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Title: LOG TRUCK PERFORMANCE ON CURVES AND FAVORABLE GRADES

Abstract approved: J Sessions
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This paper describes the results of a study of log truck travel speeds in three locations in Western Oregon on favorable grades and curves. Independent variables of grade, curve radius, width, ditch depth, superelevation, sight distance, time of day, and maximum engine braking horsepower were regressed against speed. Only grade and curve radius were found to be important variables affecting speed. Regression equations are presented for both the empty and loaded trucks.

Speeds were found to be independent of grade for favorable grades less than 11 percent and strongly influenced by grades steeper than this. On sections of road not controlled by alignment, the method of Byrne et al., 1960 (BNG) and the Vehicle Operating Cost Model (VOCM), Sullivan, 1977 were shown to predict downhill speeds

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Thanks also to the USDA, Forest Service for their help and support while doing this study. The Forest Engineering staff at Oregon State University deserves special recognition for providing a first-rate academic experience during my studies.

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Typed by Judith Sessions for Ronald K. Jackson

LOG TRUCK PERFORMANCE ON CURVES AND FAVORABLE GRADES

by

Ronald Kelton Jackson

A PAPER

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LOG TRUCK PERFORMANCE ON CURVES AND FAVORABLE GRADES

I. INTRODUCTION

In 1977, a survey of the log trucking industry in Oregon indicated that approximately 12.1 billion board feet of timber was hauled over a distance of 203 million miles of federal, state, and private roads. These numbers do not include off-highway hauling which takes place entirely on private logging roads. The survey total also include logs from out of state and logs that are handled more than once (Dikstra, 1977). While Oregon is one of the largest timber producers in the nation, other states also have significant levels of timber production and associated log trucking activity.

The hauling costs associated with this level of timber harvest activity are high. The effects of alternative road design characteristics on truck travel times can have significant effects on these hauling costs. For this reason it becomes very important to be able to predict the response of truck travel times to alternative designs, so that the most cost-effective design can be achieved. Appraisal of hauling costs on a given timber sale can also have significant impacts on the attractiveness of the sale since log hauling costs can account for approximately a third of the total harvest cost in some areas (Giles, 1986).

Currently, most U.S.D.A. Forest Service appraisals use some adapted form of the original study done by Byrne, Nelson & Googins, 1960, commonly referred to as BNG.

Few published time studies of log truck travel times have been done in recent years. The classic study of Byrne et al. is probably the most well known and widely used. During the subsequent thirty years, advances in truck technology, including the introduction of the Jacobs engine brake, changed the braking ability of log trucks on favorable grades. Previously, it had been necessary to utilize cumbersome water cooling devices to control brake temperatures while descending the steep mountainous terrain frequently encountered in logging operations in the West. These cooling devices were subject to icing in winter and required some degree of maintenance throughout the year. The added weight also reduced the payload of the truck.

In addition to better braking methods, improvements in engines, transmissions, steering, and the introduction of the citizens band (CB) radio have contributed to safer, more efficient log transportation today. Some of these technological changes can be expected to affect the accuracy of travel speed estimates based on pre-1960 truck technology. This study compares actual travel speeds to predicted travel speeds using two different methods.

II. OBJECTIVE AND SCOPE

The objective of this study was to gather and analyze log truck travel speed data on selected favorable grades and curves and compare the results to existing methods of travel time estimation. This study was limited to favorable (downhill) grades, since a major portion of the loaded haul cycle from forest to the mill is usually on favorable grades.

Objectives

Four specific objectives were identified:

1. Compare observed speeds of log trucks on curves and favorable grades with speeds predicted by the study of Byrne et al.,(BNG). Have changes in truck technology since Byrne's study had any effect on these travel speeds?
2. Compare observed speeds of log trucks on curves and grades with speeds predicted by the Vehicle Operating Cost Model (VOCM), Sullivan, 1977. How well does this model predict observed speeds?
3. Compare the BNG method with observed speeds over a portion of road to determine how well it predicts overall trip speeds.
4. Examine the appropriateness of extrapolating the BNG data to steeper grades. Today, many roads are

being built on steeper grades, and travel speeds for these grades are not available except through extrapolation of existing data.

Limitations and Assumptions

Grades in this study are considered with respect to the loaded truck. A favorable grade indicates a downhill grade for the loaded truck. An adverse grade is an uphill grade for the unloaded piggyback truck. No negative numbers for grade will be used.

This study is limited to comparing steady-state speeds in curves and on grades using the BNG and VOCM models. An overall comparison of speeds over a portion of road using the BNG method was also done. A similar comparison using the VOCM was not done.

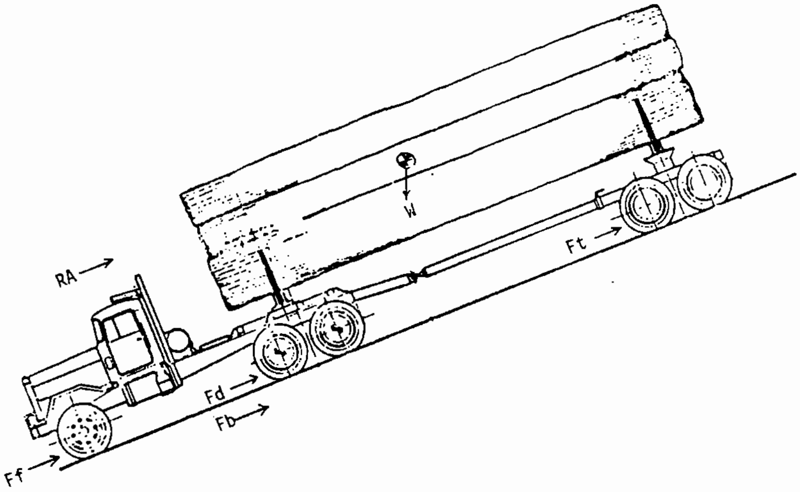
III. LITERATURE REVIEW

Factors Affecting Truck Performance

<u>Roads where speed is controlled by grade.</u>

On sections of logging roads where alignment does not appreciably affect driving behavior, grade is considered the primary factor controlling vehicle performance (Sullivan, 1977; BNG, 1960) Vehicle performance on these sections is based on a "controlled vehicle" assumption. This is a condition where the retarding forces, including engine braking--but without service brakes--acting on the vehicle, are in equilibrium with the forces generated by the road grade acting on the weight of the vehicle. Once at the equilibrium speed, the assumption is that this speed will be maintained until road conditions change. Depending on length and grade, each section of road is assumed to have some equilibrium speed associated with it for a given vehicle.

Figure 1. depicts the forces acting on a log truck on favorable grades. In this model, note that the entire braking force from the engine brake is applied to the driven wheel set. Service brakes are not considered to provide thrust to maintain equilibrium speeds. The force component providing downhill acceleration is seen to be W*Sin(Theta). Air resistance (RA) will rarely be a significant factor on typical logging roads, due to the relatively low speeds traveled.



Where: Ff,Fd,Ft=Rolling resistance for each axle set
Fb=Braking force from engine brake
Ra=Air resistance
W=Weight of truck
Theta=Grade of road

Figure 1. Forces acting on a log truck.

The retarding forces acting on the vehicle come from rolling resistance, air resistance, internal resistances, and, if curves are present, cornering resistance (Smith, 1970). Additional retarding forces required may be provided by a variety of means such as service brakes and various types of retarding devices. Engine compression brakes are the most common means of providing the needed power dissipation. Compression brakes such as the Jacobs Engine Brake (Jake Brake) provide a range of braking horsepower depending on engine size, brake type, and engine accessories. Maximum braking horsepowers on log trucks commonly range from 200 to over 300 horsepower (Stosky, 1986). The braking horsepower is a function of engine RPM and, for a given truck, depends on certain engine characteristics and accessories. For the same brake type or model, a wide range of braking horsepowers can be produced. Figure 2. shows braking horsepower vs engine rpm for eight trucks in this study. The upper curve represents the newest truck in the fleet, a 1984 Kenworth with a Jacobs model 44 brake. The other trucks are all equipped with Jacobs model 30E brakes.

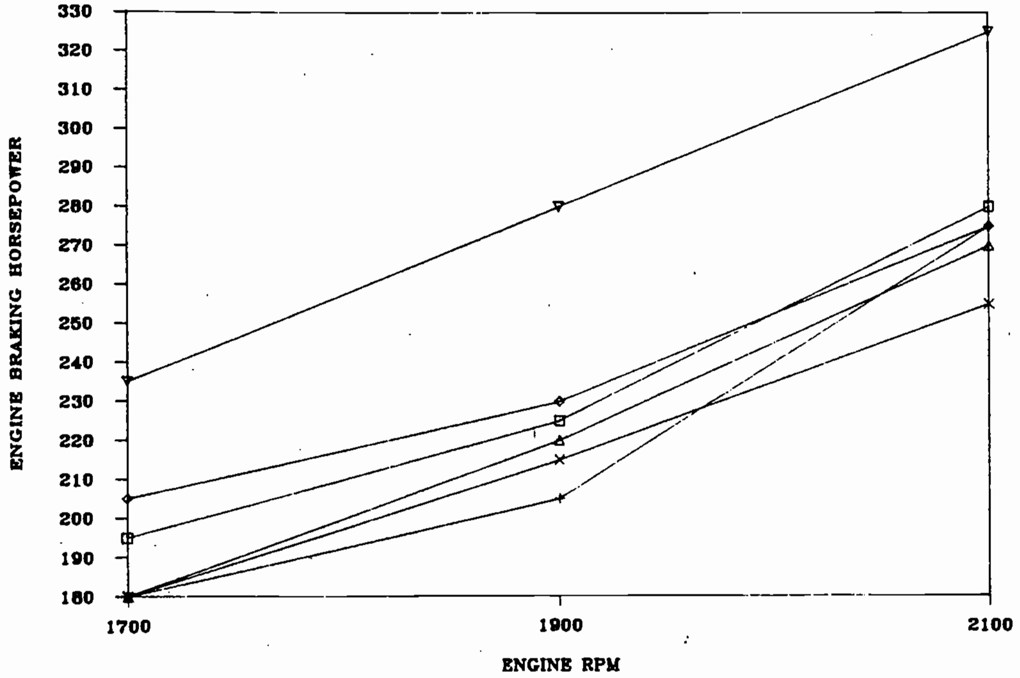


Figure 2. Engine brake horsepower curves for selected trucks in the study.

Other methods of providing the needed retarding force are oil or water operated retarders, or electro-magnetic retarders. These other methods are less common due to their size, weight, and cost (McNally, 1975).

Brake horsepower requirements to maintain an equilibrium speed are given in Figure 3. These values are net horsepower at the wheel. Actual engine brake ratings required could be about 15 percent less due to the power absorption in the vehicle running gears and engine accessories (Smith, 1970). Since a rolling resistance factor of .02 was assumed in Figure 3, the graph shows that at favorable grades between 0 and 2 percent thrust will be required to maintain speed.

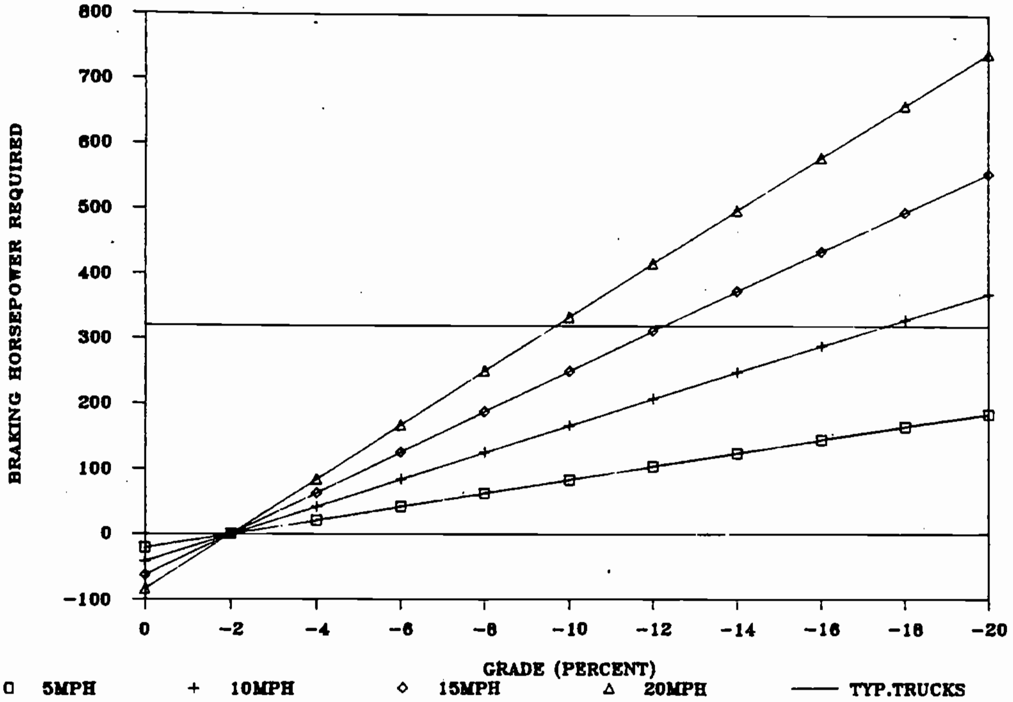


Figure 3. Braking power dissipation requirements for a typical log truck by speed and grade.

For example, Figure 3. shows that a typical loaded log truck, on roads where grade is the dominant controlling factor, could travel down a 10 percent grade at an equilibrium speed of between 15 and 20 MPH without assistance from the service brakes.

If all the needed braking horsepower were supplied by the service brakes, brake temperatures could quickly rise to the critical point. Anderson (1985) calculated that to dissipate power in the ranges shown in Figure 3. would only take about one and one-half minutes for a critical brake temperature to be reached. The use of the engine compression brake as the primary braking device allows for safer operation by saving the service brakes for speed adjustments or emergency stops. It also greatly extends brake life.

