A Computer Model for Developing Road Management Strategies

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The development of road systems in formerly unroaded agricultural areas provides an opportunity to apply road spacing theory. This analysis focuses on minimizing the cost of harvesting and transporting timber. A model is developed to optimize road spacing for three standards of road in regions with flat terrain and a uniform crop distribution. Road construction, harvesting, and haul costs are variables in the model. Optimum, economic road spacings can be determined from the model and used as a guide in developing a harvest plan. The effect of the soil condition and harvesting method on optimum road spacing is demonstrated through examples.

Underdeveloped road systems in forested areas with gentle terrain provide an opportunity to apply road spacing theory (*1*). This theory was first applied to logging operations in 1942 by D. M. Matthews (*2*). Matthews formulated a mathematical model to determine how roads could be spaced to minimize the combined costs of harvesting and transportation.

Harvesting costs relevant to the problem are the costs of skidder operation and maintenance as a function of skid distance. Transport costs include road construction and truck operation and maintenance.

Matthew's theory is discussed on the basis of total relevant cost per unit volume of wood produced. One standard of road is used to analyze the influence of soil condition and skidding equipment on optimum road spacing. An example of an application that uses typical costs from the Great Lake States region (Minnesota, Michigan, Wisconsin, Illinois, Indiana, and Ohio) is shown.

The basic equation is then expanded to include the effect of haul costs and different road standards. The influence of different logging trucks, skidding equipment, and soil condition is analyzed for the expanded model. A microcomputer program of the model is used to examine the effects of soil condition, desired road standard, equipment type, and harvest volume on economic road spacing. This information can then be applied to harvest planning and used to minimize costs.

THE BASIC MODEL

Matthew's model optimizes road spacing by balancing the costs of skidding and road construction (Figure 1). This model is based on the following assumptions:

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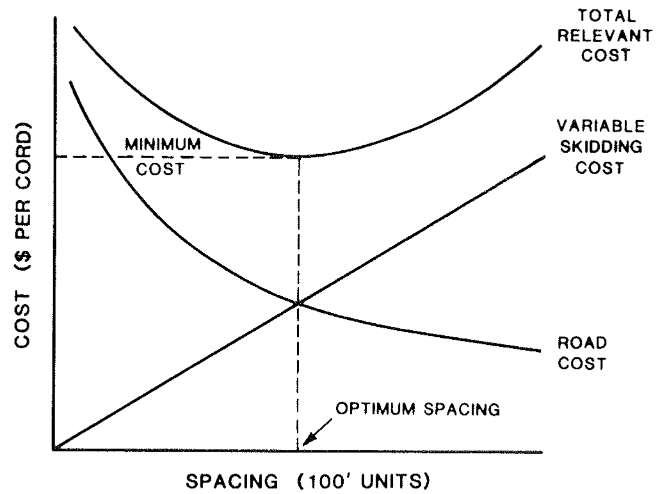

FIGURE 1 Optimizing road spacing by Matthews' approach.

- The harvest area is on flat terrain.
- Logs are skidded to the roadside from both sides of the road, where they are loaded onto logging trucks.
- The timber is distributed uniformly over the harvest area.
- Only one standard of road is used for access.
- Roads are laid out parallel and evenly spaced.

The physical layout of this problem is shown in Figure 2. This application of Matthew's theory compares costs on a unit volume basis. In the development of the basic model, a road cost and skidding cost per unit volume form the total relevant cost equation.

First, the road cost portion of the total relevant cost equation is developed. The following variables are used to develop this part of the optimum road spacing model:

R = road cost per station (station = 100 feet),
S = road spacing in stations, and
V = volume of timber per acre (1 acre = 43,560 ft^2).

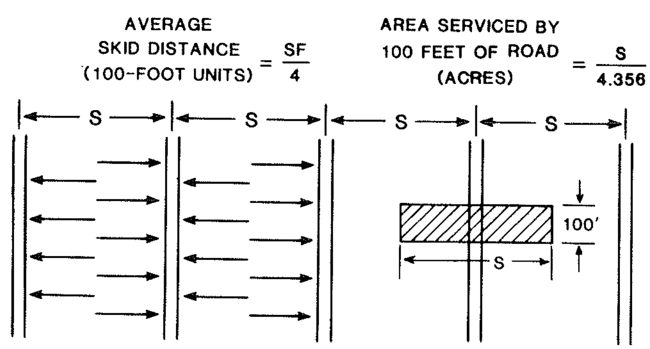

FIGURE 2 Road layout and unit area for the basic model.

Road cost per unit area is used to develop a road cost per unit volume. The theoretical unit area is shown in Figure 2.

Road cost per unit area = $4.356R/S$

The unit area is defined in acres. The factor of 4.356 is derived as follows:

$[R(\$/100 \text{ ft}) \times 1/S(\text{stations})$
$\times 1/100(\text{ft/station})]/43{,}560 \text{ ft}^2/\text{acre}$
$= 43{,}560 \times R \ / \ 10{,}000 \times S \times \$/\text{acre} = 4.356R/S$

Dividing the road cost per unit area by the volume per unit area simply changes the relationship to the following:

Road cost per unit volume = $4.356R/SV$

The skidding cost portion of the total relevant cost equation is then determined. The additional variables required are as follows:

C = machine rate or hourly cost of skidding (\$/scheduled hour);
T = distance-dependent skidding time, which is the inverse of machine speed (min/station);
F = sinuosity factor (proportion of actual skid distance to straight line distance);
U = average load size of skidding equipment (same volume units as V); and
A = actual average skid distance (Figure 2)
= sinuosity $\times$ spacing/4
= $FS/4$

Skidding cost per unit volume
= $[2 \times T$ (min/station) $\times A$ (station) $\times C$ (\$/scheduled hour)(scheduled hour/60 min)]/U (volume units)
= $(2 \times F \times S \times T \times C)/(4 \times U \times 60)$
= $TSFC/120U$

The total relevant cost model is formed by combining the road and skidding costs. The cost relationships are shown in Figure 1.

