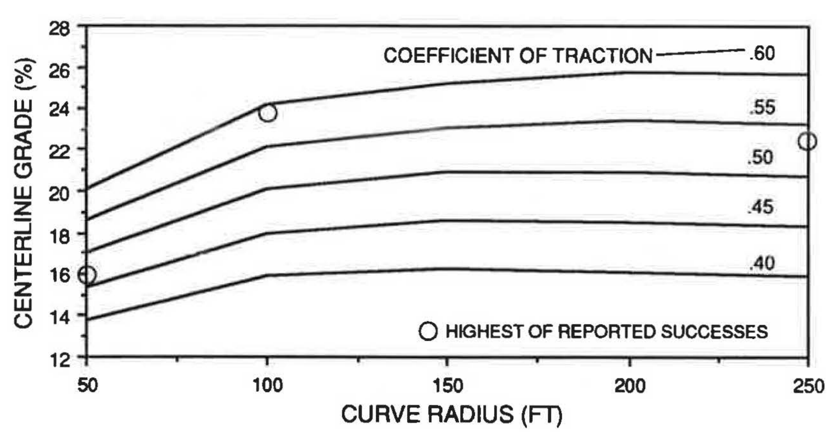


**FIGURE 6 Gradeability as a function of traction coefficient, curve radius, and −3 percent superelevation. Points of highest reported successful operations are identified.**

control of the road designer: centerline grade, road surface, curve radius, and superelevation. Understanding the interaction of these variables can provide more flexibility in road design and location.

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