

A Model for Predicting Productivity in Subgrade Preparation of Forest Roads by Excavator

S. Filipsson and L.O. Eriksson
Swedish University of Agricultural Sciences,
Department of Operational Efficiency
Garpenberg, Sweden

ABSTRACT

The effect of terrain factors on productivity in subgrade preparation by excavator was studied. The data, collected in a follow-up time study of 57 road sections, was analyzed using multiple linear regression. A prediction model that has soil moisture class and boulder frequency as independent variables was derived. The results also show that productivity varies considerably among operators. It is also apparent that the effect of the terrain is partly levelled out as the quality requirements for the performance of the subgrade are normally adjusted to the terrain conditions. It is suggested that, within a certain region, a fairly simple model can be sufficient for practical use in road network planning.

Key words: *Forest road, subgrade preparation, productivity, regression analysis, terrain factors.*

INTRODUCTION

The design of the forest road network is critical to the cost of timber transports and other operations in the forest. Road standards also affect the availability and flow of timber through the year. Forest road construction is, however, a costly undertaking and the construction of new roads has to be based on adequate planning to make sure that the total cost for transportation, road building and maintenance is as low as possible in the long run. One of the first steps in the planning process is to create an overall plan of the road network. To make this planning efficient, data concerning transportation and road building costs is required.

The construction of assembly roads costs about 70,000 to 100,000 SEK per kilometre (1 USD - 6.30 SEK). About half of that cost normally falls on subgrade preparation which includes grubbing, blasting of rocks and big boulders, ditching, culvert installations and compaction. It can be expected that the productivity of these operations is dependent on the type of terrain. The cost of final preparation,

mostly consisting of spreading and compaction of gravel on the subgrade, is not dependent on the original terrain conditions in the same way. Thus, in order to plan for a proper design of the road network it should be of importance to know what influence the terrain has on the productivity of subgrade preparation.

In Finland the cost of forest road construction has been analyzed from plans and the actual costs of a number of projects [4]. Among the factors studied that relate to the terrain, a weak dependence of the building cost of the whole road on the steepest slope along the road was found. Haarlaa [3] found that stoniness, soil moisture and number of stumps affected productivity. However, variation was great and not more than 16 percent of the variation in productivity could be explained by the independent variables (terrain factors). In several reports from the Swedish National Board of Roads, soil hardness, which in turn is a function of soil textural composition, has been demonstrated to affect excavation productivity, see e.g. Arkel [2]. The manual of The National Forestry Board [8] points at some factors that should be avoided. Rocks, boulders, steep slopes and wet soils are mentioned. Apart from terrain factors, operator skills are also of great importance for productivity [6].

The purpose of this study is to produce a prediction model that relates productivity in subgrade preparation to terrain conditions. The model is meant to be used in connection with forest road network planning.

The study is confined to subgrade preparation of assembly roads, with a width of 4 metres, by excavator on unfrozen forest land in central Sweden. The data stems from a time study of twelve road construction projects. The projects were divided into a total of 57 sections, representing the experimental units of the study. On each section the terrain conditions were described in advance. The terrain description was confined to factors that are easily measurable. The data was analyzed using multiple linear regression. A prediction model, that has soil moisture class and boulder frequency as independent variables, was derived. The results also showed that productivity varied considerably among operators.

MATERIALS AND METHODS

Twelve road construction projects were selected from three management units of the Swedish Cellulose (SCA) company. Prior to road construction activities, each project was divided into sections. These sections comprise the experimental units of this

study. For each section data was collected in three stages:

1. Description of terrain conditions before subgrade preparation.
2. Registration of time consumption during the subgrade preparation.
3. Inspection and registration of the work result, subgrade quality etc.

All data was collected between June and November 1987.

Sectioning

The data consists of 57 sections, with a total length of 10.5 km. The section length varies from 82 to 808 metres, with an average length of 182 metres.

The sectioning was done after the cutting of the right-of-way. It was desirable that the sections be as homogenous as possible with respect to terrain factors, but, at the same time, no shorter than 30 to 40 metres. Operators works on at least 15-20 metres at a time and it therefore would have been difficult to make a proper distribution of the time consumption among the sections if they were too short.