Byrne et al. (1960) developed an empirical relationship relating loaded and unloaded truck speeds to favorable grade. Their relationship was based on a variety of truck sizes and surfacings over a range of favorable grades from 2 to 16 percent. Only one data point was at 16 percent, the rest being 12 percent or less. The relationship developed was:

$$\mathrm{SPEED(MPH)}=2.4/(.03-\mathrm{GRADE})$$

The empirical relationship given by BNG for log truck travel times on favorable grades is shown in Figure 4.

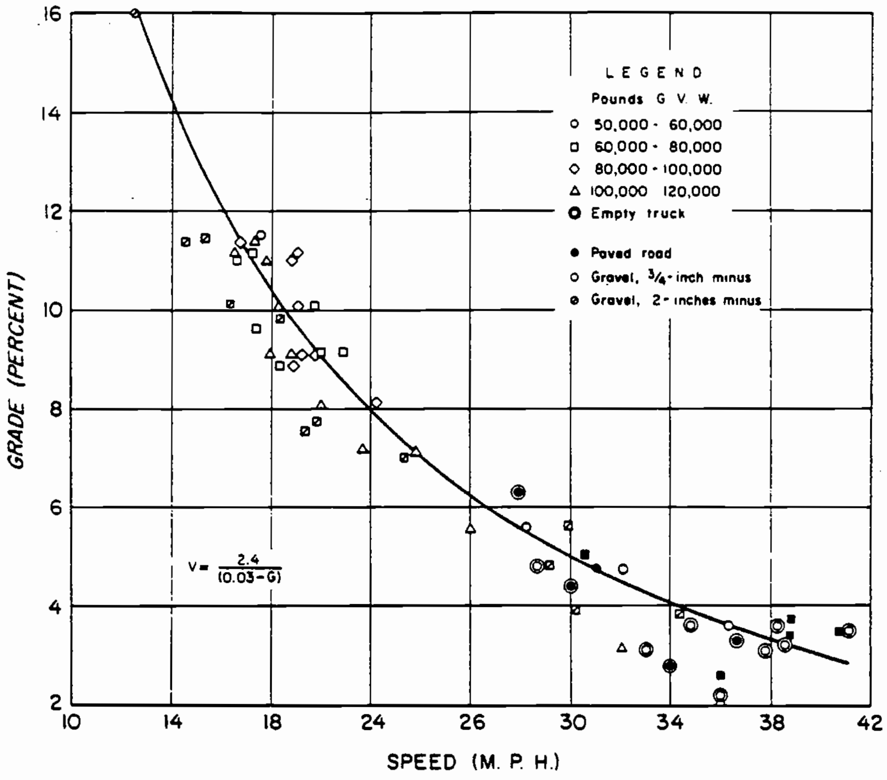


Figure 4. BNG relationship for speeds on favorable grades.

The Vehicle Operating Cost Model assumes an equilibrium condition where the driver selects a gear such that maximum braking horsepower is obtained. 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 VOCM is:

$$V(FPS)= \frac{550*B}{WG-WR}$$

Where: B=Available Engine Braking Horsepower (320)
W=Vehicle Weight
G=Road Grade
R=Rolling Resistance

Roads where speed is controlled by alignment.

Curves may affect vehicle speeds in several ways. They may reduce sight distance so speeds must be reduced in order to stop within the available sight distance. The centrifugal force created by curves may also limit speeds due to the available friction at the road surface to prevent slipping or tipping. The upper limit of vehicle speed in a curve is certainly at the limits of friction or tipping. Few, if any, drivers will drive at this point. Given this, the question becomes "what does determine the speeds at which drivers negotiate curves?".

Sight distance.

The most commonly accepted factor controlling speeds in curves on single-lane logging roads is sight distance (Byrne, et al.). Usually, the assumptions are that a driver will operate at a speed which will permit a stop within some distance correlated with sight distance. One common assumption is that the driver anticipates meeting another vehicle. An alternative assumption often used in highway design is that the driver operates at a speed that will permit stopping to avoid hitting an object in the road (AASHTO, 1984).

Sight distance is commonly defined as the line-of-sight distance between the driver's eye and an object in the road. The usual height of the driver's eye is assumed to be 3.5 feet and the object height is assumed to be 0.5 feet (AASHTO, 1984). While this definition is for a particular design vehicle (usually the smaller one commonly encountered), it may not adequately reflect the sight distance from the cab of a log truck. Byrne et al. used a height of approximately 7.5 feet in calculations of sight distance for various road geometry configurations. They also assumed a sighting point of 4.5 feet on an oncoming vehicle as the point that triggers braking reactions (Figure 5c). The middle ordinate, M, is calculated using the point of intersection of a line between these two heights with the road backslope (1:1 in the case of BNG--Figure 5b).

Actual stopping distance is not the same as sight distance. The stopping distance is the distance the vehicle travels on the roadway, which is somewhat longer than the sight distance (Figure 5a). In actual practice for larger curve radii, the differences are small.

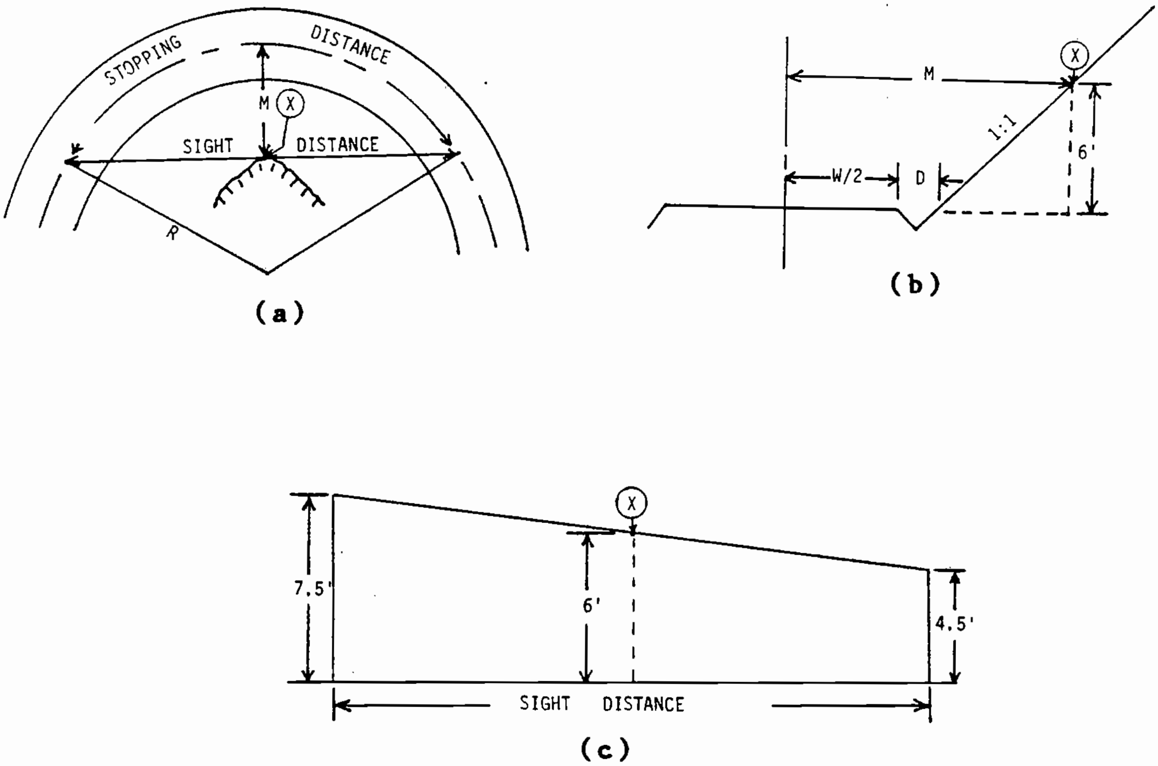


Figure 5. Sight and stopping distance geometry.

The assumption of meeting another vehicle is the basis for vehicle speed as a function of curve radius given in Byrne et al. The tables and graphs presented are based on theoretical sight distances available for a given road width, ditch width, and a backslope ratio of 1:1. The equation used to approximate stopping distance is:

$$\text{Stopping Distance (SD)} = \sqrt{(8*M*R)}$$

Once the stopping distance has been determined, the maximum speed that two meeting vehicles could stop in is obtained from the equation:

$$2*SD=8.8*V + V^2/15*F$$

Where: $2*SD$=distance required to stop for both vehicles
V=vehicle speed, MPH
F=coefficient of friction(BNG assumed a value of 0.4)

Solving for this quadratic in terms of V gives,

$$V(MPH)=\frac{-8.8\mp\sqrt{(8.8^2+4*1/15F*2SD)}}{2*(1/15F)}$$

Appendix A and E contain the derivations for these equations.

This equation for V does not include any grade term. The assumption of BNG is that the additional distance required to stop for the downhill vehicle will be exactly offset by the reduced distance to stop the uphill vehicle. For a locked wheel stop, this assumption is only valid when grade is zero. As can be seen from Figure 6., the error increases with increasing grade and will result in underestimating the stopping distance. The departure of the two lines as grade increases is a function of grade. Figure 6 does not include reaction and brake application time.

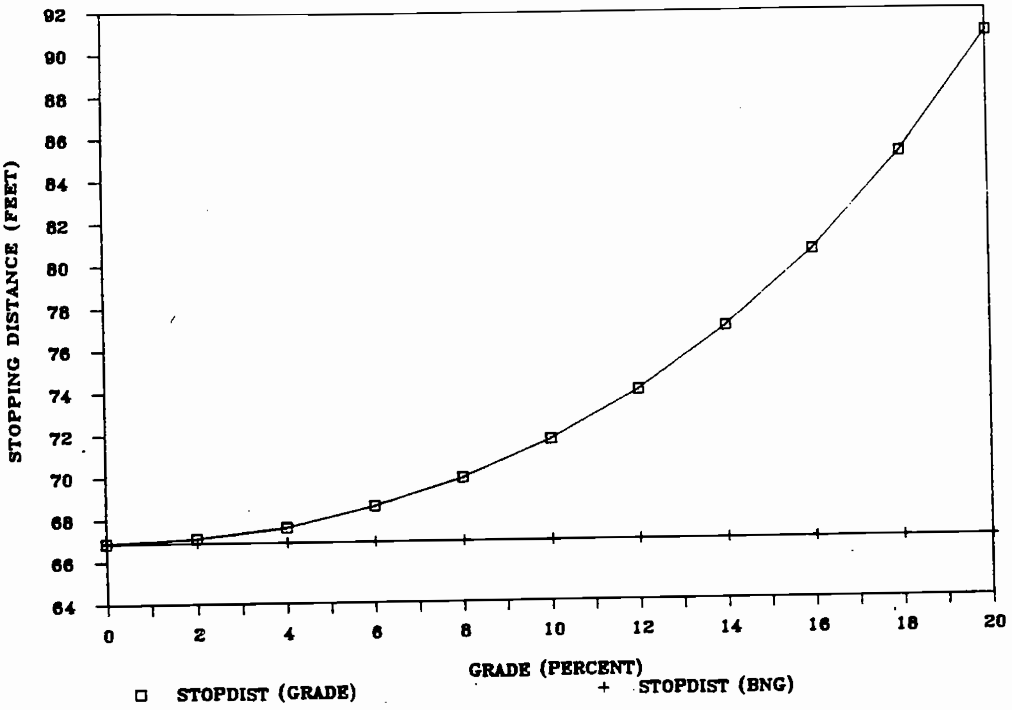


Figure 6. Combined stopping distances at 20 MPH (Coefficient of friction=0.4).

The deceleration rate obtained using a coefficient of friction of 0.4 and zero grade was 13.5 ft./sec^2 for the loaded and unloaded piggyback trucks. Under most conditions, the limiting factor in deceleration will be the coefficient of friction between the tire and the road surface. The coefficient of friction can vary greatly with surface type and weather conditions (Sessions et al., 1986), and can have a significant affect on the stopping ability of a log truck.

Since deceleration rates greater than 10 ft./sec^2 are considered uncomfortable, and values greater than 15 ft./sec^2 are used only in emergencies (Taborek, 1956), Figure 6. could be interpreted as an emergency condition stopping distance curve.

The calculated relationships between curve radius and average truck speed is shown in Figure 7 (BNG, 1960).

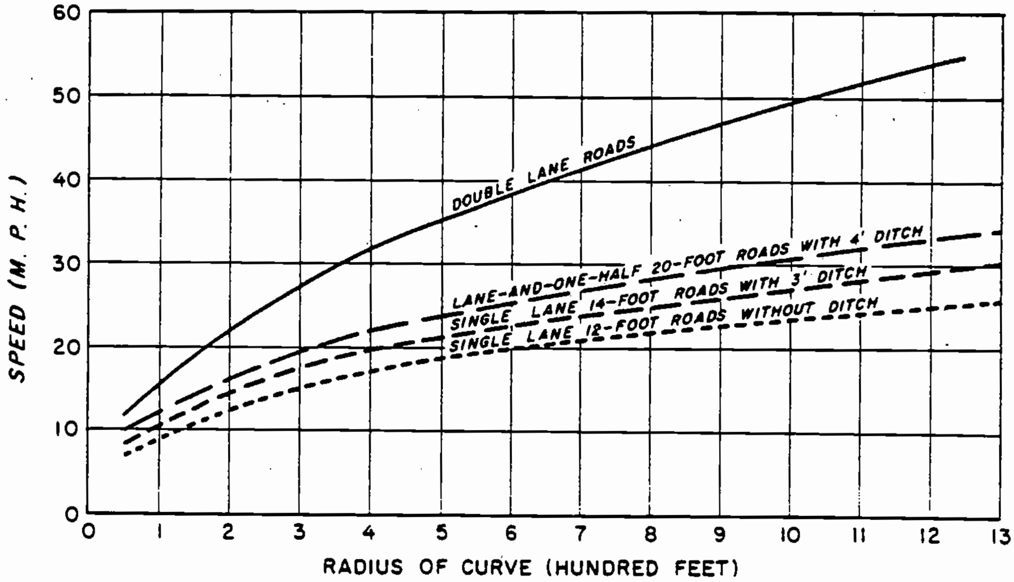


Figure 7. Speed vs curve radius (from BNG).

