Logging Truck Speeds on Curves and Favorable Grades of Single-Lane Roads

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Speeds of loaded logging trucks traveling on single-lane forest roads were studied at three locations in western Oregon to evaluate truck performance on curves and favorable (downhill) grades. Uphill speeds for the returning, empty trucks were also studied. The independent variables of grade, curve radius, width, ditch depth, superelevation, sight distance, time of day, and maximum engine-braking horsepower were regressed against speed. The results were compared with those predicted by the Byrne, Nelson, and Googins (BNG) method and the Vehicle Operating Cost Model (VOCM). Grades above 11 percent strongly influenced speeds; less steep grades only slightly affected speeds. The BNG study and the VOCM predicted downhill speeds reasonably well for straight sections of road with favorable grades between approximately 11 and 16 percent. The BNG method and the VOCM overpredicted speeds for grades steeper than 16 percent. Because of the poor alignment of the roads studied, no conclusions could be reached for favorable grades less than 11 percent. Speeds recorded for curves did not relate to the assumption in the BNG study that horizontal sight distance controls speeds or to the assumption in the VOCM that available friction controls speeds. These findings may influence future road designs. Sight distance may be less important because drivers now use citizens' band radios to learn about road conditions ahead. Technological improvements may also account for differences reported here. Overall, the BNG method underestimated round-trip travel speeds by 16.7 percent when its predicted speeds were compared with those observed over a 7.71-mile portion of a logging road.

The design and construction of a low-volume logging road influence the overall cost. A design that shortens hauling time reduces hauling cost. Therefore, it is important for designers to accurately predict how truck travel times relate to changes in road geometry so that the most cost-effective roads can be built. How truck speeds relate to road design is assumed to depend either on driver behavior or truck performance.

If a minimum-bid price is to be established for a timber sale, the appraisal of log-hauling costs can directly influence that sale. In some areas, log hauling can account for approximately one-third of the total harvest cost (*1*). Few published studies that relate log-hauling costs to truck travel times have been conducted recently. Therefore, many USDA Forest Service appraisers still consult some version of the 1960 study by Byrne, Nelson, and Googins (BNG) to estimate those costs (*2*).

However, truck technology has improved so much during the past 27 years that speeds and travel times that were estimated for older models of logging trucks may not be accurate today. For instance, the Jacobs engine brake has increased the sustained braking ability of logging trucks on favorable (downhill) grades. In addition, better engines, transmissions, steering mechanisms, and the citizens' band (CB) radio have contributed to safer, faster, and more efficient log transportation.

In addition to the BNG study, vehicle simulation models have been developed by universities, truck manufacturers, and others, but these models have not yet gained wide acceptance for use on low-volume roads. In 1975 the Forest Service participated in the development of one such model, known as the Vehicle Operating Cost Model (VOCM) (*4*). The VOCM uses physical relationships and a set of driver behavior rules to determine truck speeds.

The results are presented of a study conducted at Oregon State University during the summer of 1985 (*3*). Three major objectives of this study were:

- To compare the actual speeds of modern logging trucks on curves and favorable grades with the speeds predicted by the BNG method and the VOCM,
- To determine how well the BNG method predicts overall trip speeds by comparing estimated speeds with actual ones over a longer portion of road, and
- To examine if extrapolation of the BNG data is appropriate for grades steeper than those on which the original study was based.

The study was limited to favorable grades because most log transportation from the forest to the mill is usually on these grades. As commonly defined by road engineers, a favorable grade implies that loaded trucks travel downhill, whereas empty trucks travel uphill. This convention is used throughout this paper.

BACKGROUND ON FACTORS THAT AFFECT TRUCK PERFORMANCE

Although the BNG study and the VOCM can both be used to analyze truck travel times, they differ in their basic assumptions. In the BNG study, it is assumed that either grade or alignment determines truck speed. Uphill truck speed on straight sections of road is limited by horsepower. Downhill speed on straight sections of road is limited by sustained braking capacity. On curves, truck speed is determined by the sight distance required to stop. In the VOCM, however, grade and alignment are considered simultaneously. The VOCM assumes that sliding friction, not sight distance, determines speed on curves.

