Comparison of three methods to determine optimal road spacing for forwarder-type logging operations

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ABSTRACT: Optimum road spacing (ORS) of forwarding operation in Styria in Southern Austria is studied in this paper. In a harvesting operation it is important to compute the ORS to minimize the total cost of harvesting and roading. The aim of this study was a comparison of different methods to study ORS. Data from 82 cycles were used to develop two models for predicting the cycle time using statistical analysis of a time study data base. The ORS was computed by three methods including Matthews' formula (1942), Sundberg's method (1976), and the two statistical models for predicting the cycle time. The results gave the ORS for one-way forwarding using Matthew's formula as 1,969 m, Sundberg's model as 394.4 m, and the two time study models as 463 and 909 m. The analysis of forwarding data indicated that the speed was related to a distance which contributed to the difference between models and that the loading and unloading time may be related to one or several other study variables.

Keywords: forwarding; production; cost; travelling model; optimum road spacing

Road network planning is an important part of logging planning. The optimized road network can help minimize harvesting costs. To optimize the road network, optimum road density and spacing should be analyzed.

In Austria, the road density is 49.1 m/ha for small forests less than 200 ha, 41.8 m/ha for private forests, 33.27 m/ha for federal forests and average 45 m/ha overall (www.bfw.ac.at). Matthews (1942) developed a model to define optimum road spacing based on minimizing the total cost of skidding and roading from the viewpoint of a landowner. Major variables are removals per ha, skidding cost, road costs and landing costs. Many researchers have used Matthews' model. Additional factors influencing optimum road spacing (ORS) were identified by several researchers.

Logging method, price of products, taxation policies, landing costs, overhead costs, equipment opportunity costs, width of road and the size of landing, skidding pattern, profit of logging contractor, slope, topography and soil disturbance influence ORS (Segebaden 1964; Sundberg 1976; Peters 1978; Bryer 1983; Wenger 1984; Sessions 1986; Thompson 1988, 1992; Yeap, Sessions 1989; Liu, Corcoran 1993; Heinimann 1997; Akay, Sessions 2001; Sessions, Boston 2006).

The minimization of total cost including skidding or forwarding cost and roading costs has been used in previous studies (Picman, Pentek 1998; Naghdi 2004). However, it is important to know what kind of the costs should be minimized to reach the optimum road spacing (ORS) and what method can be applied to have more accurate and real results. In the previous studies, different methods have not been compared to introduce a more appropriate method to study optimal road spacing. The current paper uses three methods and compares the results.

Matthews (1942) and Sundberg (1976) use similar assumptions to derive their ORS formulas.

These assumptions include constant €/m^3/m cost and an even distribution of logs over the harvest area. For these assumptions, the average forwarding cost occurs at the average forwarding distance. This paper studies how optimum road spacing varies if forwarding cost (including travelling, loading and unloading cost) or travelling costs (without loading and unloading cost) are used in the calculation using observations from a forwarding study in Austria. Speed as a function of distance is examined. The optimal road spacing is also calculated using Matthews' and Sundberg's methods to see how road spacing would differ depending on the study method.

METHOD OF STUDY

Study area

The production of Ponsse Buffalo Dual (Affenzeller 2005) and Gremo 950 R cable forwarder (Wratschko 2006) was studied in Styria in Southern Austria. The description of stands is presented in Table 1. Mean harvesting volume was about 100 m^3 per ha with a mean dbh of 25 cm. The roading cost averaged at 20 €/m.

Time prediction models

Two forwarding time prediction models are developed from data collected. The first, referred to as the forwarding model. The second, referred to as the travelling model, is introduced in this paper.

Forwarding model

Ghaffarian et al. (2006) used the collected time study data base and developed the general model to predict the forwarding time.

T (min/cycle) = 81.293 – 47.886 × piece volume (m^3) – 46.795 × type of forwarder + 0.076 × forwarding distance (m) – 1.189 × slope (%)

R^2 = 0.32, adjusted R^2 = 0.284, number of observations = 82.

The value for Ponsse forwarder is 1 and the value of 0 is considered for Gremo forwarder.

