

Minimizing Road Construction plus Forwarding Costs under a Maximum Soil Disturbance Constraint

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ABSTRACT: A model is developed to minimize the sum of road construction plus forwarding costs with the constraint that rut depth caused by the forwarder cannot exceed a maximum depth during the anticipated season of operation. Road spacing, forwarder trail spacing, and forwarder capacity are used as decision variables in developing the transportation plan. The total cost was minimized using the optimum road spacing approach. The model identifies whether the cumulative rut depth caused by the forwarder exceeds the maximum allowable rut depth at the point of or prior to the spacing that minimizes the cost, and if so, the rut depth limits the road spacing. If the road spacing at the point of minimum cost is less than the road spacing at the maximum allowable rut depth, road spacing is not constrained by rut depth. This model allows planners to examine the tradeoffs between forwarder parameters, trail spacing, and trail length. The solution procedure of the model is described and a computer program is used to apply this model using a numerical example.

Keywords: logging cost, environmental impact, soil strength, vehicle mobility, rut depth

INTRODUCTION

Mechanized logging provides a safer work environment, higher quality and more consistent end products, and smaller crew sizes than conventional logging methods (Kellogg and Bettinger 1994). Ground-based cut-to-length systems teaming a harvester with a forwarder are increasingly used for thinning in the Pacific Northwest. According to a study in which logging planning and layout costs for alternative thinning systems were examined, a combination of single-grip harvester and forwarder provided the wood at the lowest cost, followed by the tractor systems, and the skyline systems (Kellogg et al. 1998). For longer traveling distances, larger payloads with a forwarder reduce the number of trips required and produce wood at a lower cost compared to skidders (Greene et al. 1987). The reduction in trips causes more soil compaction in each trip of a forwarder than a skidder due to increase in payload per trip. Wronski et al. (1994) indicated the impact on soils of mechanized ground-based logging systems was dominated by the impact of the forwarder as compared to the processor/harvester. During periods when soils are wet and of low bearing capacity, the total rut depth caused by a forwarder may lead to other problems including excessive machine downtime, relocation of operations, extra cost of increased stockpiling of timber, and reduction in wood quality in the stockpiles (Wronski et al. 1990). In order to retain the economic advantages of forwarder operations while overcoming the problems associated with soil disturbance, a transportation plan of roads and forwarder trails might be efficiently designed within the constraints of acceptable soil disturbance given anticipated soil conditions.

The rut depth caused after a number of passes is a convenient indicator of the impact of a machine on soils (Wronski et al. 1994). This paper describes a model developed to minimize the sum of road construction plus forwarding costs with the constraint that rut depth caused by the forwarder cannot exceed a maximum depth under the anticipated season of operation. This model allows a user to examine alternative transportation plans consisting of roads and forwarder trails, and choose an optimal combination of machines based on the decision variables of road spacing, forwarder trail spacing, and forwarder capacity.

SOIL TRAFFICABILITY

In order to predict the performance of a vehicle in relation to the change in soil strength during forestry applications, a number of empirical approaches have been developed (Baladi 1987). A technique developed by the US Army Corps of Engineers using a cone penetrometer has provided the greatest applicability to general trafficability assessment, while other approaches have been proven to be too complex for field use (Wronski et al. 1990). Numerous experimental observations have been made to develop a function of wheel sinkage that incorporates cone index, the tire load, and tire dimensions. A formulation (Eqn.1) has been developed based on wheel sinkage, which is expressed in dimensionless terms by the ratio of rut depth to wheel diameter (Wronski et al. 1994). Previous studies conducted by Knight et al. (1962) and Turnage et al. (1972) suggested a similar functional form:

$$z/d = 0.461 \times n^{0.5} (CI/NGP)^{-2.6} \quad (1)$$

where z = rut depth (mm)
 n = number of passes of a single loaded wheel
 CI = cone index of the soil (kPa)
 NGP = nominal ground pressure (kPa) of the tire

$$NGP = 2000 \times W/b \times d \quad (2)$$

where W = dynamic wheel load (Newton)
 b = tire width (mm)
 d = **tire diameter (mm)**