Available friction.

In Figure 7., the assumption underlying speeds on *double-lane* roads is that friction is limiting. A common equation for this condition is: (BNG; AASHTO, 1984)

$$V(MPH)=\sqrt{(R*(S+F)/.067)}$$

Where: R=Curve Radius
S=Superelevation
F=Side Friction Factor (0.16 used)

Since superelevation is usually not designed or built into logging roads because of the low speeds and occasional icy conditions, this equation simplifies to:

$$V(MPH)=1.55*SQRT(R)$$

With adequate superelevation, speeds can be expected to be up to 30 percent greater (Byrne, et al).

The Vehicle Operating Cost Model (VOCM) (Sullivan, 1977) uses a slightly different approach. It assumes that log truck speeds in curves are controlled only by available friction. It bases 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 radios permits driving beyond sight distance (Sullivan, 1986). The complete expression for this condition is shown below. The derivation of this equation is shown in Appendix B.

$$V(FPS)=\left[\frac{gC(BMU^2T^2-(WR+WG+KAV^2/8)^2)^{.5}+TS}{T}\right]^{.5}$$

Tipping.

While tipping is a concern under some conditions, most legal highway loads in western Oregon will probably not have this problem, due to the low coefficient of friction that can be developed on gravel logging roads. This would be especially true on grades where some of the resultant thrust vector is being used by the braking action or by the driving action of the powered wheels and, therefore, not available to resist side slipping.

Tipping could become a problem when high coefficients of friction are developed, such as on paved, dry road surfaces and where road conditions permit higher speeds in curves. When these road conditions are present, slipping is less likely and tipping could be more likely. Using equations developed by Sessions (1974) and assuming a height to center of gravity of 8 ft, the speed at which tipping would occur on a gravel road with a coefficient of friction of 0.4 and a curve radius of 150 feet would be approximately 34.5 mph (Figure 9.). Slipping would occur at approximately 30 mph under these same conditions. Note that under these conditions a height to center of gravity of greater than 10.8 feet would be needed to cause tipping before slipping; while for a coefficient of friction of 0.7 as on dry pavement, tipping would always occur before slipping This assumes a rigid vehicle suspension, and that all of the available coefficient of friction is used to resist sideslipping. If any braking or thrust were applied to the driven wheel set, less friction would be available to resist side slipping and slipping speeds would be lower.

Of 28 truck loads sampled in this study, the average load height was 12.5 feet, ranging from 10.5 to 13.8 feet. Height to center of gravity is dependent upon the type of load, size of logs, species, and placement. If we assume the center of gravity is at the geometric center of the load, and that the load resembled Figure 8., the height to the composite-body center of gravity would be 9.1 feet. Speeds in a 150-foot curve radius as predicted by BNG would be 12.7 MPH, well below the tipping or slipping conditions shown in Figure 9.

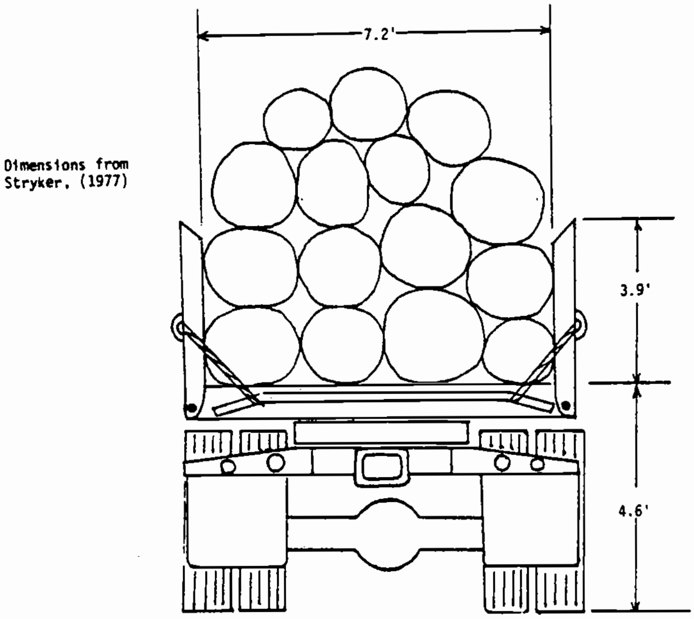


Figure 8. Assumed log truck load geometry.

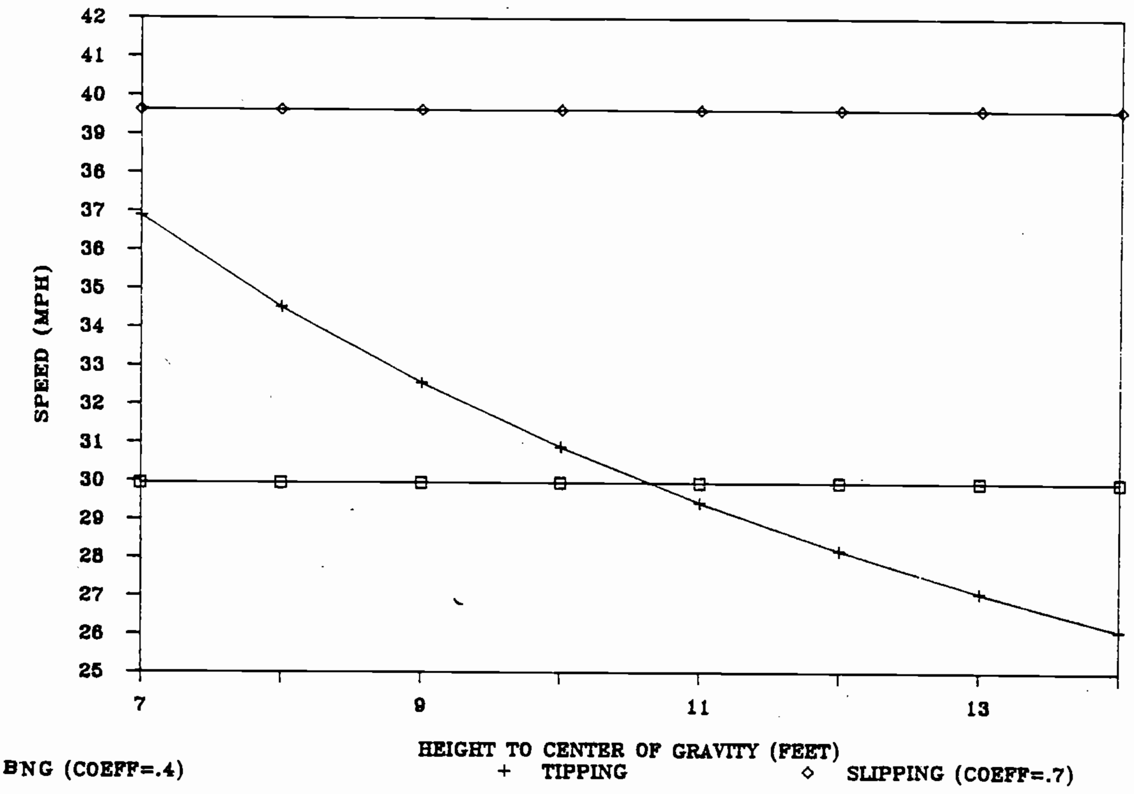


Figure 9. Tipping vs slipping as a function of height to center of gravity. (coefficient of friction=0.4, curve radius=150 ft.)

Speeds where both grade and curve interact.

The VOCM included the interaction of grade and curvature on speeds, while BNG did not.

The approach taken by VOCM is to compute the longitudinal and side force friction components and compare the resultant of these two forces with the friction available between the tire and the road. The critical tires are assumed to be the powered wheels, through which the engine braking force is transmitted. The maximum available friction is reduced by a "prudent operator adjustment" of 0.2. For example, if the coefficient of friction were 0.4, the adjustment would reduce this to 0.2.

IV. DATA COLLECTION

Data were collected at three different locations in western Oregon. Travel times were recorded for a variety of log truck makes, models, and ages. Drivers sampled included both drivers who drive a truck owned by a trucking company and are paid an hourly rate, and independent contractors who own their own truck and are paid by the gross scale of the logs hauled. A total of 21 different drivers and trucks are represented in the data. Drivers interviewed had from a minimum of ten years to a maximum of thirty years experience.

Study Area Selection

Study areas were selected for this study based on those which provided a range of favorable grades and curve radii. The segments ranged in length from 97 feet to 328 feet. Curve radii ranged from 68 feet to 500 feet. Favorable grades ranged from 2 percent to 19 percent. A total of 23 segments were studied (See Appendix J).

Study Area Description

1. Wright Creek Road No. 4711.

This road is located on the Umpqua National Forest about 30 miles east of Roseburg. It was selected because of

Figure 10. Study Area Map

the range of favorable grades present and the relatively high number of trucks available for timing. The section began at station 28+80 and continued to the top of the hill. The total length of the section was 7.71 miles. Hauling was from the STORMY timber sale, an 8.2 MMBF sale.

Road 4711 was constructed in 1967 and, for most of the length, consists of a steep, winding road. The surface was gravel, 3/4 minus, with an original design width of 12 feet. The actual measured widths were closer to 14 or 16 feet wide on the tangents and up to 30 feet in some curves. The road had been oiled with a lignin-based material about two weeks prior to the study to control dust. Favorable grades varied from 2 percent to 14 percent, with a distance weighted sample average of approximately 9 percent. Once beginning the trip down, there were only two or three flat areas until the bottom. In all, there were 20 segments on the 4711 road. Segment 9 and 15 were later dropped from the data base during analysis. Segment 9 was very close to a vertical curve and segment 15 was near an adverse section which caused some gear shifting within the test section.

2. Reedsport (Dean Creek) area.

This is a steep coastal road which accesses state land about five miles east of Reedsport. The study segment was located about 2 miles South from the junction with State

Highway 38. The segment was selected because it represented a 16 percent favorable grade. The road surface was 3/4-minus rock and in good condition.

Wren timber sale road - (4622-011 road)

This road is located on the Estacada Ranger District of the Mt. Hood National Forest, approximately 25 miles southeast of Estacada. The study segments were on the 4622-011 road which accesses a cutting unit on the WREN timber sale. This area was selected because of its steep grades. The road was approximately 0.6 miles long with an average grade of 18 percent. The road surface had been recently constructed and was in good shape. Surfacing rock was 3/4 minus.

Parameters Measured

In all, nine parameters were gathered for analysis. The parameters and the method of collection are listed below:

1. Grade.	Measured on centerline of roadway along segment length. (In percent)
2. Curve Radius	Obtained from plan and profile drawings supplied by Forest Service.

3.	Width	Measured as available running surface. In curves, the maximum traveled road width was used.
4.	Superelevation	Measured as the vertical change per foot of horizontal distance between wheel tracks in roadbed.
5.	Sight Distance	Measured as the distance a truck driver could see. A measurement of eye height of two common trucks placed the average height at approximately 7.5 feet. Measurements were taken at this height to a 4.5 ft. marker in the roadway on centerline.
6.	Time of day	Time of beginning run, empty or loaded, was recorded.
7.	Maximum engine retarding horsepower	Compiled from engine specifications for a limited number of trucks in the sample. Horsepower based on brake model, engine type, and

	engine critical parts list (CPL)number.
8. Operator type	A truck number was given to each truck. Company and independent drivers could be identified by truck number.
9. Ditch depth	Average ditch depth to the nearest 0.5 foot was recorded for each segment.

Method of Data Collection

On Wright Creek, (Road No.4711) a Hewlett-Packard 71-B handheld computer was used to record data. Appendix H contains a program listing and other information. The HP-71B was particularly useful since much of the data collection was completed while riding in the log truck cab. (Writing on a clipboard would have been very difficult.) It also had the advantage of being inconspicuous to the driver and conversations could be carried on while unobtrusively recording data by a press of the finger as we entered and left a segment. Data from the 20 segments at Wright Creek were transferred to disk storage via a program and interface to the HP-86 computer later in the evenings.

Data from the Reedsport and Wren timber sale area roads were gathered by roadside observation, because of the low volumes being hauled and the inefficiency of riding through only one segment. To collect these data by riding in the trucks would have required more days than were available.

A potential bias of the data introduced by data collection while riding with the drivers on the Wright Creek Road (No. 4711) was not tested.

V. DATA ANALYSIS

Statistical analysis of the data was done with "Numbercruncher", a statistics package available for use on microcomputers. Statistical procedures such as stepwise and multiple linear regression are available in the package.

Speeds on Grade

1. Loaded trucks.

The scatter plot for grade versus speed suggested that a non-linear transformation of the data would be needed. Theoretically, a transformation of the type 1/sin(grade) would be expected. However, no rational transformations could be found to fit well. A piecewise linear approach (Neter and Wasserman, 1983) was used and found to give the best single fit of the data using only grade. The piecewise approach also offered an explanation for the difficulty in obtaining a non-linear fit to the data.

As can be seen in Figure 11., the piecewise regression indicates that there is little effect of grade on speeds for favorable grades less than 11 percent.