R^2 = 0.949, adjusted R^2 = 0.947, number of observations = 82.

Travelling model

Stepwise regression method was applied to develop this model. Travel time including travel loaded

Table 1. Description of study sites

	First site	Second site
Stand area (ha)	2.27	1.83
Slope (%)	11	39
Stand age (years)	70–130	90
Pre-harvest stand density (*n*/ha)	1,089	729
Pre-harvest standing volume (without bark) (m^3/ha)	510.4	646
Number of harvested trees (*n*)	1,073	470
Total harvesting volume (m^3)	331.8	513
Tree volume (m^3)	0.31	0.7
Harvesting percent (%)	28.7	45
Number of trails	15	5
Length of trails (m)	40–200	190–235
Time of harvesting	spring	spring

Table 2. Table of the analysis of variance

	Sum of squares	df	Mean square	F	Significance
Regression	9,381.36	2	4,690.68	233.4	< 0.0001
Residual	1,607.81	82	20.09		
Total	10,989	84			

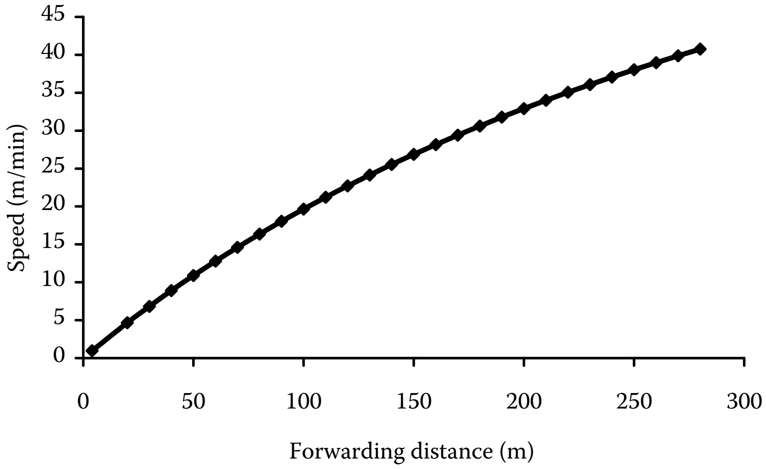

Fig. 1. Speed for different distances from the forwarding time study

and travel empty was used as a function of the variables such as forwarding distance, load volume, slope, forwarding distance × load volume and slope × load volume.

Road spacing

To study the optimum road spacing, we will apply three methods. The first was presented by Matthews (1942) and later modified by Dykstra (1983); Abelli and Magomu (1993) applied this method to study ORS for manual skidding of sulkies in Tanzania. The second method was introduced by Sundberg (1976) and applied by Huggard (1978). Both Matthews' and Sundberg's formulas are based on the minimization of costs and assumptions of constant €/m^3/m and that logs are evenly distributed over the area. Constant speed and load satisfy the assumptions of constant €/m^3/m.