Grade

On sections of logging roads in which curves do not appreciably affect driving behavior, grade is considered to be the primary

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factor that controls vehicle performance (*2, 4*). Vehicle speed on these sections is assumed to be constant. That is, the sum of the retarding forces acting on the vehicle is equal to the force component of the weight parallel to the road. The VOCM assumes that the driver selects a gear that allows the maximum sustainable speed within the capacity of the engine brake without the use of the service brakes. This maximum braking horsepower is assumed to be equal to 320 at 2100 rpm. It is assumed to be an exact balance between braking power required and braking power provided. The equation used by the VOCM is as follows:

$$V = (550 \times B) / (W \times G + W \times R) \qquad (1)$$

where

V = velocity in feet per second,
B = available engine-braking power in horsepower,
W = vehicle weight in pounds,
G = road grade as a decimal fraction, and
R = rolling resistance as a decimal fraction.

The BNG study developed an empirical relationship that related the speeds of loaded and unloaded trucks to favorable grades. That relationship was based on a variety of truck sizes and road surfaces for favorable grades that ranged from 2 to 16 percent. Only one data point was at 16 percent; the rest were 12 percent or less. The relationship developed was as follows:

$$V = \frac{240}{3 + G} \qquad (2)$$

where

V = velocity in miles per hour, and
G = road grade as a percent.

The empirical relationship given by BNG for truck travel times on favorable grades is shown in Figure 1.

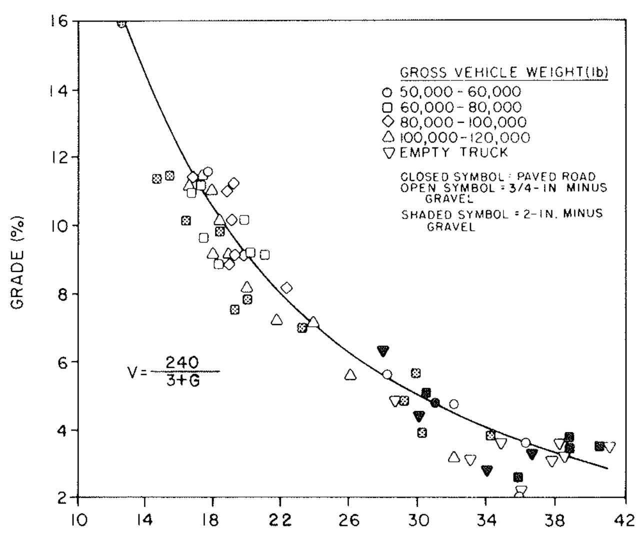

FIGURE 1 The influence of grade on the speeds of loaded and unloaded logging trucks traveling downhill on a straight section of road (*2*).

Alignment

Curves can affect vehicle speeds in two ways. They can limit sight distance so that speeds must be reduced and they create a centrifugal force that can make the truck slip or tip, depending on the available friction at the road surface. Vehicle speed on curves is ultimately limited by such slipping or tipping.

Sight Distance

Sight distance is the most commonly accepted factor controlling truck speeds on curves of single-lane logging roads (*2*). The driver will assumably maintain a speed that will permit a stop within the available distance between the two vehicles. The assumption used by BNG is that the driver anticipates meeting another vehicle traveling at the same speed. An alternative assumption often used in highway design is that the driver operates the vehicle at a speed that will permit stopping to avoid hitting an object on the road (*5*).

Sight distance is commonly defined as the line-of-sight distance between the driver's eye and an object on the road. The usual height of the driver's eye is assumed to be 3.5 ft and the object height is assumed to be 0.5 ft (*5*). Because this definition applies to average-sized vehicles, it may not adequately reflect the sight distance from the cab of a logging truck. BNG used an eye height of approximately 7.5 ft to calculate sight distance for various road widths. They also assumed a sighting point of 4.5 ft on an oncoming vehicle as the point that triggers the driver's braking reactions (Figure 2a). The hood of the approaching vehicle is assumed to be 4.5 ft above the road surface. Therefore, the average height of the tangent point on the backslope is (7.5 + 4.5)/2, or 6 ft, above the road surface (Figures 2a and b). The middle ordinate, M, is the horizontal distance from the center of the roadway to the point on the backslope that is just tangent to the line of sight between the driver's eye and the approaching vehicle (Figures 2b and c). The resulting relationships between curve radius and average truck speed, based on sight distance, are shown in Figure 3 (*2*).

Available Friction

The BNG study assumes that because sight distance restricts travel speed, it is less than a speed based on side-slipping friction. The VOCM, however, assumes that side-slipping friction determines travel speed. The authors of the VOCM base this assumption on the belief that the additional height of the driver's eye, the driver's experience and familiarity with the road, and the use of CB radios permit driving "beyond sight distance" (E. Sullivan, unpublished data).