Wronski et al. (1994) observed that logging slash laid on trails reduce the rut depth and increase the soil strength (Figure 1). They proposed $F = 1/(0.0033 \times S_D + 0.93)$ where F_s is the slash adjustment factor reflecting a reduction of NGP due to slash bed, so, NGP after each pass becomes $NGP' = F_s \times NGP$ where S_D (m^3/ha) is the slash density:

$$S_D = \frac{p \times T \times L}{w} \quad (3)$$

where p = slash as percent of extracted timber
 T = timber extracted from the unit area (m^3/ha)
 L = forwarder trail spacing (m)
 w = **width of the forwarder trail (m)**

According to Wronski et al. (1990), if the slash density is less than $100 m^3/ha$ on the forwarder trail, the slash bed can be broken after a few passes of the forwarder. In their study conditions, maximum depth of rut caused by the harvesting machines was 150 mm, slash was 40% of the weight of the timber extracted, the slash density on a 3 m wide forwarder trail was

approximately 180 m³/ha and 135 m³/ha for first and second thinning, and the slash adjustment factors were 0.66 and 0.73, respectively.

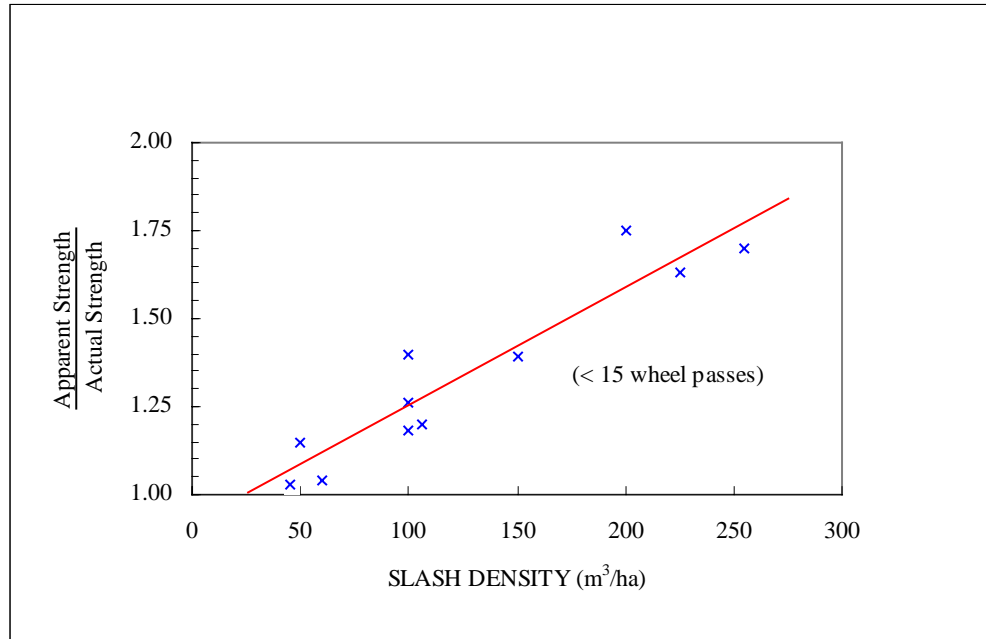


Figure 1. The apparent increase in soil strength with increasing slash density on the trail (Wronski et al. 1990).

MODEL FORMULATION

A mathematical model was developed to minimize the sum of road construction plus forwarding costs with the constraint of maximum allowable rut depth. It is assumed that the harvest area is flat, two-way forwarding is possible (Figure 2), the timber is evenly distributed over the harvest area, forwarding trails are straight and evenly spaced, roads are parallel and evenly spaced, and forwarders have four wheels. The point of minimum road costs plus forwarding costs occurs where the slope of the forwarding cost is equal and opposite to the slope of the road cost. Since loading and unloading costs per unit volume are not a function of the road spacing, they are computed separately and then added into the total cost. With respect to a maximum rut depth, two cases can occur. The cumulative rut depth (z) caused by the forwarders exceeds the maximum allowable rut depth (Z_{max}) at the point of or prior to spacing that minimizes road plus forwarding cost, and if so, the rut depth limits the road spacing (Figure 3). If the optimum road spacing at the point of minimum cost is less than the road spacing at Z_{max} (S_z), road spacing is not limited by rut depth. The model also searches for the best trail spacing that provides wood at the lowest cost assuming felling and processing costs are not affected by trail spacing. The logic diagram for the model is shown in Figure 4. The objective function used:

$$\text{Min Total Cost (TC)} = \text{Road Cost (RC)} + \text{Forwarding Cost (FC)}$$

$$TC (\$) = (R \times L) + (P \times MR)$$

The total cost (C) per unit volume can be computed as:

$$\frac{TC}{10^{-5} \times S \times L \times V} = \frac{(R \times L) + (P \times MR)}{10^{-5} \times S \times L \times V}$$

$$C = \frac{10000}{S \times V} \left(R + \frac{P \times MR}{L} \right) \quad (4)$$

where R = road construction cost (\$/m)
 P = total outhaul and inhaul time (hr)
 MR = machine rate of forwarding (\$/hr)
 S = road spacing (m)
 L = trail spacing (m)
 V = timber volume harvested per unit area (m³/ha)