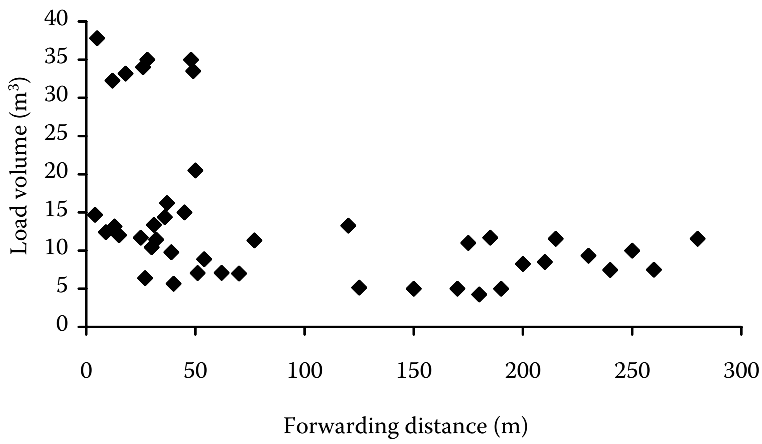

Fig. 2. Distribution of logs along the forwarding distance

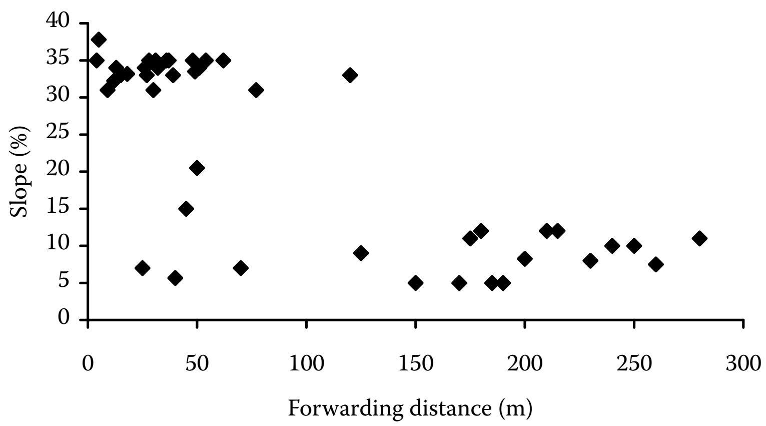

Fig. 3. Distribution of the slope of trail along the forwarding distance

Using the travelling time and travelling distance of time study data base, the velocity was computed for different distances (Fig. 1).

Fig. 1 illustrates that speed is not constant and increases with forwarding distance in this study. Naturally, machines move faster in a longer distance because of the time spent to accelerate and decelerate. However, the difference between speeds in short distance and long distance seems too high in this case study. The divergences are caused by the low load volume and gentle slope in longer distances during the studied operations (Figs. 2 and 3).

In third and fourth method, the roading cost per cubic meter is based on roading cost and harvesting volume per ha. The forwarding and travelling costs/m^3 also are determined by using forwarding time, travelling time and constant hourly machine cost regardless of the load or speed. Then the sum of roading cost and forwarding cost was plotted as a function of road spacing. The sum of roading cost and travelling cost was also determined and plotted for different road spacings.

The average road construction and maintenance cost in the study area were 16.5 and 3.5 €/m, respectively. The harvested volume averaged at 100 m^3 per ha.

Matthews' formula and Sundberg's formula

Equation (1) developed by Matthews (1942) is used. The equation assumes that the road will not be used for more than one year and all the logs will be forwarded or skidded directly to the roadside.

$$S = \sqrt{\frac{40{,}000 \times C_{\mathrm{road}}}{V \times C_{\mathrm{travel}}}} \qquad (1)$$

where:

S – optimal road spacing (m),

C_{road} – cost of the construction and maintenance of 1 m road length (€/m),

C_{travel} – cost of travelling of 1 m^3 of logs to 1 m distance (€/m^3/m),

V – stand volume density (m^3/ha).

Matthew's equation can be adapted by introducing Segebaden's network correction factor C_{net} (Heinimann 1997). The formula becomes as:

$$S = \sqrt{\frac{40{,}000 \times C_{\mathrm{road}} \times C_{\mathrm{net}}}{V \times C_{\mathrm{travel}}}} \qquad (2)$$

The formula can be rewritten as follows

$$S = \sqrt{\frac{40{,}000\ C_{\mathrm{road}} \times (4\ C_{\mathrm{net}})}{V \times C_{\mathrm{travel}}}} \qquad (3)$$

Therefore the correction factor consists of a constant of 4 and the network correction factor as C_{net}. The network correction factor is computed by dividing the effective mean forwarding distance by the geometric mean distance. Its value ranges from 1 to 2 (Segebaden 1964).

Sundberg (1976) specified the forwarding cost more precisely as

$$C_{\mathrm{travel}} = \frac{c \times t \times (1 + p)}{L_{\mathrm{vol}}} \qquad (4)$$

where:

c – operation of an extraction machine (€/min),

t – time consumption for the extraction cycle (min/m),

p – winding factor (0 for perpendicular off-road transport); a correction factor designed to allow for cases where skidding or forwarding trails are winding and not always end at the nearest point of the road and lying normally between the limits 0 and 0.50,

L_{vol} – load volume (m^3).