Most typical log loads in western Oregon will probably not be affected by tipping because of the low coefficient of friction on gravel roads in that region. In addition, less friction is available to resist side-slipping in situations in which some of the friction potential is required for braking or driving the powered wheels. Therefore, the possibility of tipping is reduced. Tipping could become a problem when high coefficients of friction are developed, such as on paved, dry road surfaces. It could also occur in cases in which road conditions permit higher speeds on curves. No model evaluated in this study considered tipping as a limiting factor for truck speeds.

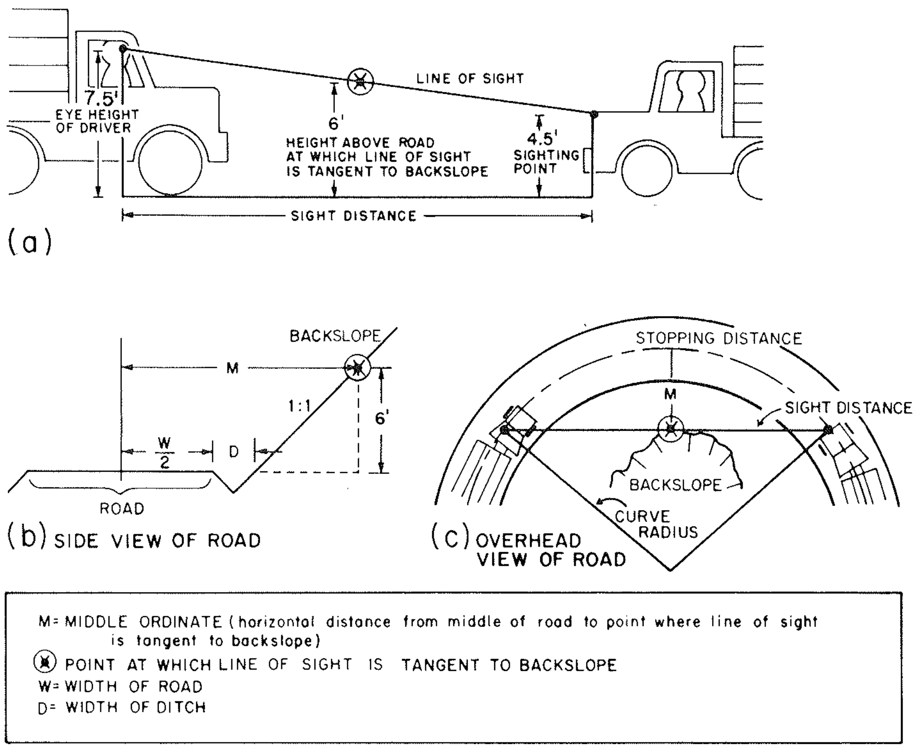

FIGURE 2 Sight distance related to road design.

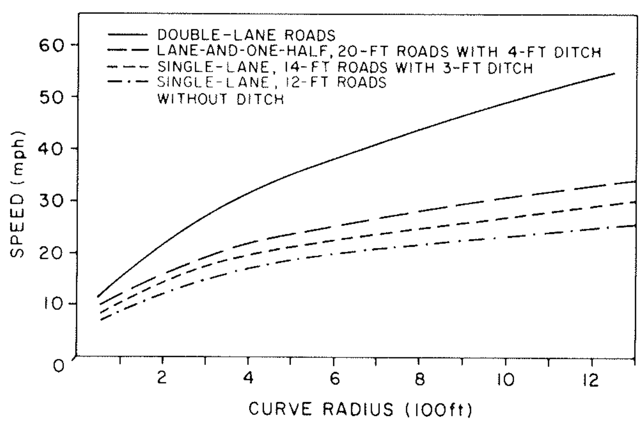

FIGURE 3 The influence of curves in logging roads of various widths on truck speed (*2*).

Interaction Between Grade and Alignment

The VOCM included the interaction of grade and curves on truck speeds, but the BNG study did not.

The approach taken by the VOCM was to compute the longitudinal and side-force friction components and compare the vector sum of these forces with the friction available between the tire and the road. The critical tires were assumed to be the powered wheels, through which the engine-braking force was transmitted. The maximum available friction was reduced by a "prudent driver" adjustment of 0.2 (*4*). For example, if the coefficient of friction was 0.4, the adjustment would reduce this value to 0.2.