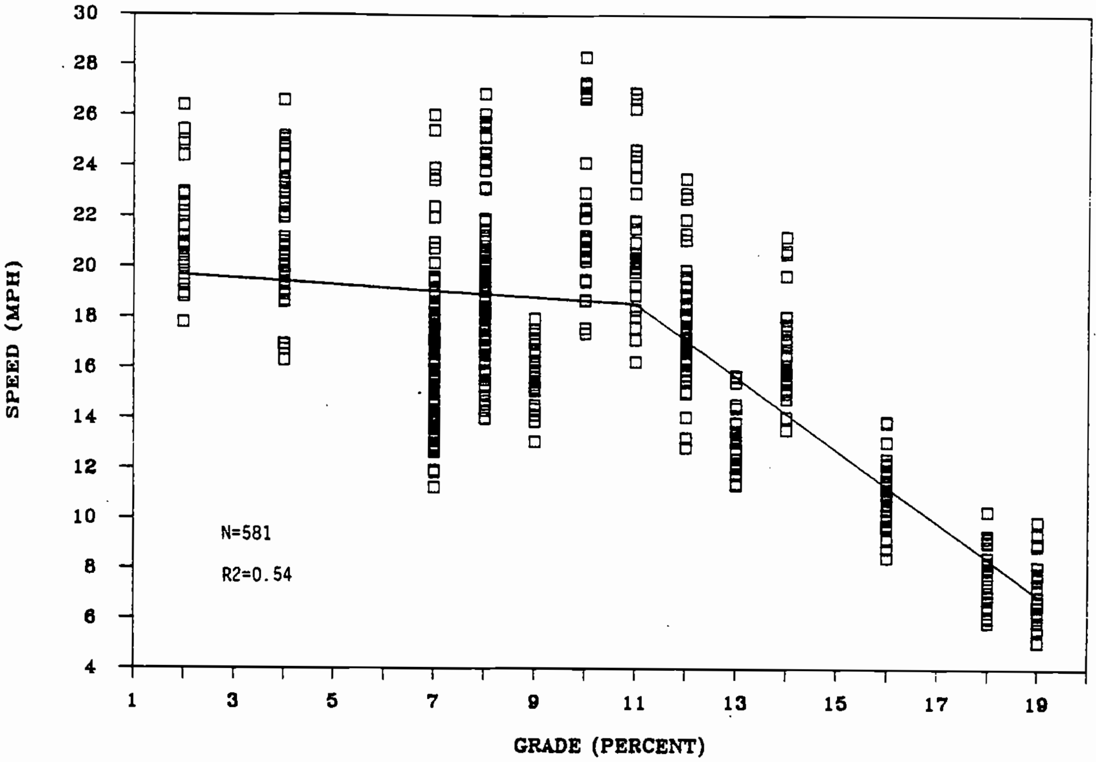


Figure 11. Piecewise regression with data points (loaded trucks).

The test for slope equal to zero for these grades gives t=-2.12, (P=.035). For favorable grades equal to or greater than 11 percent, speeds are strongly influenced by grade. (t=-12.05, R^2=.54)

The regression equation obtained was:

$$\text{SPEED(MPH)}=19.912-.123(\text{GRADE})-1.329(\text{GRADE}-11\%)(X_2)$$

$$(.058) \qquad\qquad (.1102)$$

Where: X_2= a 0-1 variable (1 if grade>=11,0 otherwise) and grade is a positive number.

The determination of the break point where grade became important was determined by repeated piecewise regression runs at 10, 11, and 12 percent. These break points were suggested by the scatter plot for GRADE vs MPH. They were evaluated by observing R^2 and the mean square error terms for each run. The plot of these observations is shown in Figure 12.

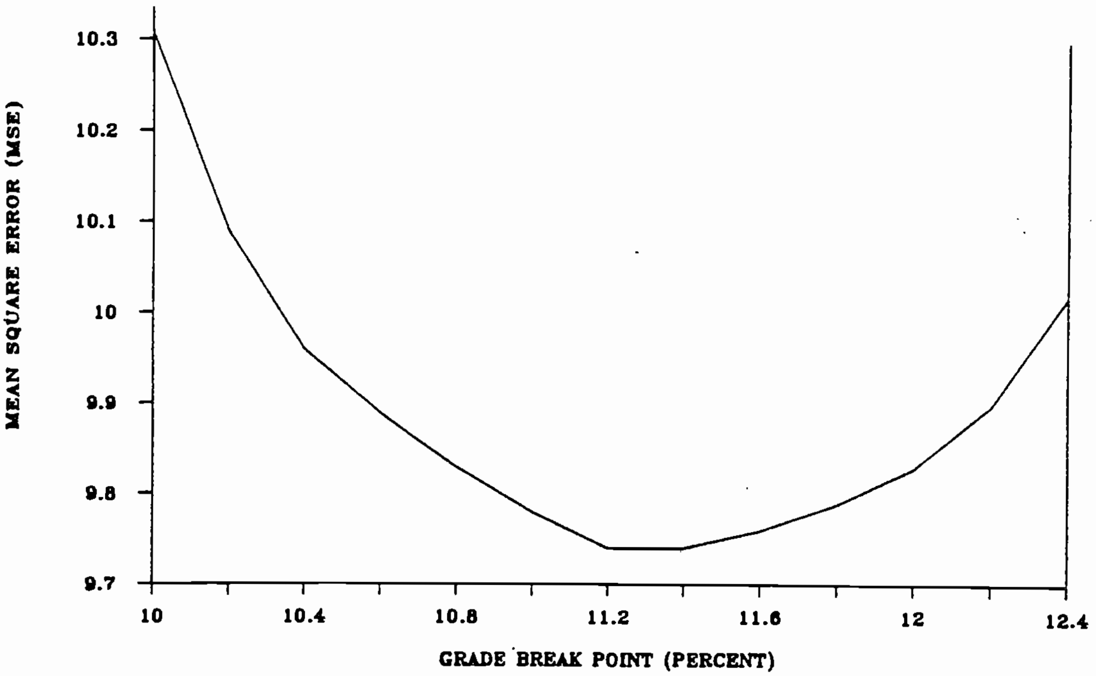


Figure 12. Grade at break point vs MSE for piecewise regression.

2. Unloaded trucks.

The returning unloaded piggyback truck travel times were also regressed on grade in a similar manner. Here again, a piecewise regression also offered the best fit of the data. The piecewise model used was the same as for the loaded trucks and the resulting regression equation using only grade was:

$$\text{SPEED} = 21.433 + \underset{(.089)}{.077}\ (\text{GRADE}) - \underset{(.172)}{1.794}\ (\text{GRADE}-11\%)X_2$$

Where : X_2=a 0-1 variable as before.

The fit for unloaded piggyback trucks was not as good as for the loaded trucks. An R^2 of .39 was obtained. The times were more variable for the unloaded piggyback trucks than for the loaded trucks. MSE for the unloaded piggyback trucks was 20.63, while the loaded truck MSE was only 9.78. This might be expected since the rules of the road put the delays due to meeting other trucks on the returning unloaded truck. The loaded trucks, once started downhill, had few observed delays.

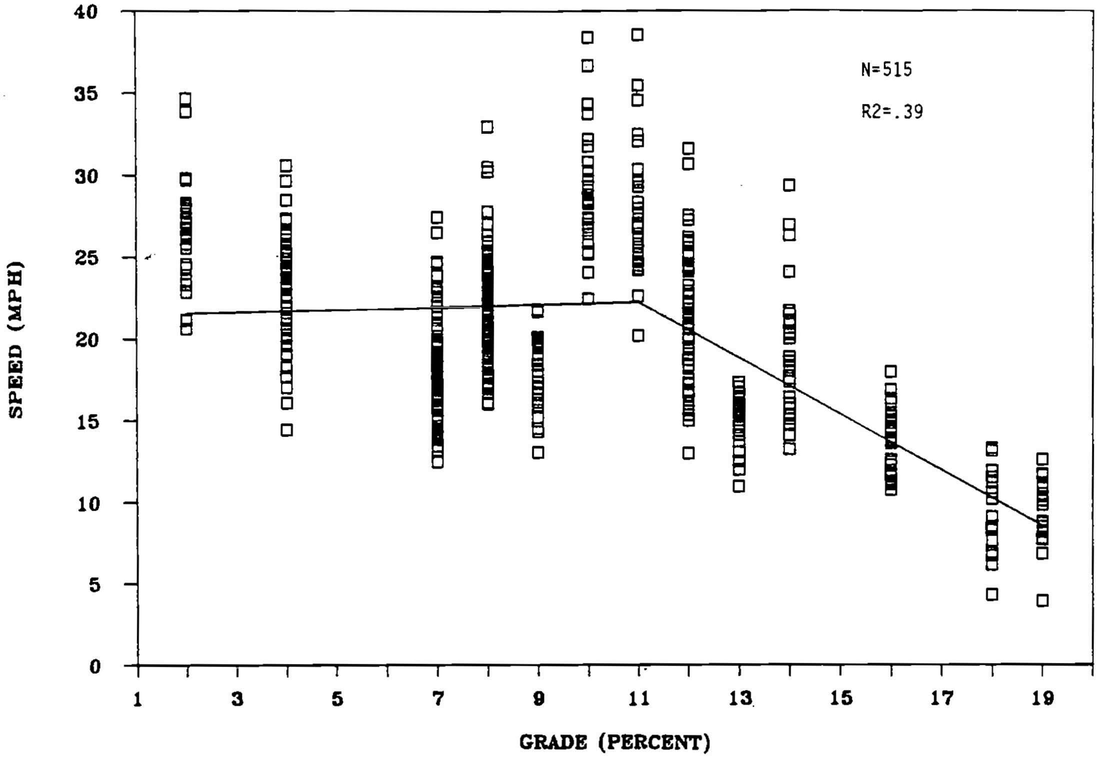


Figure 13. Piecewise regression with data points (unloaded trucks).

Speed on Curves

Since grade was seen to have little effect on speeds below 11 percent, only curves on grades less than 11 percent were regressed to estimate the relationship of 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. Normally, this relationship would tend to magnify the effect of curves on speeds, since grades would reduce speeds even more as they become steeper. However, for favorable grades less than 11 percent, little or no effect on speeds was found.

1.Loaded trucks.

A log transformation was used to obtain the best fit of the curve data. The regression equation obtained was:

$$\text{SPEED} = -.373 + \underset{(.660)}{8.239}(\text{LOG}_{10}(\text{CURVE RADIUS}))$$

R^2 was .38, while MSE was 6.57.

The plot of this equation, with the data points, is shown in Figure 14.

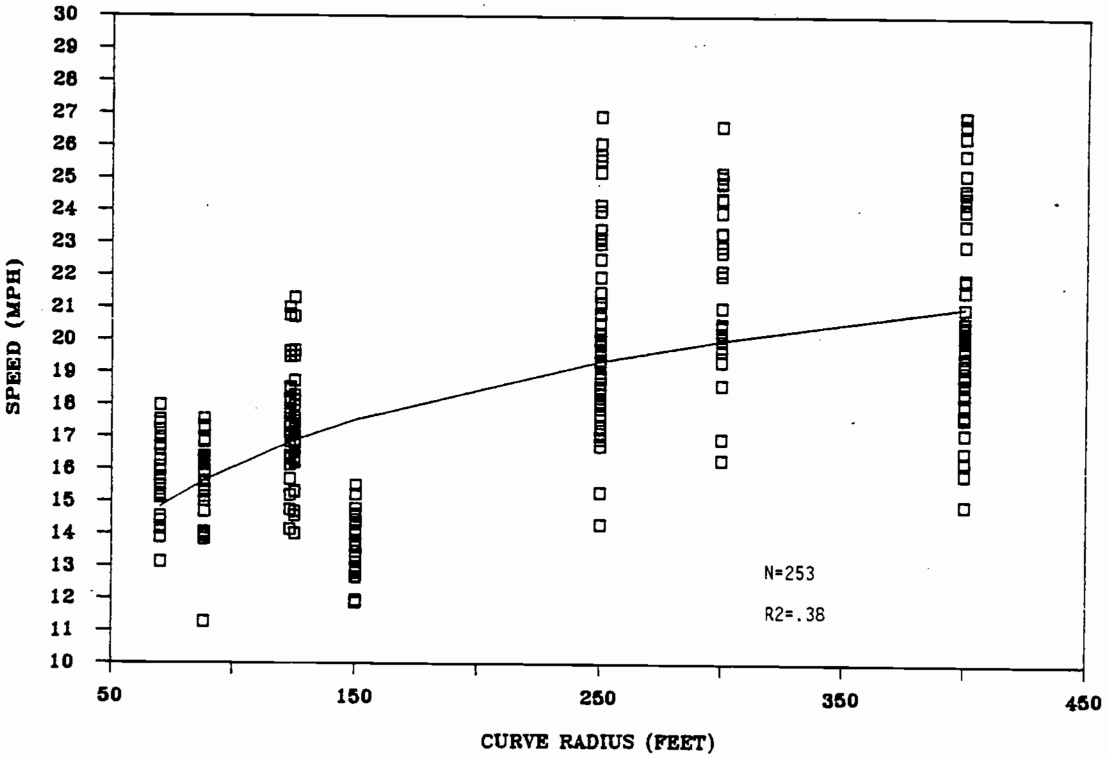


Figure 14. Loaded speeds in curves (with data points).

2. Unloaded Piggyback Trucks.

A square root transformation provided the best fit for the unloaded piggyback truck data for curves. The regression equation obtained was:

$$\text{SPEED(MPH)} = 11.800 + \underset{(.055)}{.616}\ \text{(CURVE RADIUS)}$$

R^2 was .36, while MSE was 9.20.

Here again, variance in curves was greater than for the loaded trucks, although the differences are not quite as great. Figure 15 shows this equation with the data points for unloaded piggyback trucks in curves.