Road cost for uniform terrain with gentle slope can be estimated based on previous studies. Loading, unloading, and repositioning are considered as “Constant Activities”, while traveling inhaul and outhaul are considered as “Variable Activities” in the forwarding operation. The machine rate for constant activities is calculated separately from the machine rate for variable activities. Cycle time for the constant activities is:

$$C = \left(\frac{0.5 \times Load}{0.45 \times LC} + \frac{0.5 \times Load}{0.75 \times LC} \right) \times (1 + D_C) \quad (5)$$

where $Load$ is forwarder payload capacity in m³, LC is the average load capacity of the grapple in m³, 0.5 is the average grapple cycle time in min, 0.45 and 0.75 are the grapple efficiencies for loading and unloading, respectively. Delay time (D_C) for the constant factors is 25% of the total cycle time. Cycle time for the variable activities is:

$$V = \left(\frac{Forwarding_Distance_Outhaul}{Unloaded_Speed} + \frac{Forwarding_Distance_Inhaul}{Loaded_Speed} \right) \times (1 + D_V) \quad (6)$$

where delay time (D_V) for the variable activities is estimated as 50% of the total outhaul and inhaul time. The speed of forwarders can be computed based on dynamic wheel load, flywheel power, gross thrust, and rolling resistance. The dynamic wheel load is computed based on total weight and forwarder dimensions. Eqn.7 (Ashmore et al. 1985) was used to calculate the tractive force.

$$F = W(0.47(1 - e^{-0.2C_n \times s}) + 0.28(W/WR)) \quad (7)$$

where F = gross thrust (Newton)
 W = dynamic wheel load normal to soil surface (Newton)
 C_n = wheel numeric (Wisner and Luth 1972):

$$C_n = C \times b \times d / 1000 \times W \quad (8)$$

s = tire slip (decimal)
 WR = rated load (Newton) for tire (Ashmore et al. 1985):

$$WR = 26.82 \times K \times IP^{0.585} \times b^{1.39} \times (d + b) \times 10^{-5} \quad (9)$$

where K = load factor ($K=0.75$)
 IP = inflation pressure (kPa)