It also assumes that the €/m^3/m is constant and the logs are distributed evenly over the area. Substitution of C_{forw} in formula 3 results in

$$S = \sqrt{\frac{10{,}000\ C_{\mathrm{road}} \times L_{\mathrm{vol}} \times (4\ C_{\mathrm{net}})}{V \times c \times \mathrm{t} \times (1 + p)}} \qquad (5)$$

The formulas of Matthews (1942) and Sundberg (1976) are used as the first method to derive optimal road spacing.

In the other two procedures, the roading cost per m^3 was calculated for different road spacings using road density, roading cost per m, harvesting volume per ha, and the regression of cycle time. The travelling cost per m^3 was calculated using hourly cost and time prediction model assuming the load volume and slope at their average.

The total cost was calculated by adding up roading and travelling costs. The total cost was plotted as a function of road spacing (Fig. 2).

RESULTS

The observed production of forwarding was 17.9 m^3/PSH$_0$ (productive system hour) and the mean load per trip was 10.04 m^3. Using the system cost of 120 €/hour, the forwarding cost is estimated at about 6.72 €/m^3.

Travelling model

The average travelling time was 9.98 min considering the mean load of 10.04 m^3 per trip, the average production rate for travelling is 60.36 m^3/PSH$_0$. The travelling cost would be 1.99 €/m^3.

The stepwise regression method was used to develop a travelling time prediction model. Slope of

Table 3. Summary statistics of the parameters

Parameter	Max.	Mean	Min.
Loading (min)	42.24	17.23	2.78
Loaded travel (min)	10.72	4.22	0.35
Unloading (min)	15.31	6.50	0.97
Travel empty (min)	18.67	5.76	0.40
Cycle time (min)	57.68	33.72	8.90
Distance (m)	280.00	96.64	4.00
Slope (%)	40.00	21.62	5.00
Load volume (m^3)	18.70	10.04	1.37
Piece volume (m^3)	0.49	0.14	0.04

trail, forwarding distance and load volume were used in the model.

T (min/cycle) = 0.00197 × travelling distance (m) × load volume (m^3) + 0.37906 × slope (%)

$R^2 = 0.854$, adjusted $R^2 = 0.85$, number of observations = 82.

The significance level of the ANOVA table confirms that the model makes sense at $\alpha = 0.05$.

According to the travelling model, if forwarding distance, load volume and slope increase, travelling time will also increase.

Table 3 presents the summary statistics of measurements in the time studies.

Road spacing

There are three ways of representing the forwarding cost:

$$C_{\text{forwding}} = \frac{c \times t \times D}{60 \times L_{\text{vol}}} + \frac{c \times a_0}{60 \times L_{\text{vol}}} - \frac{c \times b \times F}{60 \times L_{\text{vol}}} - \frac{c \times e \times P}{60 \times L_{\text{vol}}} - \frac{c \times f \times S}{60 \times L_{\text{vol}}} \quad (6)$$

$$C_{\text{travel}} = \frac{c \times t \times D \times L_{\text{vol}}}{60 \times L_{\text{vol}}} + \frac{c \times d \times S}{60 \times L_{\text{vol}}} \quad (7)$$

where:

D – forwarding distance (m),
L_{vol} – load volume (m^3),
F – forwarder type,
P – piece volume (m^3),
S – slope of skid trail (%).

Equations (6) and (7) are presented based on the forwarding and travelling model, respectively. To get the optimal road spacing, the first derivation of the forwarding cost function enters into further analysis, resulting in the following equations:

$$C'_{\text{forw}} = \frac{c \times t}{240 \times L_{\text{vol}}} \quad (8)$$

$$C'_{\text{travel}} = \frac{c \times t}{240} \quad (9)$$

Matthews' formula

Two-way forwarding

To calculate the travelling cost, the average travelling time of 9.98 min per cycle for an average forwarding distance of 96.64 m was used. The time of extraction per m distance was 0.1033 min for favourable trail conditions. Using the hourly cost of 2 €/min, the travelling cost would be 0.00086 €/m^3/m based on formula (9).