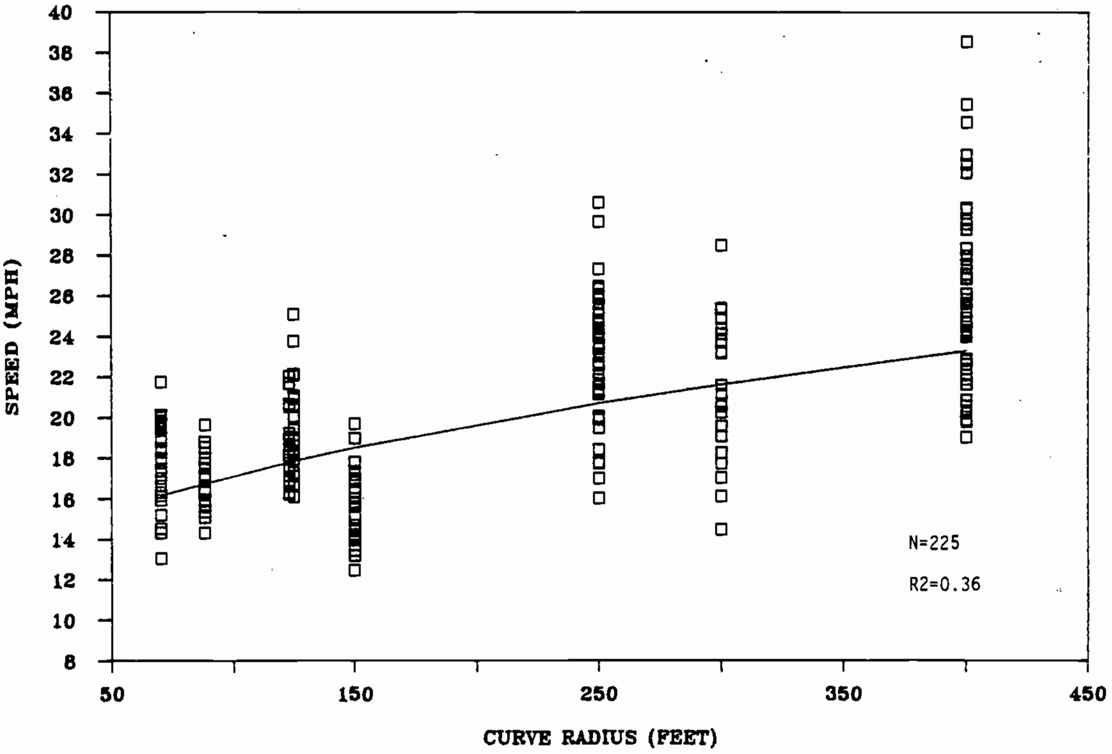


Figure 15. Unloaded speeds in curves with data points.

Comparsion With Other Methods

Figure 16 shows the regression equation for loaded truck speeds in curves compared to predicted speeds in curves based on BNG and VOCM. The curves for BNG represent both those controlled by grade and those controlled by available friction. The curve for VOCM reflects a zero percent grade. This curve will vary depending on the grade assumed. The rate of change of speed with curve radius can be seen to be greater for either BNG or VOCM compared to the regression line. The inplications of this are discussed in the Summary and Conclusions.

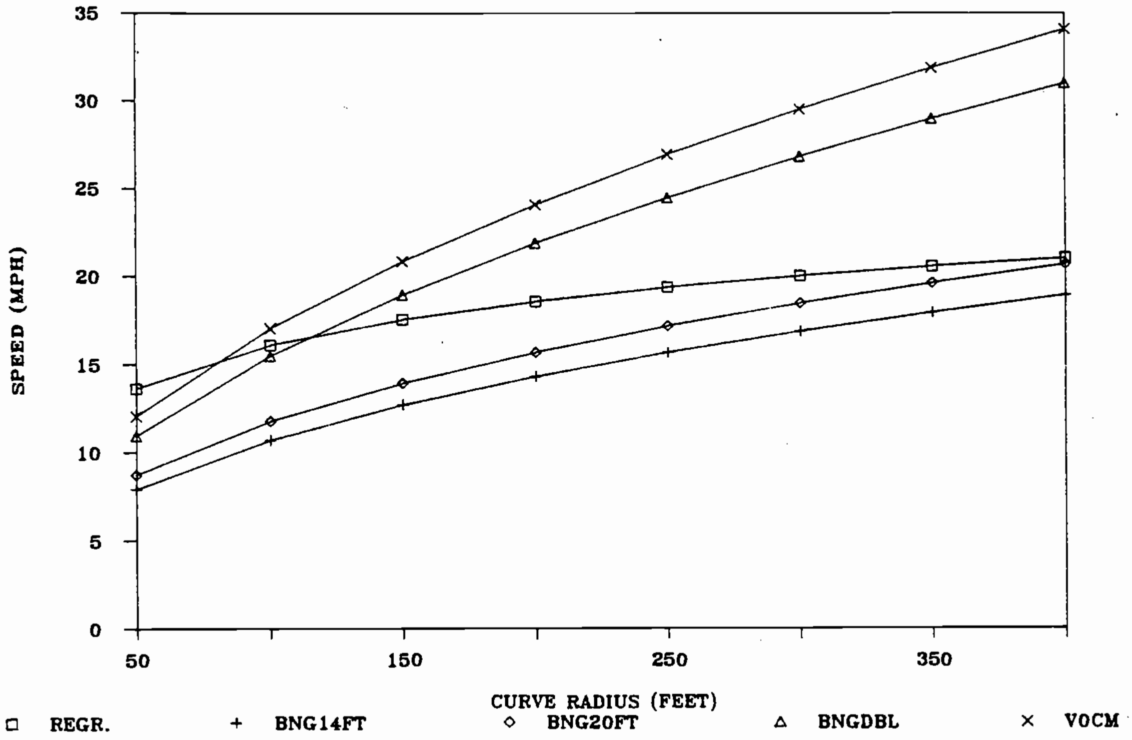


Figure 16. Speeds vs Curve Radius for BNG, VOCM, and Regression Equation.

Figure 17. shows the piecewise regression equation for loaded trucks on grades compared to the models of BNG and VOCM. The curves of BNG and VOCM appear very similar, diverging at the flatter grades. While the slope of the regression line is steeper above 11 percent, the two methods are close--between 11 and 16 percent favorable. 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 at the lower grades. The regression line below 11 percent shows the insensitivity of speeds to grade for these grades.

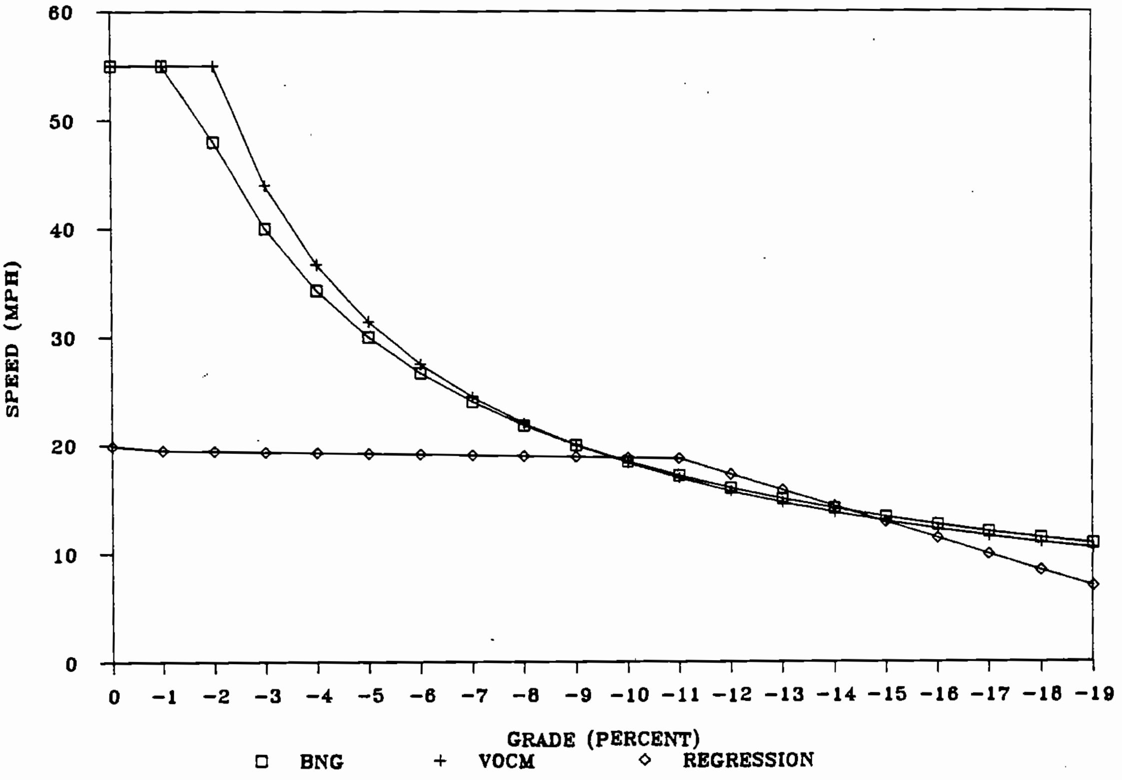


Figure 17. Speeds on grades compared to BNG and VOCM.

Overall Regression Equation

1. Loaded Trucks

The best regression model fitted to this data was:

$$\text{SPEED(MPH)} = 17.551 \underset{(.038)}{-.444}\text{(GRADE)} + \underset{(.00126)}{.0191}\text{(CURVE RADIUS)}$$

R^2 was .62, while MSE was 6.7. This equation gave the best overall R^2 and the lowest MSE of any combination tried.

2. Unloaded Piggyback Trucks:

A similar regression model was developed for the returning unloaded piggyback trucks. The best fit was obtained with the following equation:

$$\text{SPEED(MPH)}=17.059 - \underset{(.055)}{.287}\text{(GRADE)} + \underset{(.0018)}{.028}\text{(CURVE RADIUS)}$$

R^2 was .52, while MSE was 12.75.

Model Testing

The regression equations presented are based on an 80 percent subset of the full data set. A twenty percent subset was randomly selected to be set aside for model testing.

A paired t-test was performed, testing the regression model developed against the randomly selected set of data. For the unloaded piggyback truck model, a t-value of 1.64 was obtained, and for the loaded truck model, a t-value of .64 was obtained. Both of these values are within the 95 percent rejection region of the hypothesis that the models do not fit the twenty percent data subset.

(t_{95}(empty)=1.995, t_{95}(loaded)=1.993)

While this test does not guarantee the accuracy of the model under all conditions, it does indicate that it has been fitted properly and will reasonably predict travel speeds under the conditions on which the data was based.

VI. COMPARISON OF BNG METHOD WITH OBSERVED DATA.

To compare BNG predicted times to overall observed times, travel times were recorded over a large portion of the 4711 road, thus integrating varying curves, grades, and delays due to meeting other traffic. For the downhill (loaded) portion, time was recorded from the top--at the junction of the 4711-750 road--to the end of segment one at station 28+80. The overall distance was 7.71 miles. The uphill (empty) times were measured beginning at segment one and ending at segment 20, a distance of 5.89 miles.

According to the BNG method, either grade or alignment will control vehicle speed. To predict speeds of loaded trucks using BNG, if grade controlled, the 7.71-mile section of road being studied was separated into 74 segments containing distinct grades (identified from U.S. Forest Service road plans), and the length of each segment was obtained. The predicted speed using BNG was obtained for each grade and the travel time for each distance was calculated. This process was repeated for all 74 segments and the predicted total time to travel the 7.71 miles was obtained. Dividing this by the 7.71 miles traveled gave a grade-controlled speed estimate of 2.71 minutes per mile (22.1 MPH).

A similar process was used for the returning unloaded piggyback truck, except estimated speeds were developed from the equations for adverse grade shown in Appendix E. An unloaded truck weight of 25000 pounds was used, with a gross engine horsepower of 400 and an efficiency of 0.86. The unloaded piggyback travel time was calculated to be 1.60 minutes per mile (37.5 MPH).

Speeds controlled by alignment were also calculated using the BNG method shown in Appendix E. To estimate travel time where curves control speeds, using BNG requires an average curve radius and the number of curves per mile over a section of road to determine alignment classification. BNG recommends including only curves with radii less than four times the minimum curve radius in the section. (The minimum curve radius was 68 feet.) To test the effect of the "four times" rule, all curves were tallied and the two results compared. The alignment classification of "poor" did not change using either assumption (Appendix D).

The speeds obtained for the loaded and unloaded piggyback trucks on sections controlled by curves were the same--3.66 minutes per mile (16.39 MPH). These times were delay-free. An adjustment of 4.2 percent was made for traffic volume and turnout frequency and was applied to the unloaded piggyback truck travel times. Average hourly traffic on this road was eight vehicles per hour. A turnout spacing of 500 feet was used. The resulting time was 3.81 minutes per mile (15.75 MPH) for the unloaded truck.

The alignment controlled times were greater than grade controlled times (speeds were slower), so alignment was assumed to control on this road (see Table 1). The total round trip time is obtained by summing the slower times in both directions.

Table 1. Minutes per mile travel time using the BNG method

	GRADE	**CURVE**
UPHILL (UNLOADED) MIN/MILE	1.60	3.81
DOWNHILL (LOADED) MIN/MILE	2.70	3.66
TOTAL ROUND-TRIP MINUTES/MILE		7.47

Observed travel times were compared to the times estimated by BNG. Estimates of the mean and standard error were developed and 95 percent confidence limits about these means were obtained. The results are summarized in Figure 18.