Sections were demarcated on the basis of a subjective judgement of the terrain conditions along the right-of-way. Road intersections and landings were not included in the sections that were studied. The dividing lines between sections were clearly marked by numbered stakes and plastic strips. Section length was measured by a thread distance meter.

Terrain conditions

The variables were measured on three circular sample plots, of which each had an area of 100 sq. metres located at 25, 50 and 75 percent of the section length. The variable values of a section are represented by the average of the three measurements for the continuous and the semi-continuous variables and by the median for the classified variables. Summary statistics for continuous and semi-continuous variables for all 57 sections are shown in Table 1.

Soil moisture content and soil depth was estimated according to the definitions of Hägglund and Lundmark [5]. The position of the watertable is the main criterion for delimiting classes of soil moisture. Certain topographical configurations and the occurrence of moist depressions in the surface are auxiliary to this assessment. Soil moisture content was classified in four classes (figures in brackets desig-

nate the number of sections): dry (0), mesic (34), moist (23) and wet (0). Soil depth was classified in four classes according to average soil depth within the plot: deep (> 70 cm. depth; 53), fairly shallow (20-70 cm.; 4), shallow (< 20 cm.; 0) and varying (0). The average soil depth was determined from probes with an iron stick on the plot and the occurrence of rocks in the vicinity of the plot. Humus layer thickness was taken as the average of three to five measurements with a sonde and expressed in centimetres. The textural composition of the soil was determined by the use of a particle size scale and the rolling test for three soil samples on each plot. The following soil textural classes, alluvium and till respectively, were identified: gravel (13), sand (6), silt (2), sandy till (17), silty till (15) and peat (4). The ranges of particle size for the alluvial soil classes are: gravel 20 to 2 mm., sand 2 to 0.2 mm. and silt 0.2 to 0.02 mm. In sandy and silty till respectively sand and silt dominates.

Boulders were counted and classified in five classes according to the greatest diameter of the visual part of the boulder: 20-60 cm, 60-100 cm, 100-140 cm, 140-180 cm and diameters exceeding 180 cm. The diameter class was determined by ocular estimation. On one half of the sample plot it was required that the entire boulder was within the boundary of the plot, while on the other half it was sufficient if the boulder touched the boundary of the sample plot. Stump frequency was determined by counting stumps having a diameter greater than 20 centimetres. The side slope inclination of the ground was measured and noted on a percentage scale.

Table 1. Statistics for continuous and semi-continuous variables

	Min. value	Max. value	Mean value	Standard deviation
Humus layer Thickness	5	38	12.6	6.3
Boulder frequency (no/100 sq.m.)	0	7.6	1.4	1.8
Stump * frequency (no/100 sq. m.)	0	9	4.3	2.0
Side incline (%)	0	20	6.7	5.3

Time consumption

Working time on site was divided into five work elements:

1. Actual subgrade preparation.
2. Refuelling time, including time for moving to and from the fuel container.
3. Management of the work.
4. Maintenance and repair, done on site.
5. Meal breaks.

Time consumption was continuously registered by self-recording equipment installed in each excavator. This method for registration of time consump

Work results

It was decided, together with the supervisors, to have the roads appraised according to the criteria of road class 3 [9]. A road of class 3 is intended for permanent use and should, after final preparation, allow a speed of 40 kilometres per hour for loaded trucks. The sections were inspected by experienced personnel from the County Forestry Board and graded as "approved" or "not-approved" on the basis of 13 factors.

The results from the inspection show that the frequency of not-approved factors varied between sections and that there was no section completely free from criticism. However, in most cases the criticism concerned minor imperfections and the subgrade preparation should normally be finished by a road grader. The supervisors were on the whole

Table 2. The equipment, and distribution of sections among the operators

Operator No.	Machine type	Mass (tonnes)	Power (kw)	No. of sections	Length of subgrade (m)
1	Hitachi 121 LC	27	121	15	2831
2	Åkermans H 14B	27	154	12	3224
3	Åkermans H 14B	27	154	16	2113
4	Åkermans H 16C	40	193	14	2393
Total				57	10561

tion was chosen because it made it possible to collect and study sufficient data from several projects simultaneously. Another reason was that both operators and supervisors were familiar with the self-recording equipment and had experienced it as being reliable. In order to associate a certain time consumption with a particular section, the operators made notes on a special form stating point in time when he changed work element or began working in another section. Registered time consumption from the self-recording equipment and notes about work element, section etc were compiled by the supervisors.