STUDY AREAS AND PARTICIPANTS

For the sake of comparison with the previously described BNG study and the VOCM, truck performance was evaluated on roads in three portions of western Oregon: the 4711 road area in the Umpqua National Forest, approximately 30 mi east of Roseburg; the Wren timber sale area in the Mount Hood National Forest, approximately 20 mi east of Estacada; and the Dean Creek area on Oregon state land 5 mi east of Reedsport (Figure 4). The 4711 road area contained 20 segments that were

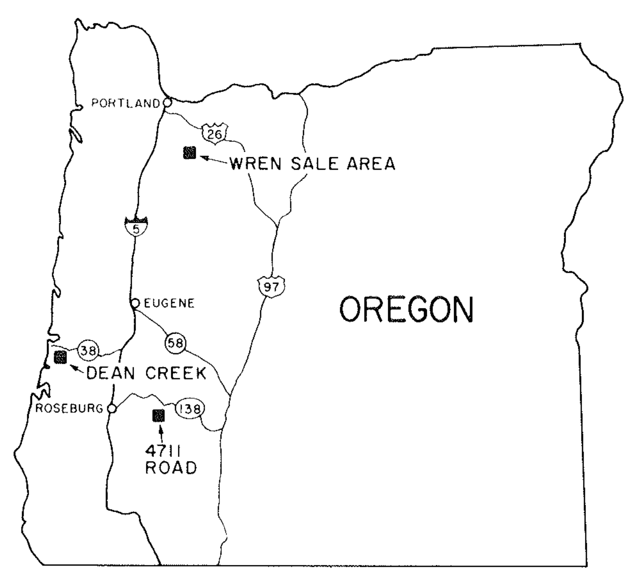

FIGURE 4 Location of study areas in which truck travel time data were collected.

located over a 7.71-mi portion of road. Only one segment was studied in the Dean Creek area. A total of 23 road segments, the lengths of which varied from 97 to 328 ft, were selected for their range of favorable grades (2 to 19 percent) and curve radii (68 to 500 ft). All roads were surfaced with 3/4-in minus gravel.

Data were collected for each road segment in the field on the grade, width, ditch depth, superelevation, and sight distance. Curve radii were obtained from plans. Information on the make, model, age, and maximum engine-braking horsepower for selected trucks participating in this study was supplied by the owners. Travel time, as well as the time of day, was recorded for each trip. Twenty-one drivers, whose truck-driving experience ranged from 10 to 30 yrs, participated. They were either employed by trucking companies that paid an hourly rate, or they owned their own trucks and were paid according to the gross weight of logs hauled.

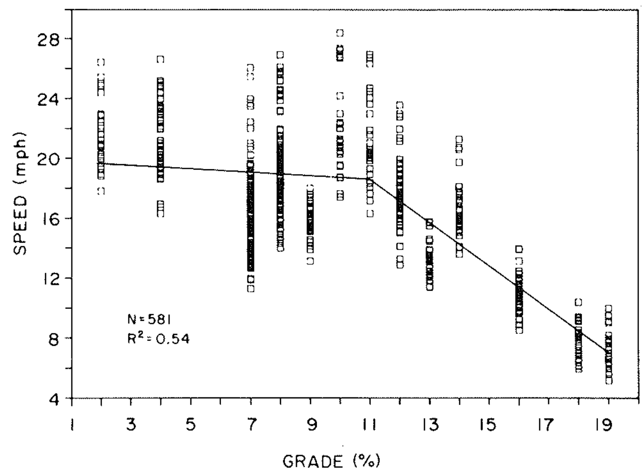

FIGURE 5 The effect of grade on the speeds of loaded trucks.

METHODS

Travel times for loaded trucks traveling downhill were recorded for each individual road segment studied in all three areas. Times were also recorded for the return runs of the empty, unloaded trucks traveling uphill. These travel times were evaluated to determine speeds as a function of curve radius and grade. In addition, overall travel time was recorded over a 7.71-mi section of the 4711 road. These times were compared with those predicted by the BNG study. Estimates of the mean and standard error were developed, and 95-percent confidence limits of these means were obtained. The relationship of the central (interior) angle to the curve radius for the 4711 road was compared with the roads in the BNG study. Multiple linear regressions were run to determine the effects of curves and grades on vehicle speeds.

RESULTS AND DISCUSSION

Effect of Grade on Downhill Speeds of Loaded Trucks

The scatter plot for grade versus speed suggested that a nonlinear transformation of the data would be necessary. No transformations using principles of mechanics could be found to fit well. A stepwise linear approach was found to give the best single fit of the data based only on grade (*6*).