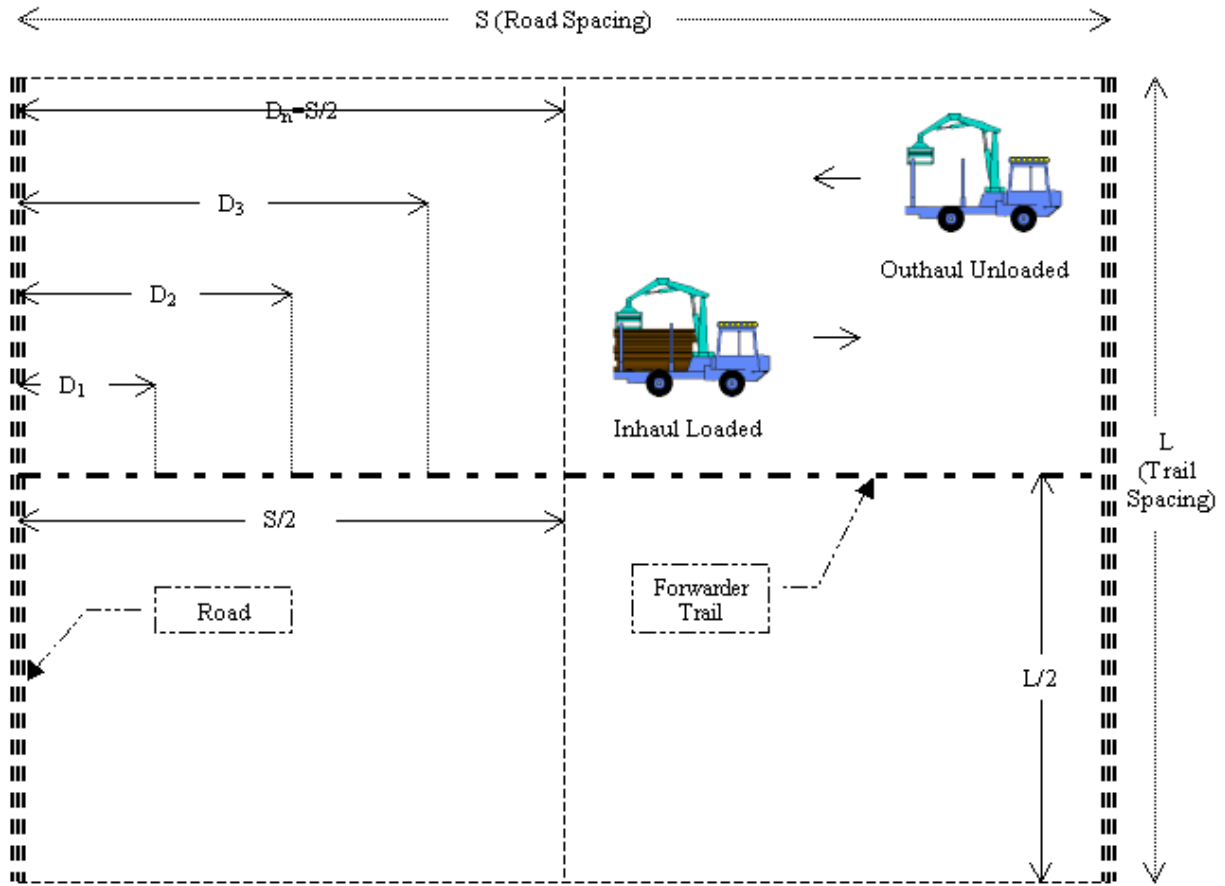


Figure 2. Two-way Forwarding Operation Layout.

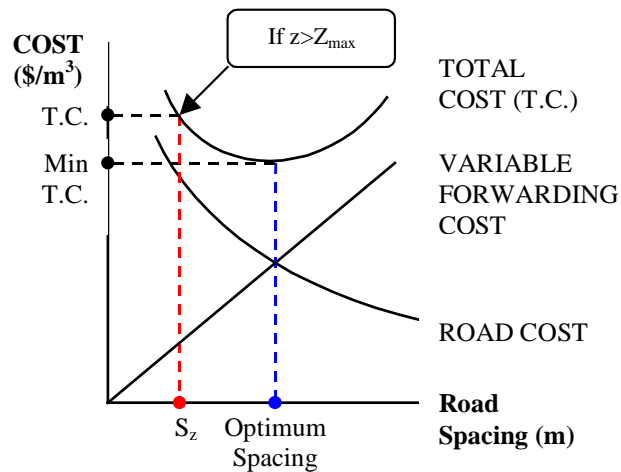


Figure 3. Physical framework of the road spacing (S_z = road spacing where Z_{max} is limiting).