Total relevant cost per unit volume = $4.356R/SV + TSFC/120U$

The purpose of this analysis is to develop a relationship to calculate the road spacing that results in a minimum cost. Applying the maxima-minima theory of calculus to this equation, the derivative with respect to spacing is set equal to zero:

$d(\text{total cost})/dS = 0$
$-(4.356 \times R)/(S^2 \times V) + (T \times F \times C)/(120 \times U) = 0$

This suggests that the optimum road spacing is as follows:

$S_{\text{opt}} = (522.72RU/TFCV)^{1/2}$

Recent work has been performed on the effect of overhead costs on road spacing. Thompson analyzed this relationship and found that by assuming the harvesting system is in balance (i.e., skidding capabilities do not exceed the felling and limbing capabilities), the system productivity will be the same as the skidding productivity (*3*). Costs independent of production (i.e., overhead costs) will vary with the system productivity and with road spacing (Figure 3). Examples of overhead costs are administration, bookkeeping, supervision, procurement, shop facilities, maintenance equipment, fuel equipment, machine transport equipment, and inventory. Because productivity is directly related to road spacing, overhead is a necessary factor to consider in the model. When overhead costs are added to the model, the equation becomes:

Total cost per unit volume = $4.356R/SV + TSFC/120U + TSFQ/120U$

where

Q = overhead costs (\$-scheduled hour)

Optimum road spacing for the basic model then becomes:

$S_{\text{opt}} = [522.72RU/TFV(C + Q)]^{1/2}$

The variables R, U, T, F, V, C, and Q will be known for a given logging situation. Optimum spacing can be determined by applying the estimated conditions to the model.

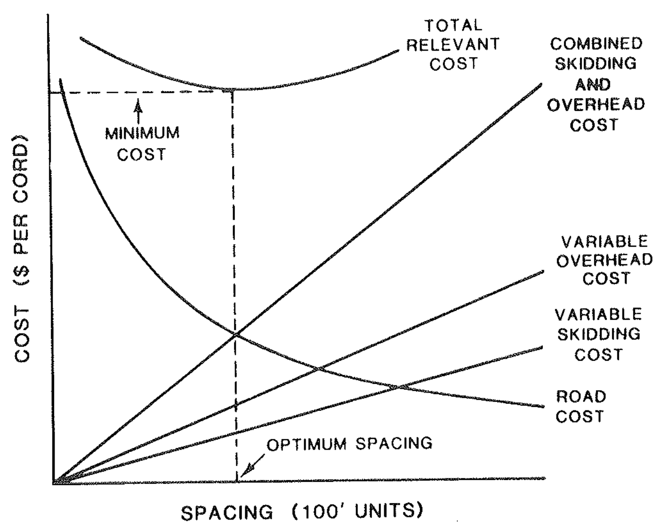

FIGURE 3 **Optimizing road spacing by including overhead costs.**

AN EXAMPLE

This mathematical model was developed for the harvest situation that utilizes one road standard on flat terrain. The application of this model is demonstrated by using three common skidding methods in three typical soil conditions. Data for these examples are taken from road construction and skidding operations in the Lake States region (Figure 4). Each cell contains the spacing versus volume relationship for a particular combination of skidding method and soil condition. These relationships are represented as graphs in Figures 5, 6, and 7. A particular timber volume removed per acre has a corresponding optimum road spacing.

$$\text{Opt. } S = \sqrt{\frac{522.72RU}{TFV(C+Q)}}$$

SKID METHOD \ SOIL TYPE	DRY	WET	ROCKY
80 Hp Cable Skidder	R = \$300/Sta U = 0.5 Mbf T = .35 Min/Sta F = 1.15 C = \$35/SH Q = \$35/SH $S = \sqrt{\frac{2783}{V}}$	R = \$435/Sta U = 0.5 Mbf T = 0.6 Min/Sta F = 1.25 C = 36.75/SH Q = \$35/SH $S = \sqrt{\frac{2113}{V}}$	R = \$400/Sta U = 0.5 Mbf T = .45 Min/Sta F = 1.20 C = \$36.75/SH Q = \$35/SH $S = \sqrt{\frac{2698}{V}}$
60 Hp Forwarder	R = \$300/Sta U = 1.1 Mbf T = 1.0 Min/Sta F = 1.2 C = \$30/SH Q = \$35/SH $S = \sqrt{\frac{2212}{V}}$	R = \$435/Sta U = 1.1 Mbf T = 1.25 Min/Sta F = 1.3 C = \$31.50/SH Q = \$35/SH $S = \sqrt{\frac{2315}{V}}$	R = \$400/Sta U = 1.1 Mbf T = 1.0 Min/Sta F = 1.25 C = 31.50/SH Q = \$35/SH $S = \sqrt{\frac{2767}{V}}$
110 Hp Grapple Skidder	R = \$300/Sta U = 0.95 Mbf T = 0.3 Min/Sta F = 1.10 C = \$50/SH Q = \$50/SH $S = \sqrt{\frac{4514}{V}}$	R = \$435/Sta U = 0.95 Mbf T = 0.55 Min/Sta F = 1.20 C = \$52.50/SH Q = \$50/SH $S = \sqrt{\frac{3193}{V}}$	R = \$400/Sta U = 0.95 Mbf T = 0.4 Min/Sta F = 1.15 C = 52.50/SH Q = \$50/SH $S = \sqrt{\frac{4213}{V}}$

FIGURE 4 Optimum road spacing calculations for three skidding methods in three soil conditions (basic model).