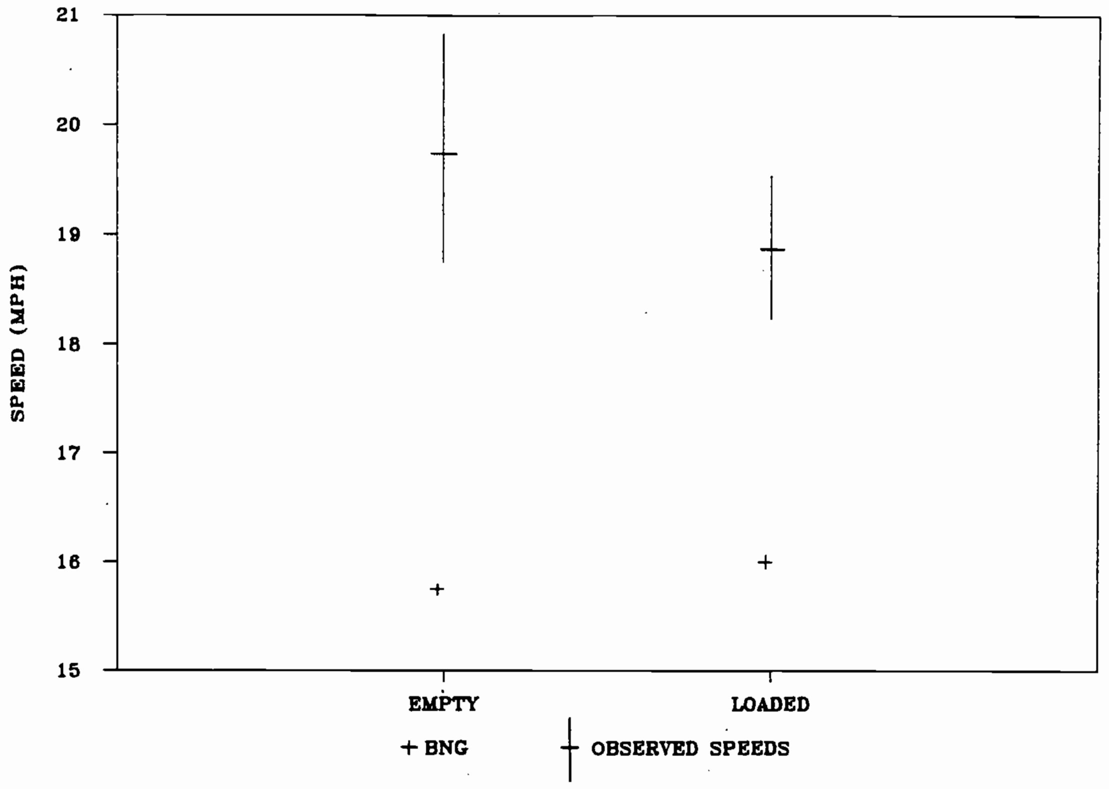


Figure 18. Comparison of observed speeds with speeds predicted by BNG. (95 percent confidence limits shown).

Empty trucks were observed to travel an average of 4.4 percent faster than loaded trucks. However, the variation was large enough that no statistically significant difference between loaded and unloaded truck speeds could be determined. Speeds of the empty trucks were 20.2 percent faster than that predicted by BNG, while the loaded speeds were 13.1 percent faster than predicted. Round-trip speeds averaged 16.7 percent faster than predicted using BNG method. Travel speeds for both empty and loaded trucks appeared to be approximately normally distributed (see Appendix F).

A comparison of the relationship of central angle to curve radius for the 4711 road was made to see if this road were similar to roads in the BNG study. The two relationships are shown in Figure 19. It would appear that the two are similar and probably represent many logging roads in the West. The differences at 500 ft. curve radius might be accounted for by the small sample of 500 ft. curves on the 4711 road (only 4 curves were 500 ft. radius).

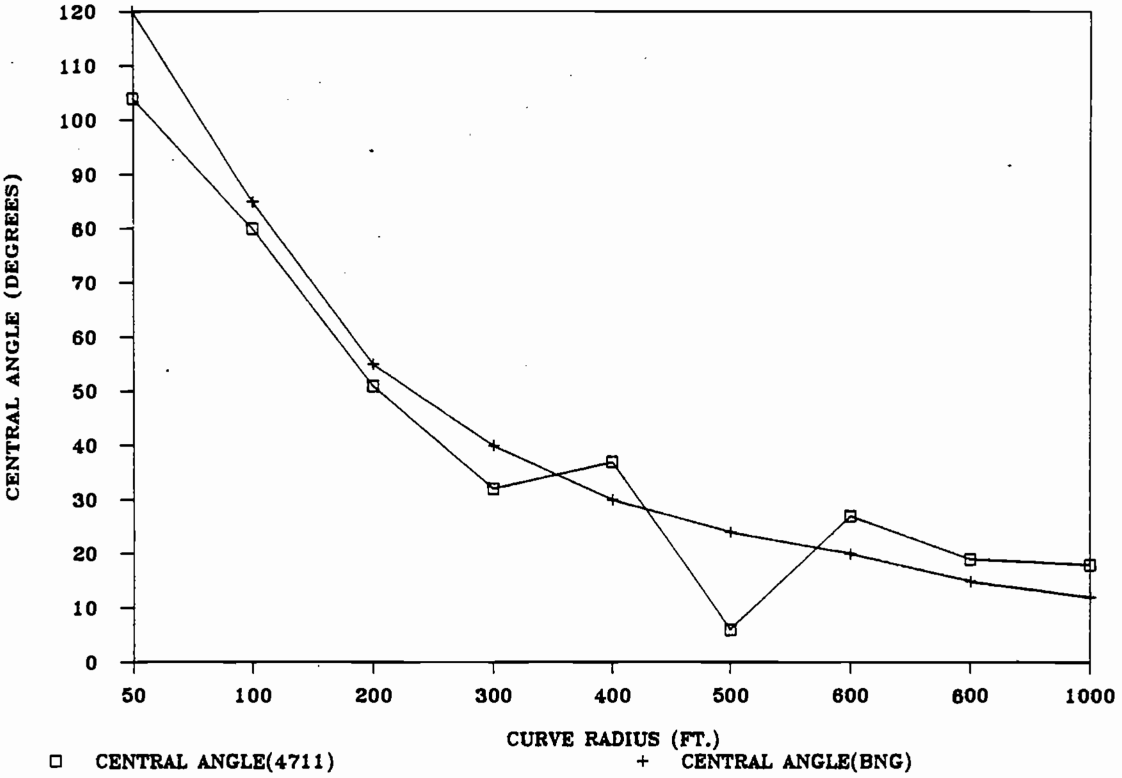


Figure 19. Central angle vs curve radius for 4711 road compared to BNG roads' data.

VII. DISCUSSION

Speed On Grades

Downhill (loaded) truck speeds are shown to be independent of grade up to 11 percent (Figure 11). On favorable grades steeper than 11 percent, grade strongly influences truck speeds. The most probable explanation is that alignment sets the speeds on these roads when grade is less than 11 percent. This is typical of many forest logging roads where alignment would be classified as poor, as on this road. The graph of BNG showing speed vs favorable grade (Figure 4) is for roads free of the effects of alignment. In the mountainous terrain of the Northwest, few logging roads will be completely free of the effects of alignment. When selecting sites for this study, it was difficult to find any road sections which were not influenced to some degree by alignment.

It appears that both the BNG and VOCM methods 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 due to the poor alignment of the roads, no conclusions could be drawn concerning the speed vs grade relationship of these methods on grades below 11 percent.

Uphill unloaded travel times were affected by grade in a manner similar to the loaded trucks. Uphill times would be expected to be limited by alignment, traffic, and other factors, but not limited by grade as shown in Figure 13. The horsepower to weight ratios for unloaded piggyback trucks were sufficient to permit travel uphill at nearly 38 MPH, if grade was the only limiting factor. The data offers no explanation for the similarity in speeds between the unloaded and loaded trucks. Several drivers commented, however, that, "you generally go downhill in the same gear that you go uphill in".

Speed on Curves

Figure 16 shows the relationship between curve radius and truck speeds observed in this study. The relationship between curve radii and speed indicated that truck speeds were less sensitive to increasing radii than predicted by either BNG or VOCM. The slope of the regression equation produced is somewhat flat above 150 feet radius. This implies that truck speeds for this road are not affected by changes in curve radii as much as might be predicted by BNG or 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 trucks to "see" ahead by using them. The number of trucks per hour using this road also proved helpful, since they were able to provide more frequent information on the various road segments. This CB contact alerted the drivers to non-logging traffic on the road. The small amount of non-logging truck traffic also reduced the probability of meeting other vehicles.

Under these circumstances, it might be expected that drivers would drive more nearly at speeds that followed an available friction relationship. However, the VOCM method, which uses this assumption, also did not predict speeds accurately. This may be due, in part, to the frequency of curves on the entire road. The effect of road sections ahead or behind a given segment may be expected to influence speeds. A driver might not accelerate to a speed permitted by a 300 foot curve, when a 150 foot curve is just ahead. The BNG rule is to calculate alignment class with curves less than four times the smallest curve radii present. This "look ahead" relationship may be the basis for the four-times rule.

The possible influence of road sections immediately ahead or behind the segments studied was tested. Regression analysis was used to test the significance of curve radius ahead, curve radius behind, grade ahead, and grade behind each segment studied. Only grade behind was found to be statistically significant, although weakly ($t=-2.09$).

Generally, the road conditions immediately ahead or behind a segment would tend to affect speeds in that segment. This is because the upper limit to speeds would still be limited by the curve or grade the truck was on, even though the next road segment might permit higher speeds. Speed would expect to be reduced only by road conditions immediately adjacent to a 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 or behind a segment of road. Figure 20 shows a conceptual view of the expected effects of the "look ahead" relationship.

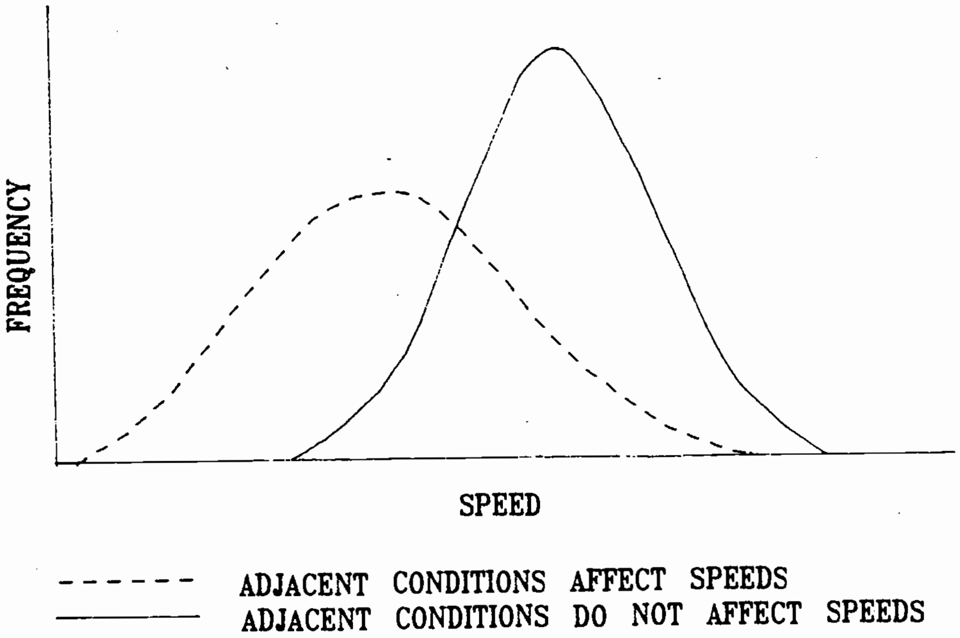


Figure 20. Conceptual effects of road conditions adjacent to a study segment.

Since speeds were found to be relatively unaffected by road conditions immediately ahead or behind the road segments, the comparisons of observed data to the other models are valid. BNG and VOCM, when modeling speeds in individual curves or on grades, do not include road conditions ahead or behind the segment being evaluated. For this reason, the comparisons made may be conservative. If adjacent road sections had affected the observed speeds, the differences between the observed speeds and the speeds predicted by BNG and VOCM would be even larger--if the observed speeds were adjusted to eliminate the effects of adjacent segments.

Several drivers mentioned the importance of planning evasive action when driving in curves. With the curve widths on this road, it was sometimes possible for two meeting trucks to pass, provided they both kept to their sides of the road. This sometimes resulted in using a shallow ditch or other area that was not actually part of the usable road width.

Overall Speeds - General Comments

Transmission and final drive ratios available to the driver may have an effect on the range of speeds chosen, within a normal range of engine speeds. To minimize shifting on short stretches of road, the drivers appear to select the best overall gear to drive in, and then use service brakes to provide the added necessary braking. This allows for truck speed variations within the limits of the normal engine operating range. The drivers were observed running in 5th direct, high range, at approximately 1900 RPM. This resulted in speeds around 20 MPH. Drivers made speed adjustments by applying light pressure to the service brakes.

VIII. SUMMARY AND CONCLUSIONS

This project has researched log truck travel times on typical logging roads in western Oregon. Travel speed data were collected for a variety of grades, curves, truck types, and drivers in three different locations.

Travel speeds on favorable grades were found to be weakly influenced by grade below 11 percent. Above 11 percent, speeds were strongly influenced by grade. Due to the types of road segments studied, no conclusions could be reached concerning the BNG or VOCM methods' ability to predict speeds on favorable grades less than about 11 percent. Between 11 and 16 percent, the predictions of the two models are reasonably close to one another and to the values predicted by the regression equation developed. Above 16 percent, however, BNG and VOCM overestimate travel speeds. Since the BNG method was based primarily on data below 12 percent, with only one point at 16 percent, the method 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 single lane roads in curves has been sight distance (BNG, 1960; Oglesby, 1963 & 1970; AASHTO, 1984). Travel speeds in curves on the

4711 road did not follow this assumption. 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. The primary reason suggested here for the speed behavior in curves is the extensive use of the Citizens Band (CB) radio. 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 since all trucks used their radios.

The implications of this finding could have important consequences for road design and construction. If previous assumptions concerning the effects of various road geometry factors upon speed are not valid, these faulty assumptions may be leading to designs that are more expensive than needed. The marginal benefits of increased hauling speeds gained from alignment improvements may not be realized to the extent predicted if the models overestimate the gains from alignment improvement. The rate of change of speeds with curve radius are more rapid than the observed data shows. If the observed relationships are accurate, the reduced travel time predicted for improved alignments may not be as great as expected (Figure 16).

Construction costs can be greatly increased by increasing the radius of curve in a given situation. When comparing speeds predicted by BNG to observed speeds, it can be seen that observed speeds on a 100 foot curve radius were equal to speeds predicted by BNG for a 250 foot radius curve (Figure 16). Nelson (1955) calculated costs for excavation and hauling for a variety of curve radii in a representative situation. For a 100 foot curve radius, the excavation quantity required on a 28 percent sideslope was 1800 cubic yards. For a 250 foot radius curve the excavation quantity was 8500 yards (4.7 times more). Assuming a cost of $1.50 per cubic yard for excavation, this would result in a cost difference of $10,050.00 for this one curve.