The stepwise regression in Figure 5 indicates that when a favorable grade is less than 11 percent, there is little effect on speeds. The regression equation obtained was as follows:

$$\text{SPEED (mph)} = \underset{(0.058)}{19.912 - 0.123}\,(\text{GRADE}) - \underset{(0.1102)}{1.329}\,(\text{GRADE} - 11\%)\,(X_2) \qquad (3)$$

where

X_2 = a 0 to 1 variable (1 if grade $\geqq 11$, 0 otherwise) and grade is a positive number.

The break point was determined by repeated stepwise regression runs at 10, 11, and 12 percent. These break points were suggested by the scatter plot for grade versus miles per hour and were evaluated by observing R^2 and the mean square error terms for each run.

Downhill, loaded-truck speeds were slightly affected by grades less than 11 percent (Figure 5). Favorable grades steeper than 11 percent strongly influenced truck speeds. The most probable explanation is that curves influence the speeds on roads in which the grade is less than 11 percent. This is typical of many logging roads, like the 4711 road in this study, the alignment of which would be classified as poor by the BNG system (*2*). When sites were selected for this study, it was difficult to find any road sections that were not influenced to some degree by alignment.

It appears that the BNG and VOCM methods both predict speeds reasonably well for favorable grades between 11 and 16 percent. For steeper grades, the observed speeds were slower than would be predicted by both methods. In this study, because of the poor alignment of the roads, no conclusions could be reached on speed versus grade for grades below 11 percent.

Effect of Grade on Uphill Speeds of Unloaded Trucks

Travel times for the returning, unloaded piggyback trucks were also regressed on grade in a similar manner. A stepwise regression also best fit the data in this situation. The stepwise model was the same used for the loaded trucks, and the resulting regression equation in which only grade was used was as follows:

$$\text{SPEED} = 21.433 + \underset{(0.089)}{0.077}\,(\text{GRADE}) - \underset{(0.172)}{1.794}\,(\text{GRADE} - 11\%)\,X_2 \qquad (4)$$

where

X_2 = a 0 to 1 variable, as shown.

The travel times were more variable for the unloaded piggyback trucks than for the loaded trucks; R^2 was 0.39. Grade seemed to affect the travel times of these trucks when they were traveling uphill as much as it affected the times of the loaded trucks traveling downhill. The plot of this equation and the data points are shown in Figure 6.

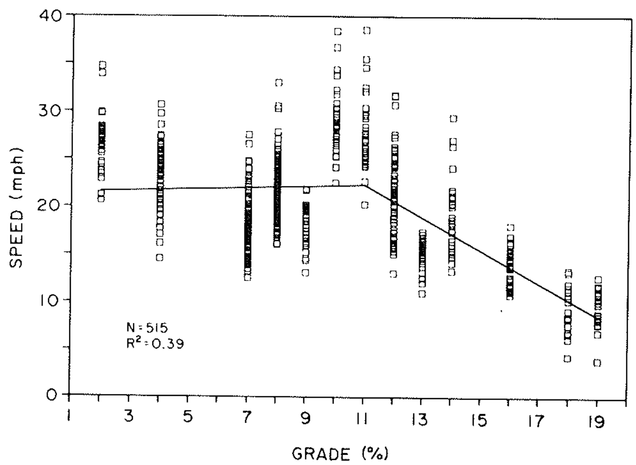

FIGURE 6 The effect of grade on the speeds of unloaded trucks.

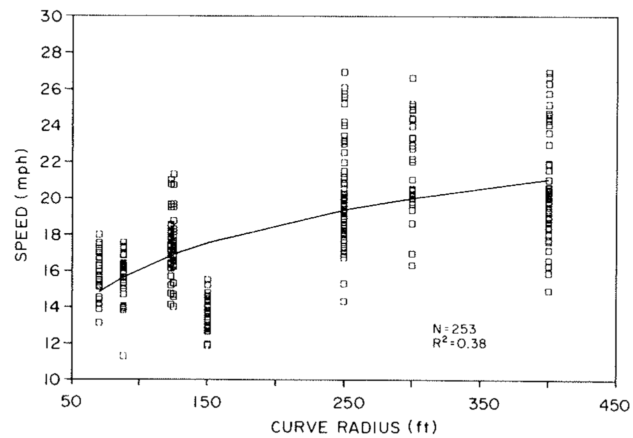

FIGURE 7 The effect of curves and grades of less than 11 percent on the speeds of loaded trucks.