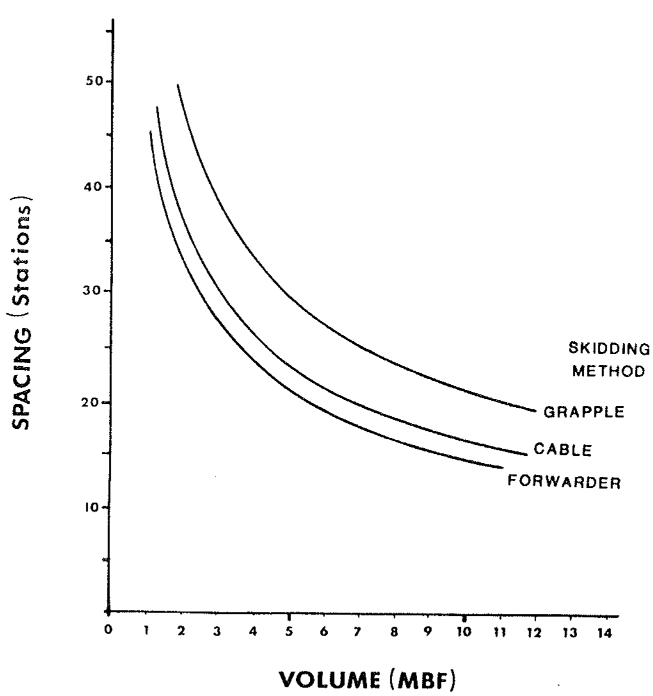

FIGURE 5 Road spacing vs volume for three skidding methods in dry soil (basic model).

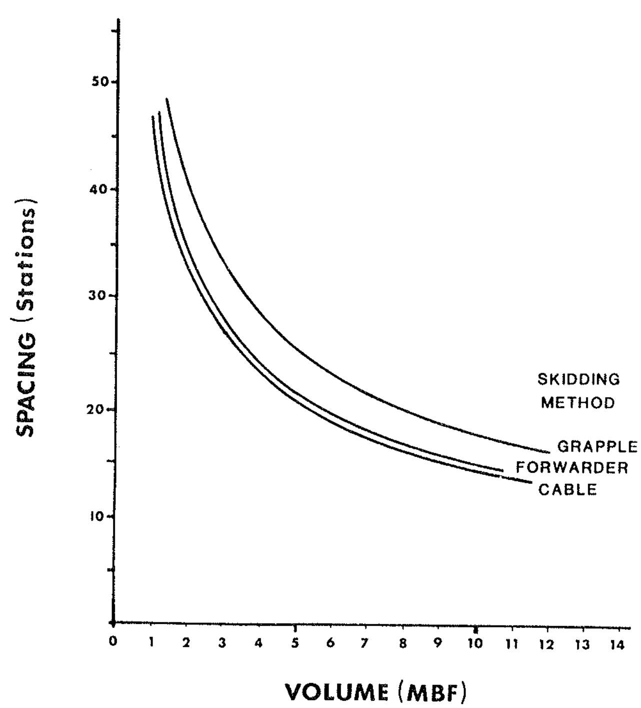

FIGURE 6 Road spacing vs volume for three skidding methods in wet soil (basic model).

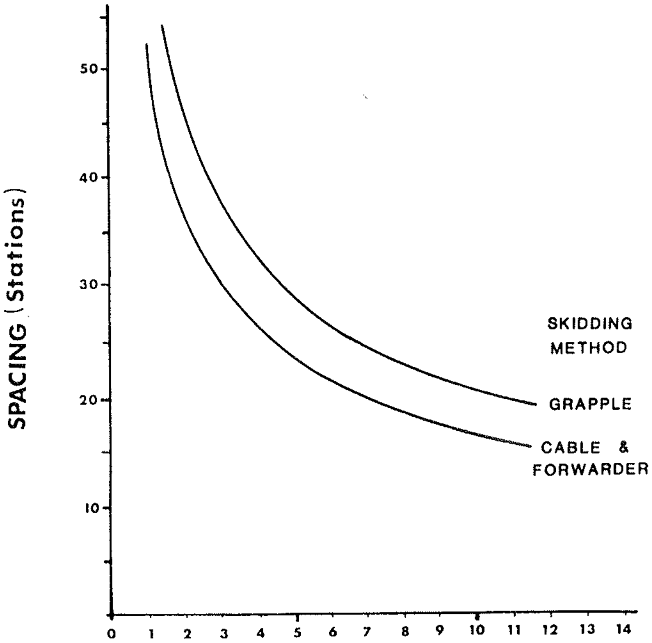

FIGURE 7 Road spacing vs volume for three skidding methods in rocky soil (basic model).

One conclusion that can be drawn from the graphs is that optimum road spacing decreases as timber harvest volume increases for situations in which one road standard on gentle terrain is used. This means that for greater volumes of timber removed, it is more economical to build roads closer together than to skid logs greater distances.

DEVELOPING THE EXPANDED ROAD SPACING MODEL

The basic model was developed for one standard of road situations. The model is based on minimizing the sum of the road construction, skidding, and overhead costs. Two additional road standards and haul costs are included in the expanded road spacing model to make the model more realistic.