The predicted reduction in travel time by going from a 100 foot to a 250 foot curve radius would be greater using BNG than using the observed data. If the full reduction in travel time assumed did not occur (as may be the case, based on this study) the extra excavation would not have provided the same benefits as anticipated.

The estimate of the differences between speeds on curves is felt to be conservative, since the calculations for speeds using BNG are based on a constant velocity on curves and grades and do not include the acceleration or deceleration present in this study. If these factors were included, BNG would predict even slower times, which would make the differences greater than observed.

In general, the BNG method was found to underestimate travel speeds by 16.7 percent, on a representative segment of logging road. For the 8.2 MMBF "Stormy" timber sale volume, this error is equivalent to a $1.27/MBF (20%) overestimation of hauling costs over the 7.71 mile section studied, or a total of $10,395.00 for the entire appraised sale volume (Appendix G).

IX. SUGGESTIONS FOR FURTHER RESEARCH

Since this study looked at only three areas in Oregon, it was not possible to study travel speeds under all combinations of grade. Especially lacking were favorable grades free of alignment for less than 11 percent, the area where grade was found to not have any significant effect. One area of further study would be to gather data on roads in this category to verify the equation of BNG and VOCM in the range of 0 to 11 percent. Another area would be to do a survey of logging roads in the West to try to characterize them by alignment category. The 4711 road is considered by BNG a "poor" alignment road. To determine applicability of the study results, it is necessary to know what proportion of various haul roads in the West are in the various categories.

It is important to understand why sight distance did not control speeds as assumed by BNG and others. Currently, most design speed assumptions are based on sight distance controlling speeds. These assumptions may result in inaccurate hauling cost appraisals as shown, and incorrect road design decisions. The affect of the CB radio on log truck travel speeds would be important to quantify. This paper speculates that CB use is one of the major factors for increased speeds in curves.

Another factor that may be of significance in explaining truck speeds on logging roads is the overall alignment classification of a road. The influence of curve frequency may be important in setting an apparent upper limit on speeds on a road where alignment controls speeds. A study involving other alignment classifications than "poor" as in this one might improve travel time prediction methods.

A more complete evaluation of the VOCM by simulating a complete section of road would provide a better comparison with the method used by BNG.

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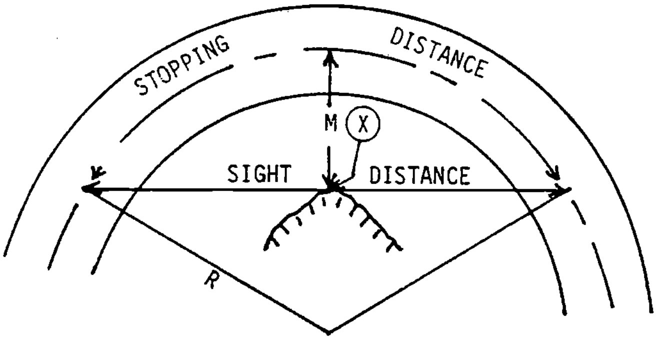
APPENDIX A.

Derivation of the approximation formula for stopping distance used by BNG.



1. $M=R-(R-M)$
2. $(SD/2)^2 + (R-M)^2 = R^2$
3. $(SD^2/4) + R^2 - 2MR + M^2 = R^2$
4. $SD^2=(4R^2-4R^2+8MR-4M^2)$
5. $SD=SQRT(8MR-4M^2)$

If the value of R is large compared to M, the term $-4M^2$ can be dropped with little error:

6. $SD=SQRT(8MR)$

Also, for large curve radii, the difference between straight-line sight distance and actual stopping distance available on the roadway is small:

7. SD=STOPPING DISTANCE=SQRT(8MR)

This assumption was used by BNG.

APPENDIX B.

Derivation of equation for equillibrium velocity in curves used by VOCM.

VOCM assumes vehicle speeds will be controlled by the limits of available friction (Mu) adjusted by a "prudent operator" factor of 0.2. The critical wheels are assumed to be the driven wheels. The model doesn't include weight transfer due to grades or curves, or that other wheels may become the critical ones.

The basic equation is:

$$BM_U^2T^2=(LF)^2+(SF)^2$$

Where: BMu=Mu(max)-0.2
LF=Longitudinal force
SF=Side force.
Wt=Weight per tire.

From this we get:

$$BMu^2T^2=\left[(WR+WG+KAV^2)/8\right]^2+\left[(WtV2/gC)-WtS\right]^2$$

Where: W=gross vehicle weight.
R=rolling resistance.
G=grade.
K=air density.
A=frontal area.
g=gravitational constant.
C=curve radius.
S=superelevation.
Wt=weight per tire.
V=velocity.

Solving in terms of V:

$$V(FPS)=\left[\frac{gC\left[BMu^2T^2-\left[(WR+WG+KAV^2)/8\right]^2\right]^{.5}+WtS}{Wt}\right]^{.5}$$

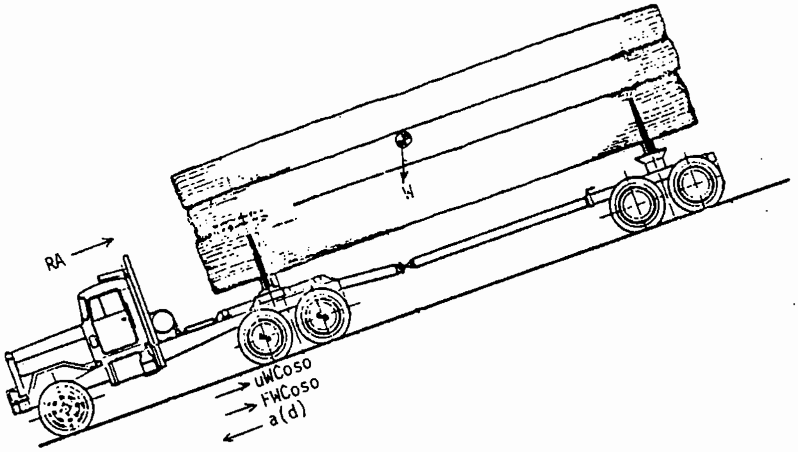
Ignoring air resistance gives:

$$V(FPS)=\left[\frac{gC\left[BMu^2T^2-\left[(WR+WG)/8\right]^2\right]^{.5}+WtS}{Wt}\right]^{.5}$$

APENDIX C.

Derivation of the minimum stopping distance,S, given V,MU,F,and Grade.

Truck Model:



$$F=MA$$

$$A=F/M=\frac{MU(W)(COS(THETA)+F(W)(COS(THETA)+W(SIN(THETA)+RA}{W/G}$$

NOTE: If we can neglect the air resistance term, RA, W (weight) cancels,therefore deceleration is independent of vehicle weight given adequate braking capacity.

$$A=G(MU+F)COS(THETA)+G(SIN(THETA)$$

Since $V=AT$,

$$ds/dt=AT$$

and, $ds=(AT)dt$

$$S=1/2AT^2$$

and, $S=\frac{V^2/A}{2}$

$$S=\frac{v^2}{2\ G(MU+F)COS(THETA)+G(SIN(THETA)}$$

APPENDIX D.

CHARACTERISTICS OF 4711 ROAD USED IN EVALUATING SPEEDS BY BNG.

AVERAGE CURVE RADIUS (FT.)	ALL CURVES	4X RULE
-uphill	209.42	152.65
-downhill	213.69	156.98
NO. OF CURVES		
-uphill	103	83
-downhill	122	96
NO.CURVES/MILE		
-uphill	17.5	14.1
-downhill	15.8	12.5
ALIGNMENT FACTOR		
-uphill	12	14
-downhill	11	13

Alignment Factor=Average Curve Radius/No. Curves per Mile.
(A factor of less than 20 is considered "poor")
Note: There was very little difference between the "4X" rule and using all curves on this road.

In addition, the following characteristics were also noted:

AVERAGE DISTANCE WTD. GRADE	7.9 percent
AVERAGE WIDTH	14-16 feet

TRAFFIC LEVEL

Approximately 40 loads per day were hauled, beginning at 4 AM and ending at approximately 3 PM.

40*2/11=7.3 trucks/hour empty and loaded.

In addition, approximately 5 non-logtruck vehicles used the road daily.

5/11=.5 vehicles/hour.

Total vehicle per hour=7.8 = 8 vehicles/hour.

TURNOUT SPACING

There were 51 constructed turnouts in 5.89 miles of the 4711 road.

Spacing=(5.89 * 5280)/51 = 610 feet/turnout.

Since other opportunities exist for two trucks to pass, such as in wide curves, etc. , a spacing of 500 feet was used.

From the above traffic level and turnout spacing data, delay times (increased travel times) were calculated using the methods in BNG.

For 500 foot turnout spacing:

5 vehicles/hour = 2.6 percent increase
10 vehicles/hour= 5.4 percent increase

Eight vehicles/hour would then be a 4.2 percent increase in travel time.

Round-trip minutes per mile was then calculated using the methods of BNG. (see Appendix 5)

	GRADE	CURVES
UPHILL(UNLOADED)MIN/MILE	1.60	3.81
DOWNHILL(LOADED)MIN/MILE	2.70	3.66
TOTAL ROUND-TRIP MINUTES/MILE...........		7.47

Increasing the time for the empty trucks by 4.2 percent for delays due to meetings gives:

3.66 * 1.042 = 3.81 minutes per mile
(or 15.75 miles per hour)

Round-trip travel time is the sum of the two slower times; in this case 7.47 minutes per mile as controlled by alignment, not grade.

APPENDIX E.

DESCRIPTION OF SOME ASSUMPTIONS IN "THE LOGGING ROAD HANDBOOK"; BYRNE, NELSON, AND GOOGINS,1957.

A. SPEED IN GRADES.

1. **Favorable:** Speeds on favorable grades are described by the empirical relationship:

$$V(MPH) = 2.4/(.03-Grade)$$

This relationship includes empty trucks as well as loaded so delays to empty trucks are probably included.

2. **Adverse:** Speeds on adverse grades are calculated based on horsepower of the engine, efficiency, grade, rolling resistance, and air resistance. The equation given is:

$$(HP)(E)(550)=(WGV)+(WRV)+(KAV^3)$$

Where: W=vehicle weight.
G=grade
E=engine efficiency
R=rolling resistance
Paved =.013
Gravel =.018
Dirt =.022
K=.00215
$A=69\ ft.^2$
HP=Engine horsepower

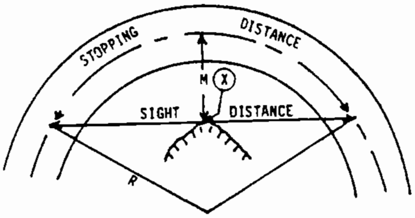
B. SPEED IN CURVES.

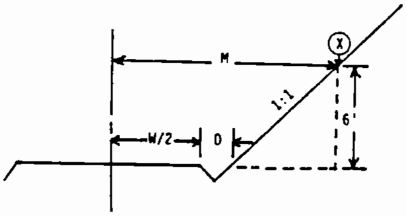
1. Favorable. speeds in curves are controlled by one of two factors; sight distance or available friction. For single lane and lane and one-half roads, sight distance controls. For double laned roads, friction controls.

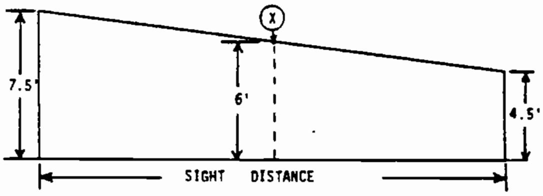
a. **Sight distance.** Sight distance is calculated based on the geometry of several assumed road types. Backslope used for sight distance calculations is 1:1. The three categories of road for which sight distance controls speed are:

i. Single lane, 12 ft. without ditch.
ii. Single lane, 14 ft. with 3 ft. ditch.
iii. Single lane, 20 ft. with 4 ft. ditch.

From these cross-sections, calculations of sight distance for the single lane roads are made according to the section drawings shown below.







Sight distance is calculated from the formula:

Sight Distance=SQRT(8*M*R)

Where: M=middle ordinate.
R=curve radius.

This gives a close approximation to the actual distance along the centerline of the road instead of the chord distance. Errors are very small at the higher curve radii and less than three percent for small curve radii.

Note that sight distance is calculated based on an eye height of 7.5 feet. This is the eye height of a typical log truck. BNG assumes that sight distance on single lane roads will be the distance that permits two log trucks approaching each other to stop without colliding. The height at which M is determined is six feet. This is based on a 4.5 ft. high sighting point on the oncoming vehicle as the point which triggers braking.

Once sight distance has been calculated, the maximum speed from which it is possible to stop in this distance is then obtained from the following equation:

$$2SD=2*\text{Stopping Distance}=8.8*V + V^2/(15*f)$$

Where: V=Speed, mph
f=Coefficient of traction.(0.4 used)

2SD=Stopping distance for two vehicles

This equation includes a 3 second braking plus reaction time. Solving this quadratic equation for V gives:

$$V(MPH) = -8.8+SQRT(8.8^2-4*.167*(-2SD))/.333$$

This equation assumes a coefficient of friction of 0.4 and that both vehicles are traveling at the same speed, and that grade effects will compensate when stopping.

b. Friction limited.

On double lane roads where sight distance is not as important, the limit on safe speed is where side slipping occurs. This limit is expressed by the equation:

$$V(MPH)=SQRT(R*(S+f))/.067$$

Where: R=curve radius
S=superelevation
f=side skid factor (.16 used)

However, since logging roads are usually built with little or no superelevation, the equation simplifies to:

$$V(MPH)=SQRT(1.55*R)$$

This equation was used by BNG for double lane roads.

2. Adverse.

a. Sight distance is calculated the same as for favorable grades.
b. Speeds are calculated the same as for favorable grades. However, speeds for unloaded trucks are decreased by a percent due to the assumed rules of the road which say that emptys will pull over for loaded trucks. No delays due to meetings are assumed to occur to loaded trucks.