Uphill travel speeds could be expected to be limited by alignment, traffic, grade, and other factors. If grade was the only limiting factor, the horsepower-to-weight ratios for these unloaded piggyback trucks would permit uphill travel at nearly 38 mph. The data offer no explanation for the similarity in speeds between the unloaded and the loaded trucks.

Effect of Curves on Speeds

Because a grade below 11 percent had little effect on speeds, only curves on portions of the road with grades less than that were regressed to estimate the relationship of a grade-free curve radius on speeds. Some interaction between grade and curve radius was present in the data, however. Curve radius decreased with an increase in grade. This relationship would normally tend to magnify the effect of curves on speeds, because as grades became steeper they would reduce speeds even more. However, little or no effect on speeds was found for favorable grades less than 11 percent.

Loaded Trucks (Downhill)

A logarithmic transformation was used to best fit the curve data for loaded trucks. The regression equation obtained was as follows:

$$\text{SPEED (mph)} = -0.373 + \underset{(0.660)}{8.239}\ [\text{LOG}_{10} \cdot (\text{CURVE RADIUS})] \qquad (5)$$

The plot of this equation, with the data points, is shown in Figure 7.

Unloaded, Piggyback Trucks (Uphill)

A square-root transformation best fit the data for unloaded piggyback trucks on curves. The regression equation obtained was as follows:

$$\text{SPEED (mph)} = 11.800 + \underset{(0.055)}{0.616}\ (\text{CURVE RADIUS})^{0.5} \qquad (6)$$

The variance was once again greater than for the loaded trucks, although the differences were not quite so great. The plot of this equation, with the data points for unloaded piggyback trucks on curves, is shown in Figure 8.

As mentioned earlier, the speeds of the unloaded piggyback trucks on sections of curved road were the same as those of the loaded trucks.

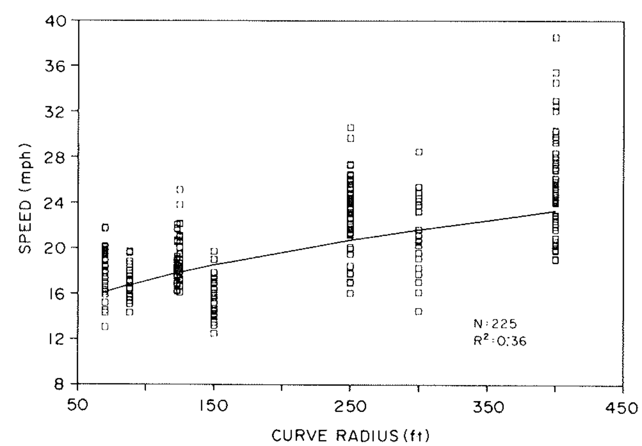

FIGURE 8 The effect of curves and grades of less than 11 percent on the speeds of unloaded trucks.

Comparison of Observed Times on Road Segments With the BNG Study and the VOCM

The plot of the stepwise regression equation for speeds of loaded trucks on grades compared with speeds predicted by BNG and the VOCM is shown in Figure 9. The curves of BNG and VOCM appear very similar and diverge at the flatter grades. Although the slope of the regression line is steeper, above 11 percent, the BNG and VOCM methods both accurately predicted speeds for favorable grades between 11 and 16 percent. Travel speeds appear to fall off more rapidly than BNG or VOCM would predict. A default speed of 55 mph was assumed as the upper limit of vehicle speed. The regression line for grades below 11 percent shows the insensitivity of speeds to grade in the range from 2 to 11 percent.

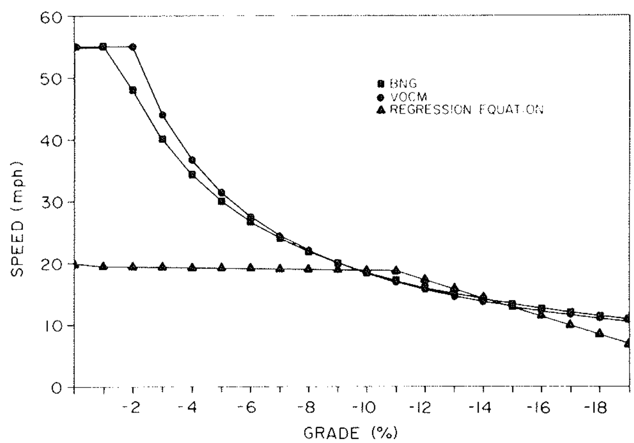

FIGURE 9 Comparison of observed speeds of loaded trucks on grades, with speeds predicted by the BNG study and the VOCM.