A description of a typical forest access system in the Great Lakes States is important to understand the expanded model. Costs considered in this model begin after trees are cut, limbed, and left in tree lengths or sawed into log lengths. Harvesting equipment, such as rubber-tired skidders, forwarders, or crawler tractors, is used to transport logs to the roadside where they are loaded onto logging trucks.

Three standards of roads are used in this expanded model: Class V, Class III, and Class I. These definitions were taken from Table 1 of the *Timber Appraisal Handbook*, which was developed by the U.S. Department of Agriculture, Forest Service (*4*).

Class V roads are built to allow passage of logging trucks. The presence of rocks, roots, and large ruts prevents passage of passenger cars. Forest users, whether commercial, recreational, or administrative, must use light trucks or four-wheel drive vehicles to gain access. Speeds are usually less than 5 mph. Class V roads usually access the timber harvest area from connections to higher standard Class III roads.

Class III roads are more costly than Class V roads. Class III roads follow the natural topography, when possible. They are usually 12-ft-wide, single-lane roads with turn-outs and turn-arounds. Curves are not geometric, but have radii greater than 100 ft. Maximum grades are 15 percent and truck speeds are about 15 mph. Selected aggregates are used to reinforce weak areas of the subgrade. Class III roads are usually passable by passenger cars most of the year. They commonly access timber harvest areas from connections to higher standard Class I roads.

Class I roads, or collector roads, are 18 to 24 ft wide and have minimum curve radii of 400 ft. Grades are less than 8 percent and truck speeds are about 35 mph. Class I roads usually have a crushed gravel surface, and passenger cars can use these roads most of the year. Class I roads are used for recreational and administrative access as well as for timber harvesting access.

The transportation network that provides typical forest access includes all systems used to move the log from the stump to the mill. The log moves from stump to roadside by rubber-tired skidders, forwarders, or crawler tractors. The log then travels from roadside to mill by logging trucks over Class V, Class III, and Class I roads.

An understanding of the transportation route for logs from the stump to the mill aids in an understanding of the development of the expanded road spacing model.

The following assumptions are needed to develop this model:

- The harvest area is on flat terrain.
- The logs are skidded to Class V roads from both sides.
- The timber is distributed evenly over the harvest area.
- Three road standards are used for access (Classes V, III, and I).
- Roads are laid out in a parallel grid pattern and are evenly spaced.

The physical layout of this problem is shown in Figure 8. Following the same logic used in the development of the basic model, Class I and Class III road costs per unit volume are as follows:

Class I road costs per unit volume = $4.356R_1/S_1V$
Class III road costs per unit volume = $4.356R_3/S_3V$

The subscripts identify the class of road being considered.

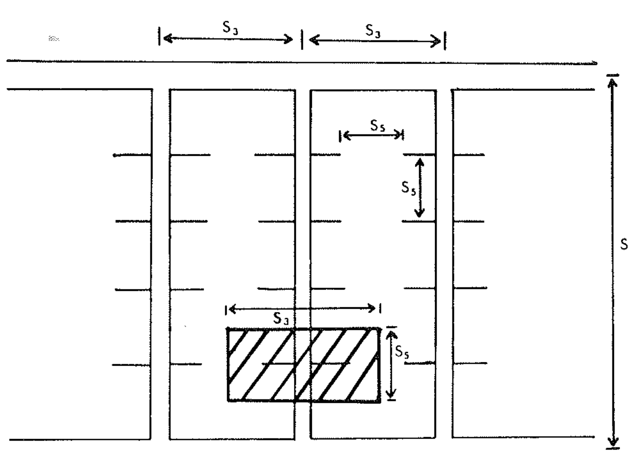

FIGURE 8 Road layout and unit area for the expanded model.

Because the Class V road lengths in the model are not infinite within the unit area, or, in other words, they are dead-ended, the Class V road cost per unit volume relationship will look somewhat different than the relationships developed for Class III and Class I roads.

As in the basic model, a unit area, as shown in Figure 8, results in the following relationship:

Class V road costs per unit volume = $4.356R_5(S_3 - S_5)/S_3S_5V$

Because of the perpendicular relationships between road classes, the cost of hauling along Class V and III roads becomes important in the model. Haul costs are based on distance, travel speed, load size, and truck operation and maintenance. The average haul distance on a Class III road is $S_1/4$, which must be doubled for two-way travel. Therefore, the cost of hauling along Class III roads is as follows:

Haul cost on a Class III road per unit volume
= [2 × (average haul distance (station)) × cost ($-scheduled hour)]/[52.8 (station/mi) × travel speed (mi/scheduled hour) × load size]
= $HS_1/105.6WP_3$

where

H = hourly cost of owning and operating trucks ($/scheduled hour);
P = average travel speed (mi/scheduled hour) (subscript denotes road class); and
W = load capacity of truck in same volume units as V.