If machines work in an unfavourable and steep terrain, the estimated variable time or cost should be increased to reflect the additional time to go the equivalent direct distance. For example, if it is expected that the forwarder must travel 1.2 km to go 1 km, then the travel cost per direct distance is increased by 20% (Matthews 1942), i.e. from 0.00086 to 0.00103 €/m^3/m.

The calculations yielded the optimal road spacing for two-way and one-way forwarding using Matthew's formula of 2,784 m and 1,969 m respectively.

Sundberg's formula

Considering C_{net} of 1 and p of 0.25 as average value and input, the other variables in the formula for ORS would be computed. The mean travel time was 9.98 min for the average travelling distance of 96.64 m. Therefore the time to travel 1 m loaded and light would be 0.103 min. Considering C_{net} of 1 for

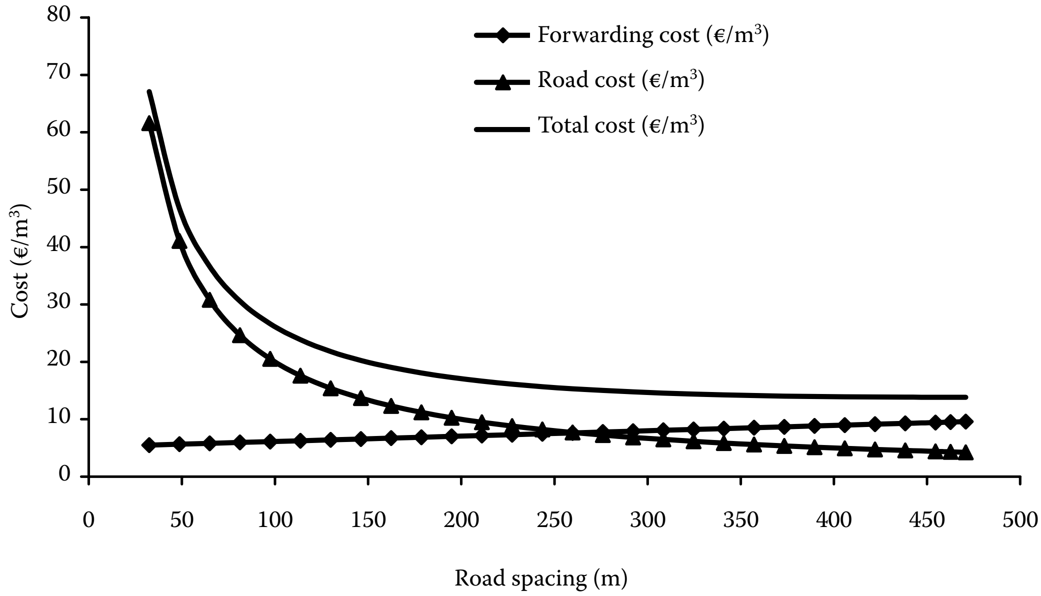

Fig. 4. The total cost summary and road spacing for one-way forwarding using the forwarding model

two-way forwarding, Sundberg's formula yields the optimal road spacing of 557.7 m. For one-way forwarding, the optimal road spacing would be 394.4 m.

Minimization of total costs

For different road spacings, roading cost, travelling cost, forwarding cost and total cost per cubic meter were plotted using a created Excel worksheet.

The existing forest road density in Styria is about 49.3 m/ha. Considering the average forwarding distance of 125 m of forwarding operation sites in Styria, *K* (correction factor) may be evaluated as 6.16 by the following formula (FAO 1974):

$$\text{Dist} = \frac{K}{RD} \tag{10}$$

where:
Dist – average extraction distance (km),
RD – road density (m/ha),
K – terrain factor.

Road spacing was evaluated from this formula:

$$\text{Road spacing (m)} = \frac{10{,}000}{\text{Road density (m/ha)}} \tag{11}$$

ORS using forwarding model

In this case, the forwarding model was used to plot the total forwarding and roading cost per m^3 for different road spacings (Fig. 4).

Based on the calculation, the minimum total cost is 13.84 €/m^3 and the corresponding road spacing is 463 m. In other words, if one-way forwarding is applied, the ORS would be 463 m. The optimal road density and average forwarding distance are 21.6 m per ha and 285 m, respectively.