The plot of the stepwise regression equation for speeds of loaded trucks on curves compared with speeds predicted by BNG and the VOCM is shown in Figure 10. The curve shown for the VOCM reflects a zero grade. This relationship between curve radii and speed indicates that truck speeds were less sensitive to increasing radii than either the BNG or the VOCM predicted. The slope of the regression equation produced is somewhat flat above a 150-ft radius. Truck speeds for road 4711 do not appear to be affected by changes in curve radii as much as might be predicted by BNG or the VOCM.

The assumption that sight distances control vehicle speeds was not valid for the roads used in this study. A major contributing factor may be the extensive use of CB radios by the truck drivers. These radios, in effect, extended the sight distance in the curves by allowing the drivers to "see" ahead.

Under these circumstances, it might be expected that drivers would maintain speeds that depended on the type of road surface. However, the VOCM method, which uses this assumption, also did not agree with the observed speeds. This may be due in part to the distribution of curves on the entire road. A driver might not accelerate to a speed permitted by a 300-ft curve when a 150-ft curve is just ahead. According to the BNG study, alignment class is calculated by using only curves less than four times the smallest curve radii present. The "look ahead" relationship may be the basis for the four-times rule.

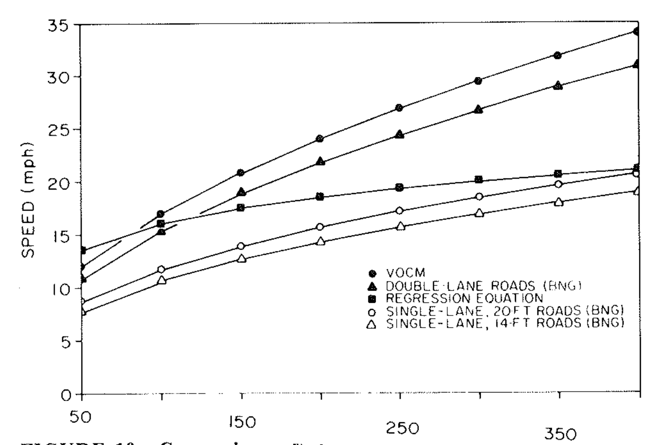

FIGURE 10 Comparison of observed speeds of loaded trucks on curves, with speeds predicted by the BNG study and the VOCM.

Road conditions immediately ahead of or behind a segment could reduce speeds in that segment if the truck has to accelerate from a slower segment or has to decelerate before approaching a slower segment. An exception to this might be a segment on an approach to a momentum grade, where short-term speed increases could be quickly dissipated on the adverse grade ahead. Road conditions adjacent to the segment would also be expected to produce more variability in observed speeds for a given curve radius or grade. This is due to the wide range of possible road conditions immediately ahead of or behind a segment of road.

When the BNG study and the VOCM model speeds in individual curves or on grades, road conditions ahead of or behind the segment being evaluated are not included. For this reason, the comparisons made in this study are probably conservative. If adjacent road sections had affected the observed speeds, the differences between the observed speeds and the speeds predicted by the BNG study and the VOCM would be even larger.

Several drivers mentioned the importance of planning evasive action when driving on curves. Because this road was wide enough at the curves, the drivers of two meeting trucks could sometimes pass by each other, provided each kept to his own side of the road. This sometimes resulted in the use of a shallow ditch or other surface that was not actually part of the normal road width.

Comparison of Observed Times on Road 4711 With BNG-Predicted Times

In order to compare overall observed times with BNG-predicted times, the minutes required for traveling over the 7.71-mi portion of Road 4711 were recorded. According to the BNG method, either grade or alignment controls vehicle speed (*2*). Under the influence of grade, an average estimated speed was computed to be 2.71 min/mi (22.1 mph) for each loaded truck. The returning time for each unloaded piggyback truck was calculated to be 1.60 min/mi (35.5 mph). Under the influence of alignment, the speeds for the loaded and the unloaded piggyback trucks on Road 4711 were the same: 3.66 min/mi (16.39 mph). These times were delay-free.