Following a similar logic and remembering that Class V roads are not continuous through the unit area defined in the model, it is found that:

Haul cost on a Class V road per unit volume
= $(2 \times ((S_3 - S_5)/4) \times H)/(52.8 \times W \times P_5)$
= $H(S_3 - S_5)/105.6WP_5$

The costs of skidding and overhead are the same as in the basic model: $TS_5F(C + Q)/120U$. At this time all of the road, skid, overhead, and haul cost factors used in the expanded model have been developed and the final total cost equation is as follows:

Total cost per unit volume
$$= 4.356R_1/S_1V + 4.356R_3/S_3V + 4.356R_5(S_3 - S_5)/S_3S_5V + HS_1/105.6WP_3 + H(S_3 - S_5)/(105.6WP_5) + TS_5FC/120U + TS_5FQ/120U$$

The partial derivative of the total cost equation in regard to each road standard defines the spacings that result in minimum cost. This allows the optimum spacing to be determined for each road standard.

$$S_{1opt} = [(4.356R_1/V)/(H/105.6WP_3)]^{1/2}$$
$$S_{3opt} = [(4.356(R_3 - R_5)/V)/(H/105.6WP_5)]^{1/2}$$
$$S_{5opt} = [(4.356R_5/V)/(TF(C + Q)/120U - H/105.6WP_5)]^{1/2}$$

An analysis of the equation for the optimum spacing of Class I roads (S_{1opt}) shows that S_{1opt} is heavily dependent on the cost of hauling along Class III roads and the cost of constructing Class I roads. The optimum spacing occurs at the point where these costs are in balance (Figure 9). The relationship does not contain the factors for skidding and overhead costs, which indicates that the spacing of Class I roads does not depend on these variables.

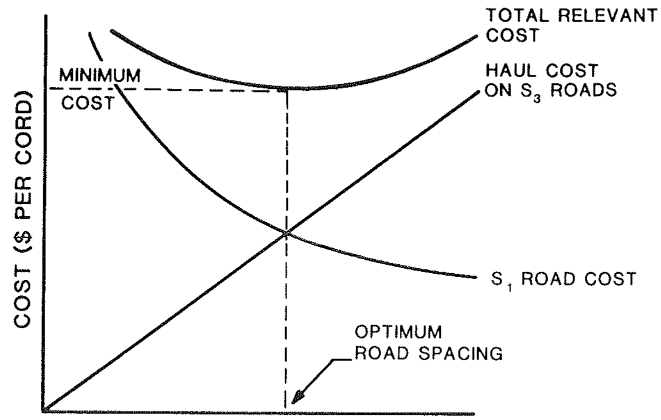

FIGURE 9 Optimizing the spacing of higher standard roads.

Four truck classes and three soil conditions were chosen (Figure 10) to illustrate the effect haul cost has on the relationship for S_{1opt}. The resulting curves (Figures 11, 12, and 13) show how S_{1opt} varies with typical values of these variables. It was assumed that the cost of constructing Class I roads is independent of soil condition.

The equation for the optimum spacing of Class III roads does not contain skidding and overhead costs. This indicates that the spacing of Class III roads does not depend on these variables. Soil condition, however, does affect the spacing of Class III roads, because road construction costs (R_3) are variable costs that depend on soil condition. Typical values are listed for each variable as a function of truck type and soil condition in Figure 14. The type of haul truck used has some effect on the spacing of Class III roads, as shown in Figures 15, 16, and 17. It also appears that slight changes in haul truck speed have a significant effect (4 to 5 stations) on the optimum road spacing.

Finally, an analysis of the equation for optimum spacing of Class V roads (S_{5opt}) shows that optimum spacing depends on the type of haul truck as well as the skidding method. Because skidder operating costs depend on soil condition, the optimum spacing for Class V roads also depends on soil condition.

The effect on Class V road spacing when different kinds of logging trucks are used is shown in Figure 18. This indicates that the haul factor in the optimum road spacing equation for Class V roads (S_{5opt}) is negligible because there is little difference in the value of the optimum spacing between the trucks. This effect can be attributed to the road ends. If Class V roads were extended until they met, the equation for optimum spacing of Class V roads would be exactly the same as for the basic model.

THE COMPUTER PROGRAM

The basic and the expanded optimum spacing models were adapted for use on a microcomputer. The application is menu-

$$\text{Opt. } S_1 = \sqrt{\frac{4.356R_1/V}{H/105.6WP_3}} \qquad R_1 = \$1900/\text{sta}$$

TRUCK \ SOIL	DRY	WET	ROCKY
A Flat bed 4 x 2 Single axle	H = \$30/SH W = 3 MBF P_3 = 14 mph $S_1 = \sqrt{\frac{1,220,000}{V}}$	H = \$30/SH W = 3 MBF P_3 = 17 mph $S_1 = \sqrt{\frac{1,490,000}{V}}$	H = \$30/SH W = 3 MBF P_3 = 16 mph $S_1 = \sqrt{\frac{1,260,000}{V}}$
B Flat bed 6 x 4 Tandem axle	H = \$35/SH W = 4 MBF P_3 = 15 mph $S_1 = \sqrt{\frac{1,500,000}{V}}$	H = \$35/SH W = 4 MBF P_3 = 19 mph $S_1 = \sqrt{\frac{1,900,000}{V}}$	H = \$35/SH W = 4 MBF P_3 = 17 mph $S_1 = \sqrt{\frac{1,700,000}{V}}$
C Truck tractor 4 x 2 Single axle with tandem trailer	H = \$50/SH W = 5 MBF P_3 = 13 mph $S_1 = \sqrt{\frac{1,140,000}{V}}$	H = \$50/SH W = 5 MBF P_3 = 17 mph $S_1 = \sqrt{\frac{1,490,000}{V}}$	H = \$50/SH W = 5 MBF P_3 = 15 mph $S_1 = \sqrt{\frac{1,310,000}{V}}$
D Truck tractor 6 x 4 Tandem axle with tandem trailer	H = \$55/SH W = 6 MBF P_3 = 14 mph $S_1 = \sqrt{\frac{1,300,000}{V}}$	H = \$55/SH W = 6 MBF P_3 = 18 mph $S_1 = \sqrt{\frac{1,700,000}{V}}$	H = \$55/SH W = 6 MBF P_3 = 16 mph $S_1 = \sqrt{\frac{1,530,000}{V}}$

FIGURE 10 Optimum Class I road spacing calculations for four truck types in three soil conditions (expanded model).