The registered time for work element 2 (refuelling) cannot be adequately associated with a certain section. Therefore, the total time per road used for element 2 was distributed among the sections in proportion to work element 1 (productive working time).

Productivity was defined as metres per E_5 -hour (effective time including delay times shorter than 5 minutes,) [7], calculated on time consumption for work elements 1 and 2. The productivity varied between 5 and 22 metres per E_5 -hour. The average productivity was 12.7 metres per E_5 -hour, with standard deviation 4.5 metres.

satisfied with the subgrade as far as it had been carried out. An inspection of the data did not show any correlation between productivity and volume of criticism. On these grounds it was decided not to exclude any sections from the analyses.

In conjunction with the inspection of the subgrade quality the area of passing-points and other planes attached to the subgrade was measured. In addition to that, the number and dimensions of culverts in each section were registered. It was expected that construction of planes and culvert installation would impair the productivity rate.

Work method, machines and operators

The subgrade preparation was performed by special contractors who had been engaged by the SCA company for several years for road construction work. They were all familiar with the working techniques and standards of performance in general. The operators were hired on an hourly basis. Each contractor worked on his own and had to construct the subgrade without the help of staking or profiles. The only guidance given was the 30 to 60 meter wide

right-of-way showing direction through the landscape. Decisions about the proper location of culverts, passing points etc were made by the operator as they came along.

Four excavators, two Åkerman H14B, one Åkerman H16C and one Hitachi 121LC are represented (Table 2). The Åkerman H 14B and the Hitachi machines are of similar size, one class smaller than the H16 machine. Excavators about this size are generally regarded as most suitable for this particular kind of work.

Definition of independent variables in the analysis

Soil moisture classes "mesic" and "moist" are the only two classes that are represented in the data. The variable is defined as a dummy variable with the value "mesic" representing the reference level. The soil textural classes were rearranged according to the definitions of "digging-classes" [10], which summarizes resistance in digging and normal utilization of bucket volume for different soils. Soil types belonging to the easiest digging class were given the value 1 and so on up to digging class 5.

Preparatory analyses indicated that boulders in the smallest size class (20-60 cm) had no effect on productivity. In the final analysis the material is divided into three boulder frequency classes: less than 1, between 1-4 and more than 4 boulders bigger than 60 centimetres per 100 sq. metres. The first class represents the reference level while observations belonging to the second or third class have the value 1 of the appropriate dummy variable.

Stump frequency is given as a dummy variable. The frequency of less than 4 stumps per 100 sq. metres represents the reference level.

Both operators and supervisors were of the opinion that a slight side slope inclination has a positive effect on productivity while a steep incline or none at all normally has the opposite effect. Side slope inclination is here given as a dummy variable where the reference level corresponds to inclinations less than 8 or more than 15 percent.

It was presumed that the installation of culverts and the construction of planes would have a negative effect on productivity. Culverts are included in the analysis as the total cross-sectional area in sq. metres of culverts per kilometre of subgrade. The area of planes is included as the total area in sq. metres of passing points and other kind of planes per kilometre of subgrade.

Since the operators used different machines it is not self evident how much of the effect depends on operator and how much on machine characteristics. An operator and his machine here represents an operating unit. Operating unit is included as a dummy variable with operating unit 1 as reference. Each of the other operating units is represented by a dummy variable.

Variation was very slight for the soil depth variable and it was therefore excluded from the analysis. Since humus layer thickness and soil moisture were highly correlated, the correlation coefficient being 0.60, one of the two variables should be excluded. A reliable estimate of the variable value is more easily obtained for soil moisture than for humus thickness. Considering the practical usage of the prediction model it was therefore decided to exclude the humus layer thickness variable.

RESULTS

Multiple regression was used to analyze the dependence between different factors and productivity. It was presumed that the different operations, which usually occur in a certain sequence, would be affected by the different terrain factors one after the other. Therefore an additive model was chosen. A multiplicative model was also tested, but gave no improvement in the coefficient of determination.