Because unloaded trucks are expected to give the right-of-way to loaded trucks, an adjustment of 4.2 percent was added to the travel time of the unloaded piggyback truck for a total of 3.81 min/mi (15.75 mph) (*3*). The times were greater on curves than on grades; therefore, alignment was assumed to be the influencing factor on this road. The total round-trip time was obtained by adding the slower times in both directions.

The earlier mean speeds predicted by BNG are compared with the mean speed and 95-percent confidence limits for the observed data in Figure 11. It is shown in this figure that the mean speeds predicted by BNG are outside the 95-percent confidence limits of the observed data of this study, and therefore are quite different from them.

The estimate of the differences between speeds on curves is believed to be conservative because the calculations for speeds from BNG are based on a constant speed on curves and grades (*2*). These calculations do not include the acceleration or

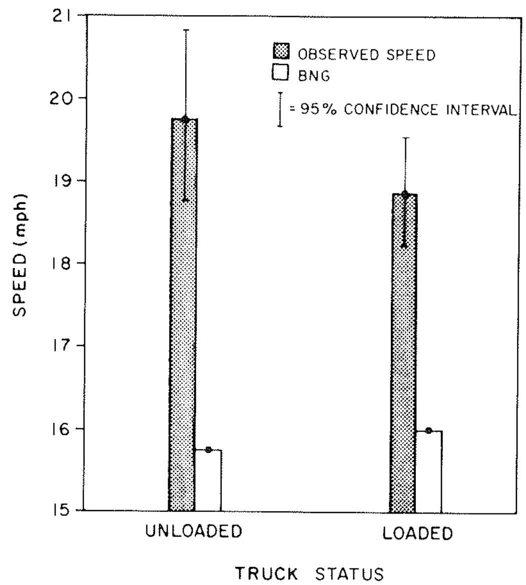

FIGURE 11 Comparison of observed speeds of loaded and unloaded trucks, with speeds predicted by the BNG study.

deceleration present in this study. If these factors were included, BNG would predict even slower times. Obviously, that would make the differences between BNG predictions and observed times even greater.

When the relationship of central angle to curve radius for Road 4711 was compared with the road in the BNG study, the two roads were found to be similar (*3*). They are probably representative of many logging roads in the West.

Overall, empty trucks were observed to travel an average of 4.4 percent faster than loaded trucks. However, the variation was great enough that no statistically significant difference between the speeds of loaded and unloaded trucks could be determined. Speeds of the empty trucks were 20.2 percent faster than those predicted by BNG, whereas the speeds of the loaded trucks were 13.1 percent faster than those predicted (*2*). Travel speeds for both empty and loaded trucks appeared to be approximately normally distributed.

The BNG method was generally found to underestimate travel speeds by 16.7 percent on Road 4711. For the 8.2-million-board-feet in this timber sale, this error is equivalent to a $1.27 per thousand board feet, or 20-percent, overestimation of hauling costs for a section of road similar to the 7.71-mi segment studied. That overestimation amounts to a total of $10,395 for the entire appraised sale volume.

SUMMARY AND CONCLUSIONS

When favorable grades were below 11 percent, they slightly influenced travel speeds. When grades were above 11 percent, they strongly affected speeds. Because of the types of road segments studied, no predictions could be made from the BNG method or the VOCM for speeds on favorable grades less than about 11 percent. The predictions of the two models and the values predicted by our regression equation are reasonably similar for favorable grades between 11 and 16 percent. Above 16 percent, however, BNG and VOCM overestimate travel speeds. Because the BNG method was primarily based on data below 12 percent, with only one point at 16 percent, it may give questionable results beyond 16 percent. The equation derived in this study predicts speeds on favorable grades above 11 percent reasonably well.

A widely accepted explanation for speeds on curves in single-lane roads is related to sight distance (*2, 5, 7, 8*). Travel speeds on curves on Road 4711 did not follow this explanation. Measured sight distance was not found to be an important variable in predicting speeds; the assumption by BNG that sight distance controls speed did not appear to be valid. It is suggested that the primary reason is the extensive use of the drivers' CB radios. These radios allowed the drivers to extend their "sight distance" to permit faster speeds in curves, with a higher degree of safety. This assumption was not tested because all truck drivers used their radios.

The relationship between curve radii and truck speed indicates that speeds were less sensitive to increasing radii than was predicted by either BNG or the VOCM. These findings could have important consequences for future road design and construction. If the presumed effects of various road geometry factors on speed are not valid, then the benefits of increased hauling speeds gained from alignment improvements may not be fully realized.

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