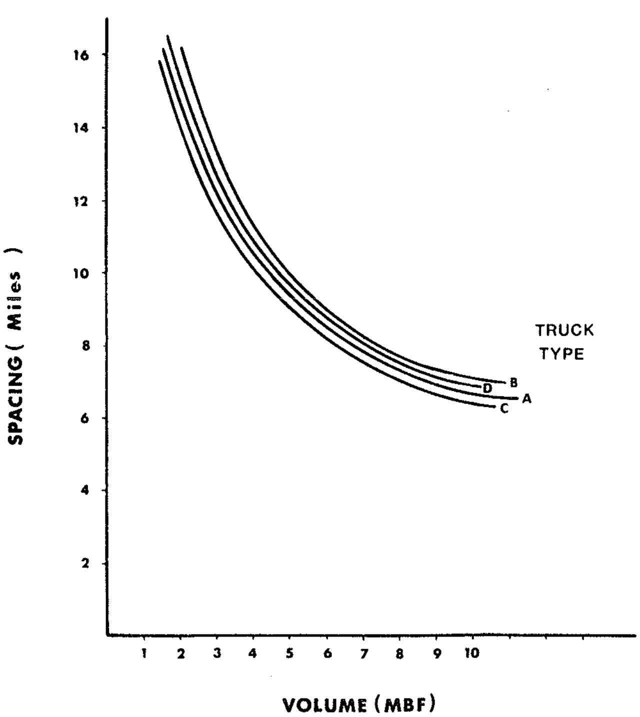

FIGURE 11 Class I road spacing vs volume for four truck types in dry soil (expanded model).

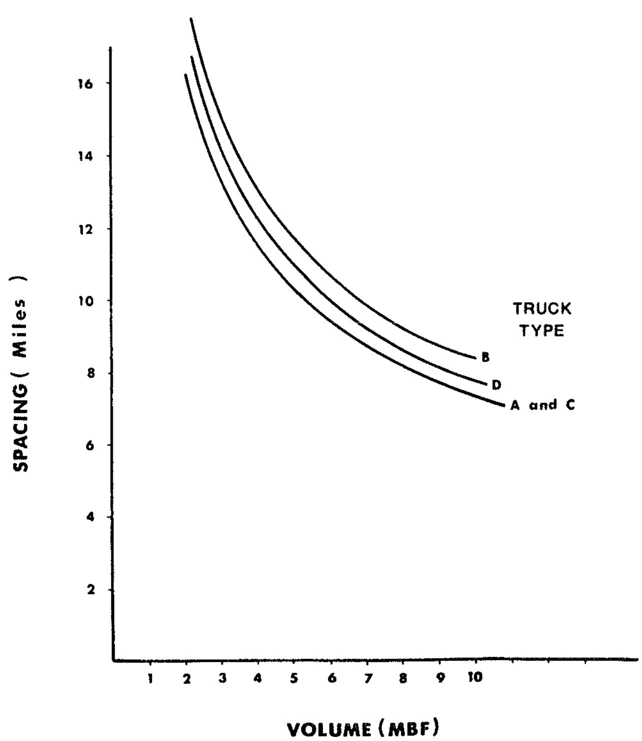

FIGURE 12 Class I road spacing vs volume for four truck types in wet soil (expanded model).

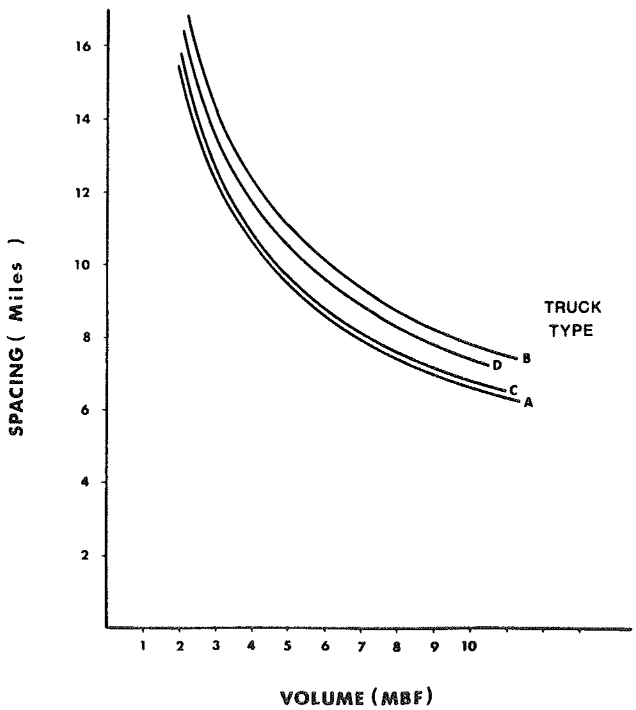

FIGURE 13 Class I road spacing vs volume for four truck types in rocky soil (expanded model).

driven and interactive; descriptive prompts are provided for all data elements. Optimum road spacing can be computed and displayed for single or ranges of volume estimates. Users can vary any of the dependent factors and instantly see the effects on optimum road spacing.

The software for the model is a LOTUS 1-2-3 template (*5*). Any microcomputer capable of running LOTUS 1-2-3 can use this program. Knowledge of spreadsheet operation is not necessary, although spreadsheet experience would aid in further exploration of the model.