Once the equations above have been solved for V, the time required to travel one mile (min/mile) is obtained from:

$$T=(1/V)*60$$

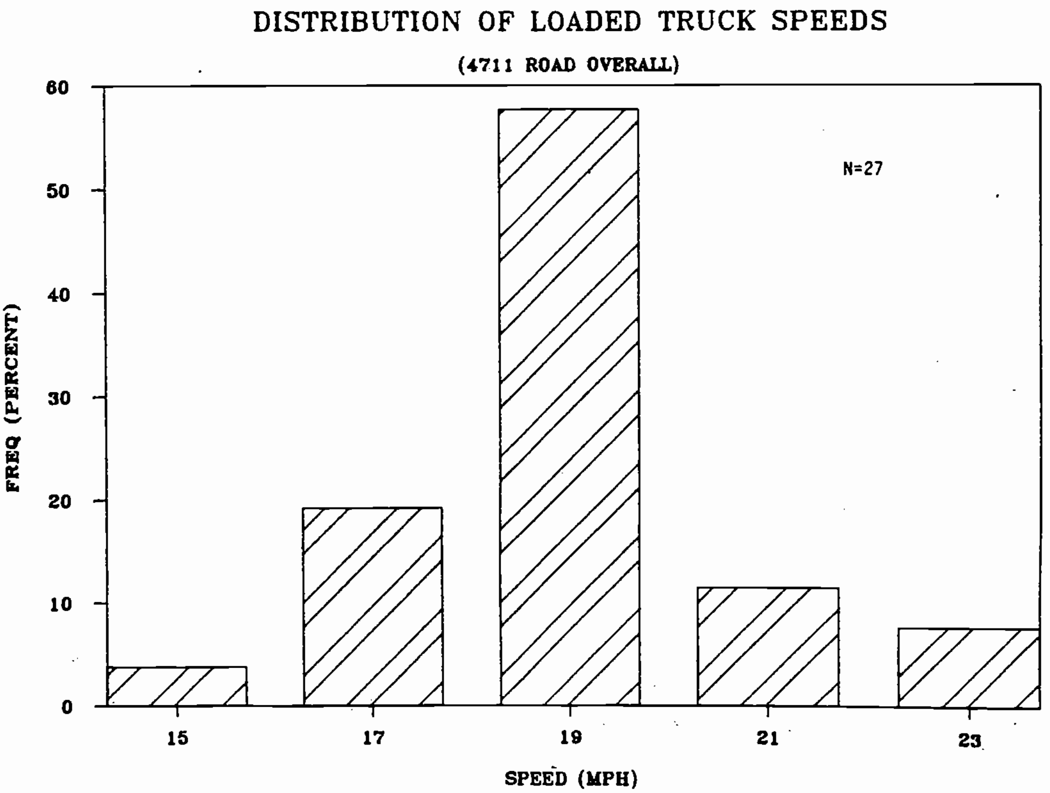
C. USING THE EQUATIONS.

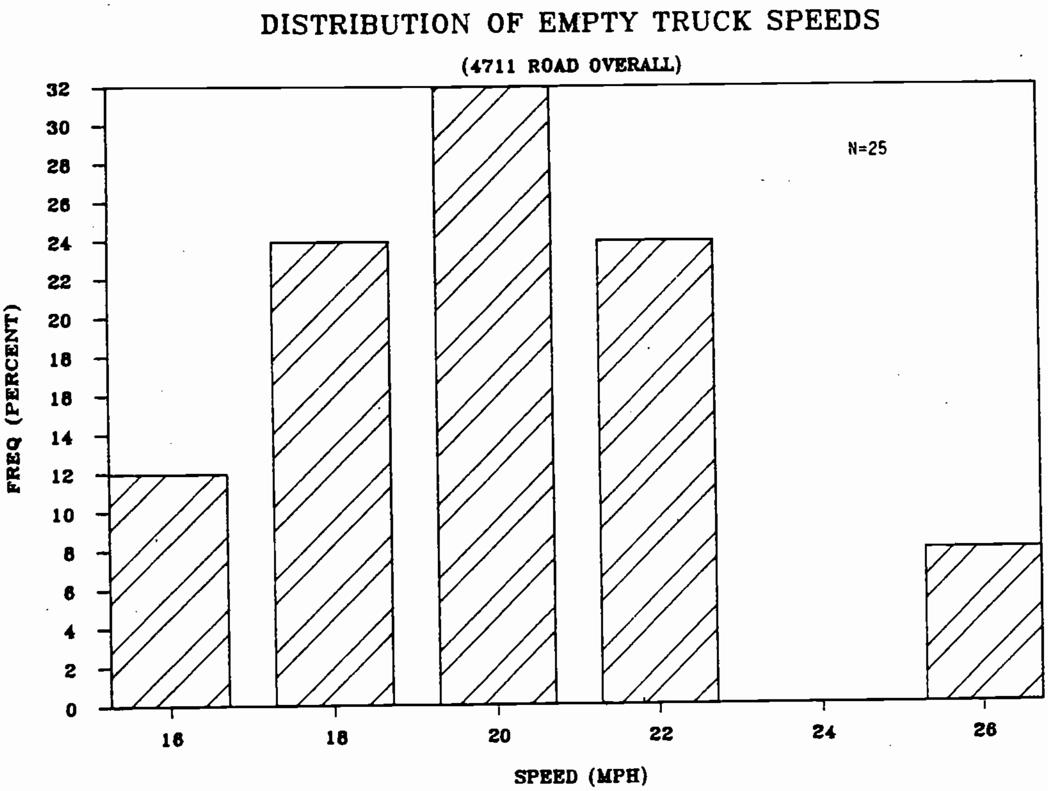
BNG provides tables for round-trip travel times for log trucks on a variety of grades and classes of alignment. These tables contain no delay times. The user adjusts these overall times by a given percent based on the turnout spacing and number of vehicles per hour present on a road. These percent adjustments are from assumptions used by BNG. Using these adjustment factors on the round-trip travel times in BNG will put a delay time on both loaded and unloaded trucks. This appears inconsistent with the rules of the road assumed by BNG which put no delay on the loaded trucks.

The exact method of developing the round-trip travel time tables in BNG is not clear. However, the numbers can be obtained by using the equations for curve and grade limited conditions. A value for curve radius must be assumed to give the curve controlled speed (times) at a reference point of 0 percent grade. The round-trip travel times on various road surfaces can be obtained by substituting the appropriate value of rolling resistance, R, in the equation for grade speed. A "B" value of 5.3 for empty trucks, and 1.9 for loaded loaded trucks was used in the table development.

APPENDIX F.

Distribution of Truck Travel Speeds





APPENDIX G

COST COMPARISON USING OBSERVED DATA AND BNG PREDICTED DATA.

Assume an hourly operating cost of $40.00 per hour for the truck and driver.

$$\frac{\$40}{60\text{ min.}} = \$.667/\text{minute}$$

1. Cost to haul over 4711 road using observed travel times.

Mean Loaded Time......24.53 minutes
Mean Unloaded Time....23.47 minutes
Round Trip Time.......48.00 minutes

Cost Per Trip=$.667*48.00 min. =$32.02/Trip.

Based on District Records, the average load hauled contained 5.043 MBF.

$$\frac{\$32.02}{5.043} = \$6.35/\text{MBF.}$$

2. Cost to haul over 4711 Road using BNG-predicted travel times.

Predicted Loaded Time: 3.66 min.* 7.71 mi.=28.22 minutes.
Predicted Unloaded Time: 3.81 min.* 7.71 mi.=29.38 minutes.
Round Trip Time Predicted....................=57.60 minutes.

Cost Per Trip=$.667/min * 57.60 min.=$38.42

Using Same Average MBF/load:

$$\frac{\$38.42}{5.043} = \$7.62/\text{MBF.}$$

3. Costs For the "Stormy" Timber Sale with 8.2 MMBF Appraised Volume.

A. Predicted Cost = $7.62/MBF * 8200 MBF = $62465.00
B. Observed Cost = $6.35/MBF * 8200 MBF = $52070.00
Difference = $10395.00
or: $1.27/MBF.

APPENDIX H

HP-71 Data Collection Program Listing

```
10 ! PROGRAM NAME 'TRKTIME'
20 DISP "TRUCKTIME PROGRAM"
30 WIDTH 32 @ DELAY .5
40 INTEGER I,R,N
50 DESTROY T$,Q$,E$,R,S$,F$
60 INPUT "NAME OF FILE  ";T$
70 INPUT "HOW MANY SEGMENTS ?";N
80 DIM S(N)
90 INPUT "TRUCK NO.?";Q$
100 INPUT "EMPTY OR LOADED?";E$
110 I=0
120 ASSIGN #1 TO T$
130 S$=TIME$
140 PRINT #1;T$,Q$,E$,S$
150 DISP "READY TO START TIMING"
160 IF E$="L" THEN 190
170 FOR I=1 TO N
180 GOTO 200
190 FOR I=N TO 1 STEP -1
200 IF KEY$="#38" THEN T0=TIME ELSE 200
210 DISP "TIMING SEGMENT";I
220 IF KEY$="#38" THEN T1=TIME-T0 ELSE 220
230 F$=TIME$
240 T0=TIME
250 S(I)=T1
260 IF E$="L" THEN Z=I-1 ELSE Z=I+1
270 DISP "SEGMENT";I;"DONE"
280 INPUT "IS DATA OK???";D$
290 IF D$="+" THEN 300 ELSE 330
300 PRINT #1;I,S(I)
310 DISP "READY FOR SEGMENT";Z
320 GOTO 370
330 PRINT #1;I,99.99
340 DISP "SEGMENT";I;"DELETED"
350 WAIT .2
360 DISP "READY FOR SEGMENT";Z
370 NEXT I
380 F$=TIME$
390 PRINT #1;F$
400 DISP "END OF THIS RUN"
410 ASSIGN #1 TO *
420 DISP "FILE ";T$;"  CLOSED "
430 END
```

APPENDIX I

CB Radio Notes.

It is speculated that the use of Citizens Band (CB) radios in log trucks has influenced the travel times and safety of log truck travel today. Since their introduction in the 1960s, CB radios have been widely accepted. All log trucks in this study used them.

Drivers used the radios to keep track of the location of other trucks. In addition, the radio communications served to alert drivers to the presence of non-logtruck traffic on the road system such as woodcutters, recreational vehicles, or Forest Service personnel. Many of these non-logging related vehicles either did not have radios or did not know the agreed-upon channel assignments of the logging traffic. The uncertainty of the locations of these contributed to an alert attitude by the drivers. As one driver put it "These cars without CB radios are the ones that keep you on your toes..especially the Forest Service ones painted low-visibility green." The importance of visually contrasting colors was mentioned by one older driver who discussed driving before the days of CB radio. He said that before radios, drivers had to constantly look for a telltale trace of dust, a glint of sunlight on chrome, or colors. Also it was important to mentally keep track of where other trucks should be in the cycle between landing and unloading sites. One driver commented that some drivers today rely too much on the radio as their "eyes" and are not paying enough attention to the road as in the past.

Another use of the radios is to communicate with the loader operator to help get the maximum legal load, properly distributed among axles. The driver is able to read scales in the truck and let the loader operator know when he is fully loaded to the proper weight.

All of the radios used were purchased by the drivers themselves. The company provided a commercial radio for the company trucks, but the drivers used the CB's for all normal communications. The company radio was used only for occasional contact with the shop or dispatcher. The CB's also provided a social function. Some drivers used the radio frequently to pass the time of day chatting with other drivers within range. It also is used to obtain help when breakdowns occur.

All the drivers felt that vehicles entering an active logging haul route should have a CB radio. Many felt it was the responsibility of the Forest Service to manage the safe flow of traffic on their roads. Warning signs advising drivers entering the road system that logging traffic was present were in place, but no mention of the CB channel in use was posted.

Some forests and other regions are using designated CB channels for various road systems and provide CB radios for Forest Service vehicles, while others do not. In many areas, drivers post their own signs. These are sometimes in the form of "pie plates" tacked to trees, or painted marks on a rock or the road surface. On the 4711 road, the drivers marked each mile post with flagging and a painted number on a tree or rock to provide a highly visible check point. This action, while apparently necessary from the drivers standpoint, is criticized by some Forest Service officials who do not care for the visual impacts of the markings.

APPENDIX J

SEGMENT DESCRIPTIONS

SEGMENT	WIDTH (FT)	LENGTH (FT)	CURVE RADII	GRADE (%)	SUPER (%)	SIGHT DIST. (UP)	SIGHT DIST. (DN)	DITCH (FT)
1	18	328	300(R)	-4	0	297	238	1.0
2	22	238	88(L)	-7	6	178	101	0
3	17	175	STR.	-7	0	231	222	1.0
4	17	248	STR.	-8	0	500	500	1.0
5	30	111	70(R)	-9	4	106	95	0.5
6	23	223	70(R)	-12	4	133	112	0
7	16	132	STR.	-8	0	250	250	1.0
8	16	165	250(L)	-14	4	141	137	1.0
9	18	105	500(L)	-3	3	314	188	1.0
10	22	280	123(R)	-7	9	109	102	1.0
11	19	248	400(L)	-8	5	199	184	1.0
12	24	189	125(R)	-8	8	115	110	1.0
13	16	150	STR.	-2	0	198	194	1.5
14	19	206	150(R)	-7	8	129	126	0
15	19	111	125(L)	-2	9	162	162	1.5
16	18	251	250(L)	-4	12	158	154	1.5
17	19	222	400(L)	-11	3	224	206	1.0
18	15	206	STR.	-10	0	226	222	1.0
19	21	184	200(R)	-12	8	152	148	2.0
20	19	208	68(L)	-13	9	105	100	0
21	19	184	80(L)	-16	7	180	225	2.0
22	23	97	138(L)	-18	6	400	350	1.0
23	16	100	STR.	-19	0	200	500	2.0