ORS using travelling model

In this method, it is assumed that the loading and unloading time are constant. To verify this assumption, the scatter of loading and unloading time for different forwarding distances are plotted (Fig. 5). There is a weak correlation (0.47) and also very weak R^2 (0.26) for the model, which can verify the assumption.

The average time for the sum of loading and unloading was 23.73 min. The production of loading and unloading averaged at 25.38 m^3/h with the cost of 4.73 €/m^3. The travel loaded and travel empty time are dependent on road spacing, slope and load volume. The travelling time prediction model was used to plot the total cost of travelling and roading costs per m^3 for the range of road spacings (Fig. 6).

The minimum total cost of travelling and roading is 6.04 €/m^3 and its corresponding road spacing is about 909 m, which is an optimum spacing. The optimal road density and forwarding distance are 11 m/ha and 560 m, respectively.

It should be noted that the maximum forwarding distance was 280 m in the time study, but the optimal forwarding distance of 560 m is higher and out of range of the collected data base. The regression model applied here can be improved by using further time studies including travelling costs at distances longer than 560 m or more to have more accurate results.

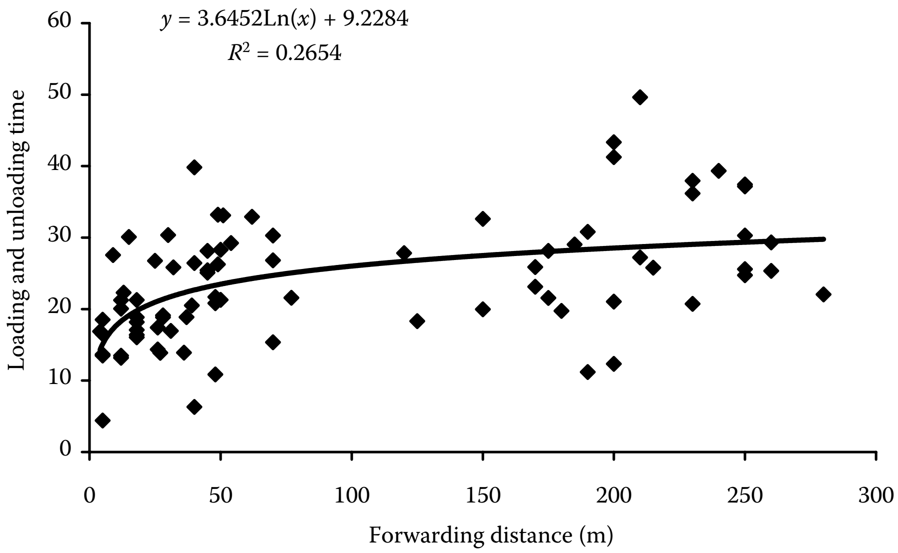

Fig. 5. Scatter of loading and unloading time with forwarding distance

DISCUSSION

Based on Matthews' formula, ORS for one-way forwarding is about 1,969 m. For Sundberg's formula, ORS would be 394.4 m for one-way forwarding. Both Matthews and Sundberg use assumptions of constant €/m^3/m. They differ in how they adjust for the terrain. Sundberg provides several explicit factors of adjusting for the terrain.

The method of total cost minimization to study ORS allows engineers to see the sensitivity of roading, forwarding and total costs to different ORS. If the forwarding model is used in the calculation, the ORS for one-way forwarding would be 463 m. But if the travelling model (similar to Matthews' method and Sundberg's formula) is used, the ORS of 909 m for one-way forwarding is yielded. The forwarding model included loading and unloading time, the travelling model did not. The difference in results between the forwarding and travelling models suggests that loading and unloading time may be related to other variables. For example, loading time varied from a minimum of 2.78 min to a maximum of 42.24 min (Table 3). If the travelling model is used, under assumption that loading and unloading times are independent of road spacing, harvesting cost is lower as compared to the forwarding model and this resulted in a greater ORS. There is a large difference between ORS (463 m and 909 m) because of the additional loading and unloading cost considered in the forwarding model which shifts the total cost line upward.