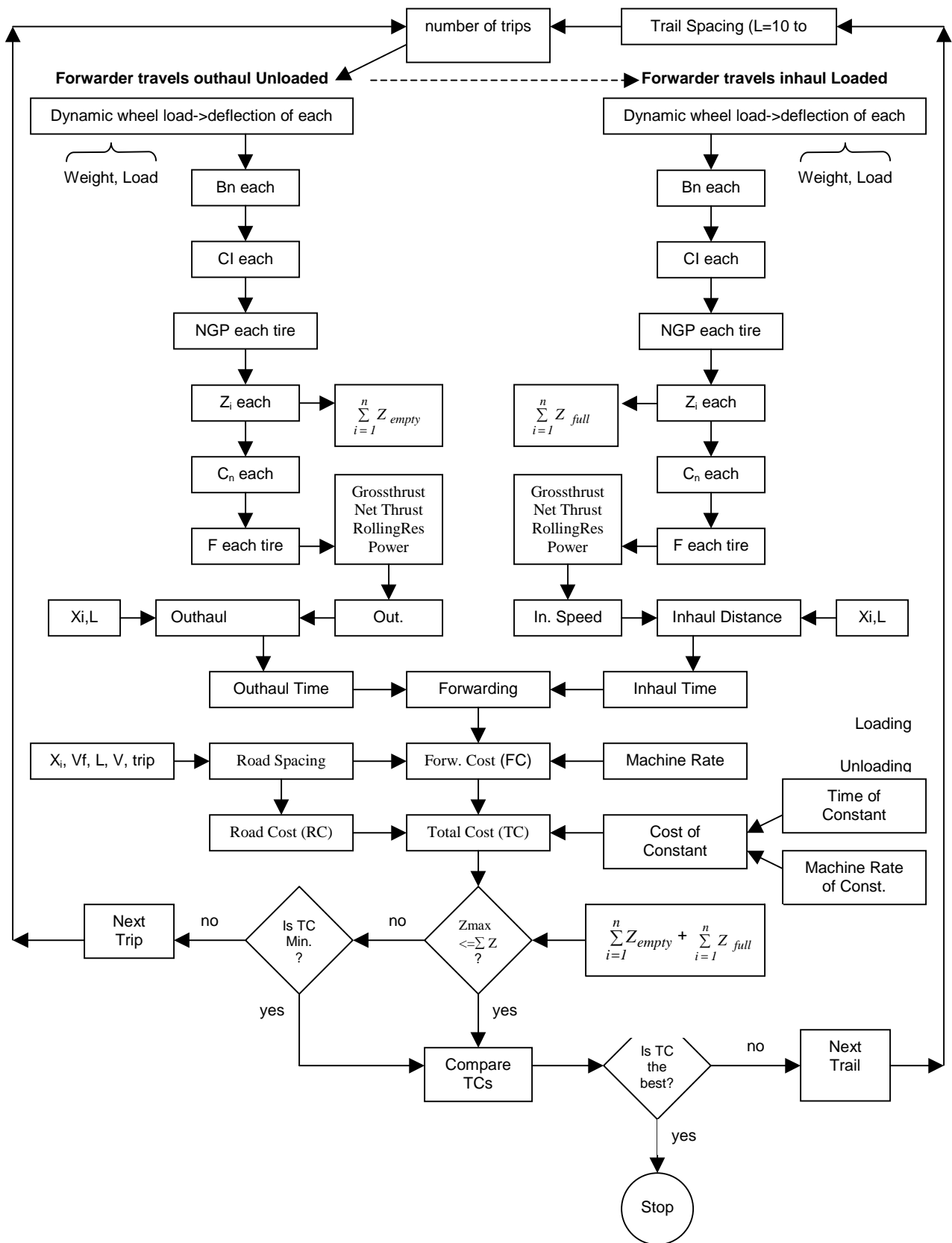


Figure 4. Logic diagram of the model.

The rolling resistance of the tire (Ashmore et al. 1985) is computed as: $RR=W((0.22/C_n)+0.20-0.10(W/WR))$. Next, the vehicle speed is calculated by $V_v=60000 \times Pwr/RR$ where V_v (m/min) is limited by the rolling resistance, net flywheel power (Pwr in kW), the maximum speed of the running gear, and terrain conditions. We assumed that trail conditions limit the maximum vehicle speed to 330 m/min (20 km/hr). To find the ground speed of the vehicle, V_v must be adjusted by the tire slip (s) that produces sufficient net thrust to overcome the sum of the resistances.

In the two-way forwarding system (Figure 2), forwarding distance inhaul is equal to forwarding distance outhaul in each trip. Forwarding distances for traveling outhaul are $D_1, D_2=2 \times D_1, D_3=3 \times D_1, \dots, D_n=n \times D_1$ where n is the maximum number of trips. D_1 , the distance that can provide the forwarder with its load capacity in the first trip, is $D_1 = 10000 \times V_f / L \times V$ where V_f (m^3) is the load capacity of the forwarder. Road spacing is computed as $S = 2 \times D_n$. The maximum number of trips is limited by rut depth or the minimum cost, whichever yields the smallest road spacing.