DISCUSSION OF THE MODEL

The expanded optimum road spacing model developed here provides a foundation for further theoretical development. Potential application exists for any harvesting situation on gentle terrain that requires road access to gather a uniformly distributed commodity and haul it to a final destination. Further development of the model could make it applicable to situations other than timber harvest.

Many opportunities exist to expand on this model. Overhead costs are incorporated into this work. They are just one of the many possible factors and costs that could be used to expand the model and make it more relevant to individual situations.

$$\text{Opt. } S_3 = \sqrt{\frac{4.356(R_3-R_5)/V}{H/105.6WP_5}} \qquad R_5 = \$125/\text{sta}$$

TRUCK \ SOIL	DRY	WET	ROCKY
A FLAT BED 4 X 2 SINGLE AXLE	R_3 = \$300/Sta H = \$30/SH W = 3 Mbf P_5 = 4.5 mph $S_3 = \sqrt{\frac{36225}{V}}$	R_3 = \$435/Sta H = \$30/SH W = 3 Mbf P_5 = 2.5 mph $S_3 = \sqrt{\frac{35650}{V}}$	R_3 = \$400/Sta H = \$30/SH W = 3 Mbf P_5 = 3.5 mph $S_3 = \sqrt{\frac{44275}{V}}$
B FLAT BED 6 X 4 TANDEM AXLE	R_3 = \$300/Sta H = \$35/SH W = 4 Mbf P_5 = 5.0 mph $S_3 = \sqrt{\frac{46000}{V}}$	R_3 = \$435/Sta H = \$35/SH W = 4 Mbf P_5 = 3.0 mph $S_3 = \sqrt{\frac{48890}{V}}$	R_3 = \$400/Sta H = \$35/SH W = 4 Mbf P_5 = 4.0 mph $S_3 = \sqrt{\frac{57830}{V}}$
C TRUCK TRACTOR 4 X 2 SINGLE AXLE WITH TANDEM TRAILER	R_3 = \$300/Sta H = \$50/SH W = 5 Mbf P_5 = 4.0 mph $S_3 = \sqrt{\frac{32200}{V}}$	R_3 = \$435/Sta H = \$50/SH W = 5 Mbf P_5 = 2.0 mph $S_3 = \sqrt{\frac{28520}{V}}$	R_3 = \$400/Sta H = \$50/SH W = 5 Mbf P_5 = 3.0 mph $S_3 = \sqrt{\frac{37950}{V}}$
D TRUCK TRACTOR 6 X 4 TANDEM AXLE with TANDEM TRAILER	R_3 = \$300/Sta H = \$55/SH W = 6 Mbf P_5 = 4.5 mph $S_3 = \sqrt{\frac{39520}{V}}$	R_3 = \$435/Sta H = \$55/SH W = 6 Mbf P_5 = 2.5 mph $S_3 = \sqrt{\frac{38890}{V}}$	R_3 = \$400/Sta H = \$55/SH W = 6 Mbf P_5 = 3.5 mph $S_3 = \sqrt{\frac{48300}{V}}$

FIGURE 14 Optimum Class III road spacing calculations for four truck types in three soil conditions (expanded model).

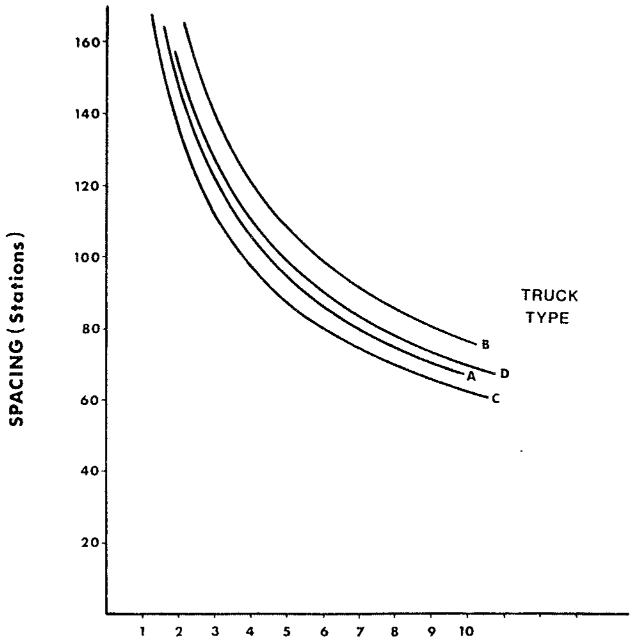

FIGURE 15 Class III road spacing vs volume for four truck types in dry soil (expanded model).

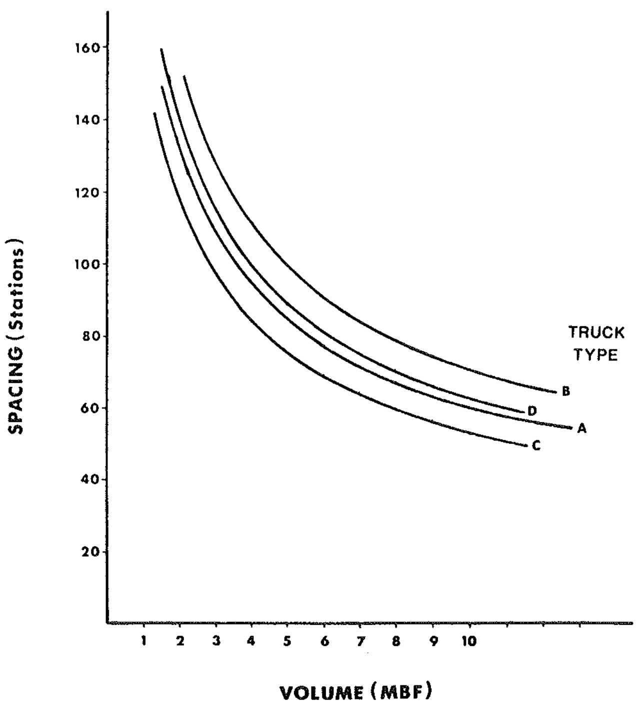

FIGURE 16 Class III road spacing vs volume for four truck types in wet soil (expanded model).