Fig. 1 shows that an increasing speed was associated with increasing forwarding distance. Since the speed is not constant for different distances, Matthews' and Sundberg's formulas would not be the appropriate methods to study ORS in this case study.

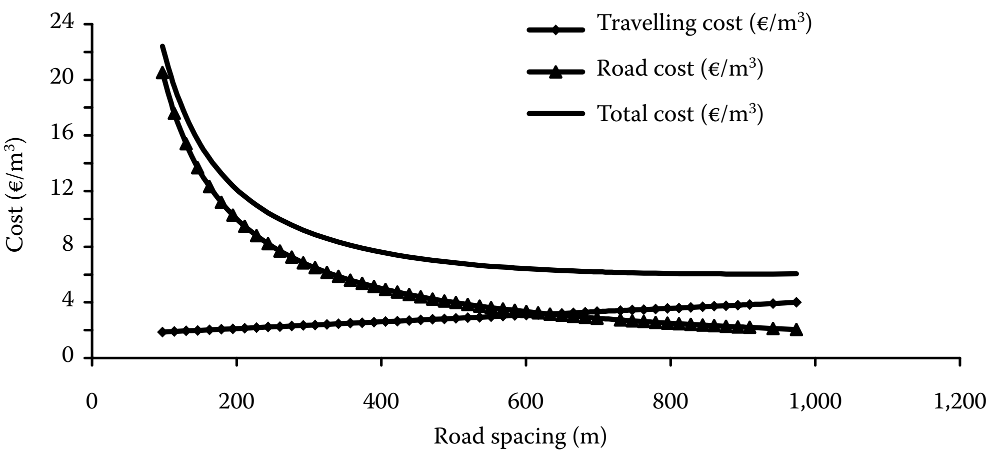

Fig. 6. The total cost, travelling cost and roading cost for different road spacings for one-way forwarding using the travelling model

Of course, both Matthews' and Sundberg's formulas could be respecified if the speed was specified as a function of distance.

Although the cycle time equations are appropriate for this study, the ORS values derived from the case study cannot be applied to other areas unless they have the same non-uniform conditions along the trail. In this case study, the non-uniform conditions were smaller loads and flatter slopes at longer forwarding distances.

The computed optimal road density is lower than the current road density in Austria because 48.3% of the forest land is owned by small private forest owners. It is also lower than the road density in the federal forests. The results of this study would be applicable to the areas with similar terrain and forest removals.

CONCLUSIONS

Optimal road spacing is an important factor in logging planning to help minimizing the total cost of harvesting and roading. The comparisons of different available methods to get optimum road spacing can be useful for planners to choose the most appropriate method based on their local conditions.

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Porovnání tří metod k určení optimálního rozestupu lesních cest pro těžební operace s vyvážením dříví forwarderem

ABSTRAKT: V práci byly studovány optimální rozestupy lesních cest pro vyvážení dříví ve Štýrsku (jižní Rakousko). Při těžebních operacích je důležité vypočítat optimální rozestup cest tak, aby se minimalizovaly celkové náklady na těžbu a soustřeďování. Cílem studie bylo porovnání různých metod používaných k určení optimálního rozestupu cest. Data z 82 cyklů byla použita pro vytvoření dvou modelů sloužících k predikci času na jeden cyklus za použití báze časoměrných dat. Optimální rozestup cest byl vypočítán pomocí tří metod včetně rovnice podle Matthewse (1942), Sundbergovy metody (1976) a dvou statistických modelů pro predikci doby cyklu. Výsledky ukázaly, že podle Matthewse byl optimální rozestup cest pro jednosměrné vyvážení 1 969 m, podle Sundbergova modelu 394,4 m a podle dvou modelů časové studie 463 a 909 m. Analýza dopravních dat ukázala souvislost mezi rychlostí a vzdáleností, která přispěla k rozdílům mezi modely, a to, že čas pro nakládku a vykládku mohl být ve vztahu s jednou či více studovanými proměnnými.

Klíčová slova: vyvážení; výnosy; náklady; dopravní model; optimální rozestup cest

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