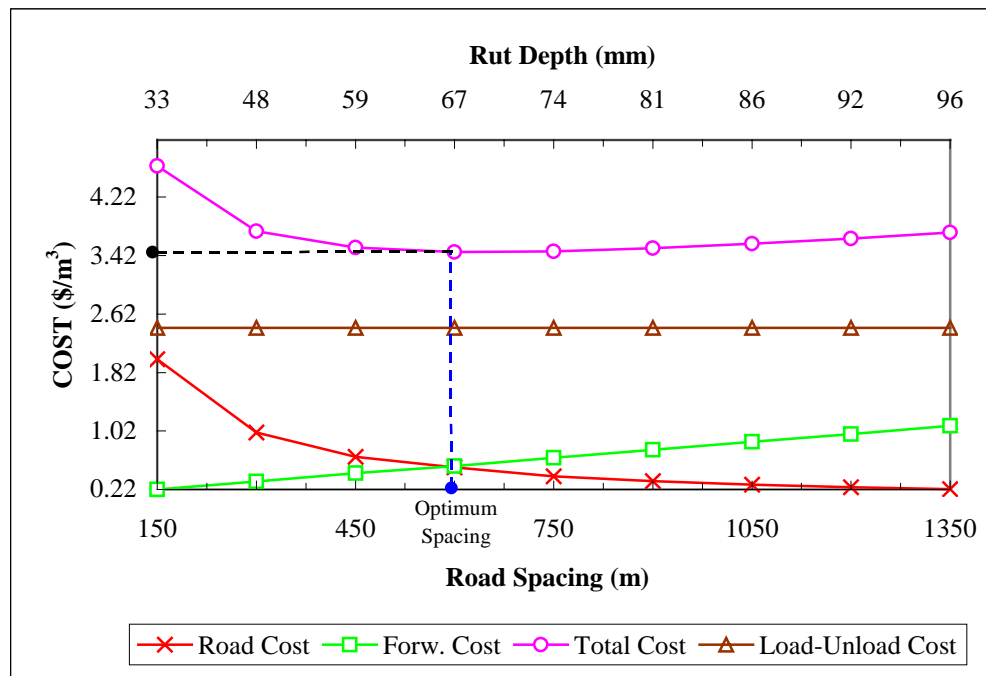


Figure 5. The total cost summary and road spacing for large forwarder.

Eqn.1 can be used to determine the cumulative effect of multiple passes by a single wheel. Since multiple wheel passes of different ground pressure affect the cumulative rut depth and the soil strength, the cone index after passage of each tire should be updated. Brixius (1988) developed Eqn.10 to relate the ratio between cone index after pass (ACI) and cone index before pass (BCI) as a function of the before-traffic cone index and mobility number (B_n).

$$\frac{ACI}{BCI} = 1.0 + (1.8 \times \exp(-0.11 \times B_n)) \quad (10)$$

This equation is applicable to compactable soil conditions where soil strength increases with traffic. It cannot be used for non-compacted soils where soil strength may decrease due to an

excessive amount of water in the wheel sinkage area. The mobility number (Eqn.11) is used to predict the combined effect of the soil-wheel parameters:

$$B_n = \frac{CI \times b \times d}{1000 \times W} \left(\frac{1 + (5 \times \delta / h)}{1 + (3 \times b / d)} \right) \quad (11)$$

where δ is tire deflection (mm) and h is tire section height (mm). The load deflection relationship for the tires was obtained from Koger et al. (1985). The tire section height, proposed by Brixius (1988), was $h = (d - (1.06 \times NRD)) / 2$ where NRD is nominal rim diameter. Since Eqn.10 was derived based on bare soil, the CI should be adjusted for the resulting effective soil strength due to slash laid on the soil. The approach used here is to adjust Eqn.11 using the slash adjustment factor. The modified version of Eqn.11 considering slash on the trail is:

$$B_n = \frac{CI \times b \times d}{1000 \times F_s \times W} \left(\frac{1 + (5 \times \delta / h)}{1 + (3 \times b / d)} \right) \quad (12)$$

During operations, a forwarder travels on a trail empty until there is sufficient timber on the ground to provide the forwarder with its maximum load capacity. The forwarder operator reverses seat direction and travels towards the landing after loading logs. It is assumed that logs are collected and bunched at the point where the forwarder starts inhaul. On outhaul, the rear tire of the empty forwarder contacts with the ground first, followed by the front tire. After the forwarder starts moving inhaul loaded, the front tire contacts with this point, followed by the rear tire. At the end of the first trip, the total rut depth caused by these 4 wheel passes will be $Z_{FirstTrip} = Z_1 + Z_2 + Z_3 + Z_4$. If $Z_{FirstTrip}$ is greater than maximum allowable seasonal rut depth (Z_{max}), then operation stops after the first trip. If $Z_{FirstTrip}$ is not greater than Z_{max} , then, the same procedure is repeated for the following trips. In the second trip, the initial CI will be CI_5 , which is the CI after the rear tire of the loaded forwarder contacted the soil at the end of the first trip. Therefore, the rut depth after the second 4 wheel passes will be $Z_{SecondTrip} = Z_5 + Z_6 + Z_7 + Z_8$. The cumulative rut depth is:

$$Cumulative\ Rut\ Depth = Z_{FirstTrip} + Z_{SecondTrip} + Z_{ThirdTrip} + \dots + Z_{trip} \quad (13)$$