As was stated in the assumptions, the model assumes that all skidding will be to Class V roads regardless of the proximity of the Class III roads to the harvest area. Class III roads are spaced rather far apart: therefore, this assumption will not significantly influence the results.

In addition, the assumed average skid distance is actually somewhat higher than $S_5/4$ because of the influence of the road

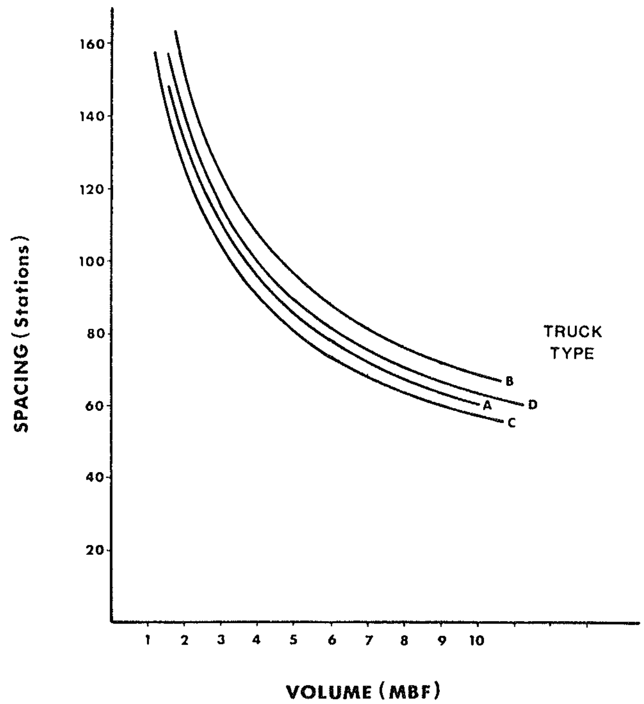

FIGURE 17 Class III road spacing vs volume for four truck types in rocky soil (expanded model).

end on average skid distance. This effect is included in the factor for sinuosity.

Some problems exist with the model. Assumptions that were made to facilitate development of the model could make its application unrealistic in some situations. Users are reminded that the model serves as a guide in the development of a harvest plan and provides information that can greatly minimize the total costs of the harvest and hauling operation. The model, however, cannot be substituted for subjective decisions regarding environmental, political, and social effects.

One might infer from some of the figures that the skidding or haul method that shows the closest spacing would have the least-cost method of skidding or hauling. This is not necessarily the case. These curves define a minimum-cost situation that relates only to road spacing. They cannot be used to make cost comparisons relative to any other factors. The user should be aware that optimum spacing does not mean optimum costs relative to each individual factor, but only relative to spacing.

A brief analysis of converting the model's optimum road spacing for an area to road density indicated that caution is required to use the model in this manner. The road density approach does not assure an even road spacing, as assumed in the model. Uneven road spacings cause the average skid distance to vary. The calculated optimum road spacing will not be accurate if the average skid distance is not accurate. Therefore, it is not recommended that the results from the road spacing model be converted to road densities.

SUMMARY

A basic model for road spacing was developed from Matthew's theory of balancing road and skidding costs to minimize the sum of these costs. Examples in which the basic model was used

$$\text{Opt. } S_5 = \sqrt{\frac{4.356R_5/V}{\frac{TF(C+Q)}{120\ U} - \frac{H}{105.6WP_5}}}$$

	A	B	C	D
Haul truck	Flat bed 4 x 2 Single axle	Flat bed 6 x 4 Tandem axle	Truck tractor 4 x 2 Single axle with tandem trailer	Truck tractor 6 x 4 Tandem axle with tandem trailer
	H = \$30/SH W = 3 MBF P_5 = 4.5 mph	H = \$35/SH W = 4 MBF P_5 = 5 mph	H = \$50/SH W = 5 MBF P_5 = 4 mph	H = \$55/SH W = 6 MBF P_5 = 4.5 mph
Optimum S_5	14.2 Stations	14.1 Stations	14.3 Stations	14.2 Stations

R_5 = \$125/sta
U = 0.95 MBF
V = 10 MBF/acre

C = \$50/SH
Q = \$50/SH
T = 0.3 min/sta
F = 1.10

FIGURE 18 Comparison of optimum Class V road spacing for four truck types (grapple skidder in dry soil).

were analyzed and it was concluded that road spacing is affected by soil condition, equipment operation and maintenance, and timber volumes. This model can be effective in determining an optimum balance between road spacing and skidding.

The basic model was expanded to make it more relevant and applicable to more situations. Haul costs and two additional road standards were incorporated into the model. Analysis of the expanded model showed that total relevant cost was most sensitive to the spacing of the lowest standard of road.

In summary, the spacing of low-volume, low-standard roads can greatly affect the layout and the total cost of a harvesting operation. The application of the model to a microcomputer provides an easy method to analyze the effects of the variable factors. This information may help to minimize the combined costs of harvesting and road building.

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