The model containing variables, as previously defined was estimated. The results showed that soil moisture, operating units 2 and 3 and boulder frequency of more than 4 had a significant effect on productivity at the 95 percent level.

A second model was formulated that contained the variables that were significant in the first model. Operating unit number 4 and the other two boulder frequency classes were also included as they are connected with the significant variables. The results of this analysis are presented in Table 3.

The parameter estimates should be interpreted as follows. At the reference level, i.e. soil moisture class "mesic", less than one boulder per 100 sq. metres and operator 1, the estimated productivity rate is 11.3 metres per E_5 -hour. If the soil moisture class changes from mesic to moist the productivity rate is estimated to decrease by 1.5 metres per E_5 -hour. If the boulder frequency is between 1 and 4 or greater than 4 boulders per 100 sq. metres, the productivity rate is estimated to decrease by 1.6 and 4.2 metres per E_5 -hour respectively. It is estimated that operating units number 2, 3 and 4 have, respectively, an average productivity level 7.2, 4.7 and 1.2 metres higher than the reference level represented by operator number 1.

Table 3. Productivity in metres per E₅-hour as a function of terrain factors and operating units^a

Independent variable	Parameter estimate m/E ₅ -hour	Standard error m/E ₅ -hour	T for H0: parameter=0	Prob> T
Intercept	11.26	0.94	12.03	0.0001
Soil Moist. class=mesic	-1.49	0.75	-1.98	0.05
Boulder freq. 1-4/100 sq. m	-1.57	0.92	-1.71	0.09
Boulder freq. >4/100 sq. m	-4.15	1.11	-3.75	0.0005
Op. unit No.2	7.21	1.18	6.15	0.0001
Op. unit No.3	4.68	1.02	4.59	0.0001
Op. unit No.4	1.16	1.05	1.11	0.27

a) F-value=14.21, Prob>F=0.0001, R²=0.67, R² adjusted=0.62

DISCUSSION

The frequency of boulders with a diameter greater than 60 centimetres and soil moisture class are the two terrain factors whose influence on productivity has been determined with greatest accuracy. It appears that with more than four boulders per 100 sq. metres productivity is greatly affected. Haarlaa [3] also found boulders and soil moisture to be most important for productivity in subgrade preparation.

From the results one could infer that productivity is surprisingly insensitive to terrain factors that are normally considered to be of importance. There are several circumstances that should be analyzed before such a conclusion is drawn. Firstly, there may be specification errors. Due to an alleged relative independence of the different operations during the subgrade preparation an additive model is used. It is however quite conceivable that there are multiplicative as well as additive relationships. Such a relationship might for instance exist between frequency of boulders and side slope; a proper side slope inclination could possibly make it easier to handle boulders.

Secondly, there may be measurement and sampling errors. However we feel that they are of minor importance with respect to most variables. The terrain factors are easy to determine and the sectioning of the roads was designed to limit sampling errors. We also have the impression that time consumption was registered with great care by the operators.

Thirdly, variables could be missing or badly defined. We have no indication that any factor has been completely overlooked. Some of our definitions may however be questioned. It is quite clear that productivity is affected by soil depth. Rocks within 1.5-2 metres of the surface may have a negative effect on productivity. This effect of rocks could not be quantified as the variable soil depth was classified as great when the soil depth was judged to be at least 0.7 metres. In the region where this study was carried out the soil depth did not vary greatly and was normally sufficient not to limit productivity. It appears that small and medium-sized stumps have very little effect on the work. With the definition used in the study, one can find a positive correlation between stump frequency and productivity. This is perhaps explained by the fact that a high frequency of stumps normally means that the stumps are small and that a number of small stumps might have less effect on the productivity than one separate large stump. But in general, stumps seem to be a minor problem using modern excavators.

Fourthly, areas with difficult terrain are avoided as far as possible when planning the road. Conditions such as rocky ground and thick humus layer are absent in the data, due to limited occurrence in the region of study. These factors may well have to be accounted for in other regions.

A related problem refers to the dependent variable of productivity. It is quite clear, from visual inspection of the completed subgrades, that the quality of the work varies between different types of terrain. As conditions become tougher, more imperfections are accepted, which means that difficulties caused by the terrain tend to be levelled out.