When the calculation is stopped either by Z_{max} or optimum road spacing, the model takes the last fully completed trip as the maximum number of allowable trips. This model is developed for flat terrain; however, it is applicable for mountain terrain on uniform slopes where slope and the strength of the soil allow forwarders to travel safely.

MODEL APPLICATION

The model was applied to a numerical example to demonstrate its use on developing a transportation plan. Rut depth, initial cone index, and slash density are drawn from the typical test data conditions of Wronski et al. (1990). Three different sizes of four-wheeled forwarders were evaluated. The machine rate for forwarding was estimated at \$120/hr, \$110/hr, and \$100/hr for large, medium, and small forwarder, respectively. The engine specifications of Cat Model skidders (528, 525, 515) were used (Caterpillar Performance Handbook Edition 27, 1996) to estimate the speed of forwarders. The cost of the constant activities was computed as a function of cycle time and machine rate (Table 1). The average repositioning time was 1.0 min. Timber volume harvested per unit area was 100m³/ha, and road cost was \$3/m. The model examined alternative trail spacing from 10 m to 20 m. Based on the given trail spacing, the density of the slash bed varied between 100 m³/ha and 200 m³/ha yielding values of slash

correction factor between 0.63 and 0.79 using a conversion factor of 1-ton equal to approximately 1m³. The width of the forwarder trail was 3 m. About 30% of the weight of the timber extracted was left behind as slash. The maximum rut depth was assumed to be 150 mm. The soil had an initial cone index of 552 kPa.

Table 1. Cycle time parameters and cost summary of constant activities for the forwarders.

Forwarder Types	Load (m ³)	Loader (m ³)	Loading (min)	Unloading (min)	Delay (min)	Cycle (min)	Production (m ³ /min)	Machine Rate (\$/hr)	Cost (\$/m ³)
Large	15.0	1.6	10.42	6.25	4.17	21.83	0.69	\$ 100	\$ 2.43
Medium	12.7	1.4	10.08	6.05	4.03	21.16	0.60	\$ 90	\$ 2.50
Small	9.5	1.2	8.80	5.28	3.52	18.59	0.51	\$ 80	\$ 2.61

The minimum total cost of road construction plus forwarding costs (\$3.47/m³) was provided by the large forwarder operating with 20 m wide trail spacing (Table 2). The optimum road spacing at the point of this minimum cost was less than the road spacing at Z_{max}, so road spacing was not limited by rut depth. The cumulative rut depth caused by the small forwarder operating with 14 m wide trail spacing exceeded the maximum rut depth prior to the point of optimum road spacing and provided wood at the highest cost (\$3.73/m³).

Table 2. The total cost summary for the forwarders.

Forwarder Types	Total Trip	Trail Spacing (m)	Road Spacing (m)	Final Rut Depth (mm)	Road Cost (\$/m ³)	Forwarding Cost (\$/m ³)	Total Cost (\$/m ³)
Large	4	20	600	67	\$ 0.50	\$ 0.54	\$ 3.47
Medium	5	20	635	75	\$ 0.47	\$ 0.61	\$ 3.58
Small	4	14	543	168	\$ 0.55	\$ 0.57	\$ 3.73

DISCUSSION AND CONCLUSION

The large forwarder equipped with wider tires produced larger contact area, reducing NGP and allowing the forwarder to travel with wider road spacing without exceeding the maximum rut depth. Evenly distributed slash on a forwarder trail can increase the effective soil strength and reduce rut depth. When all available slash is evenly distributed on forwarder trails at a 20m wide trail spacing, the maximum number of trips that forwarders completed before being limited by maximum rut depth were 25, 28, and 4 for large, medium, and small forwarders, respectively. A decrease in trail spacing required a longer trail distance to accumulate a load and leads to an increased road spacing to minimize costs. This leads to a lower road cost, higher forwarding cost, and relatively greater total cost. For all forwarders, loading and unloading costs were the

major components of forwarding cost. As shown in Table 3, total cost is relatively insensitive to road spacing over a wide range.

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