The varying quality points to the problem of using follow-up studies. In order to ensure consistent standards one would presumably have to rely on experiments. However, it makes economic sense to adjust the quality requirements to the severity of the terrain. Controlled experiments could even be misleading, since modifications of standards probably always will, and should, take place.

The efficiency of the operating units varies considerably. We would like to attribute these differences to the operators rather than to the machines. Our observations suggest that the operators of the most efficient units know the construction requirements very well, and how to fulfill these requirements efficiently in different types of terrain. They also have a good eye for balancing cuts and fills, with a minimum of excavation. Finally they do not overwork the finish of the subgrade. Nagy [6] emphasized how much productivity depends on operator skills. He considers that the differences in skill spring

from the fact that the operators are often self-trained and as a result they have developed some faulty construction techniques along with good procedures. These findings were also supported by Appelroth [1] who pointed to varying degrees of motivation as important explanations of the variation in productivity.

The analyses and comparisons stated so far were founded on sectional level data. However, a whole road project consists of a number of sections with varying terrain conditions. Naturally, the geometry of roads is planned with regard to terrain conditions. In order to build the roads as inexpensively as possible, areas with difficult rocks, boulders or bogs are avoided as far as possible. This means that each road will be built on conditions that are "normal" for that particular area. Therefore one can expect differences in average productivity to be smaller for whole road projects than for sections. Such a conclusion agrees with the results presented by Hannelius [4]. In our study the average productivity per operator, estimated on whole roads, varies by 23 percent at the most. This could be compared to the variation found on the sectional level which is in the range of 100 to 500 percent for the different operators.

To sum up, productivity in subgrade preparation is dependent on terrain conditions. However, this dependence is partly levelled out as quality requirements for the performance of the subgrade are normally adjusted to the terrain conditions. Road construction projects should be planned with due attention to terrain conditions. That means that the most difficult terrain will normally occur fairly seldom, and will therefore be of minor importance. On these grounds it seems reasonable to suggest that a simple model may well be sufficient for practical use in road network planning within a certain region.

ACKNOWLEDGEMENTS

This study was initiated and carried out through a collaboration between the forest industry company SCA and the Department of Operational Efficiency. The study was partly financed by Kontaktforskarsekretariatet at Uppsala University, National Board of Forest Technics Research and the SCA company. We would like to thank the personnel from the SCA company who were involved in the study. A special thank to Sven Nordström, County Board of Forestry, who carried out the inspections of the subgrade.

REFERENCES

- [1] Appelroth, S.E. 1986. Work study methods for comparison of manual tree planting. In: Proceedings of 18th IUFRO World Congress, Ljubljana, Yugoslavia, September 7-21, 1986.
- [2] Arkel, P. 1978. Gr vmaskiner 35-50 ton - Kapacitetsdata. DDa-rapport 78:31, Statens V ägverk.
- [3] Haarlaa, R. 1973. Maaston vaikutuksesta metsäteiden rakennukseen (On the effect of terrain on forest road construction). *Silva Fennica*, Vol 7, pp 284-309. (Engl. summary)
- [4] Hannelius, S. 1975. Metsäteiden rakennuskustannukset (The cost of forest road building). Research notes No. 30, Department of logging and utilization of forest products. University of Helsinki, Helsinki. (Engl. summary)
- [5] Hägglund, B. & Lundmark, J-E. 1977. Site index estimation by means of site properties: Scots pine and Norway spruce in Sweden. *Studia Forestalia Suecica*, No.138.
- [6] Nagy, M.M. 1978. Productivity and cost of four subgrade construction machines. Technical report no 28, FERIC.
- [7] NSR, 1978. Nordisk avtale om skoglig arbeidsstudienomenklatur (Forest work study nomenclature). Nordiska Skogsarbetsstudier nas Råd. Ås, Norway.
- [8] Skogsstyrelsen 1983. Konstruktionsteknik skogsbilvägar. Skogsstyrelsen. Jönköping, Sweden.
- [9] Skogsstyrelsen 1984. Arbetsbeskrivning för skogsväg klass 3 och 4. Skogsstyrelsen. Jönköping, Sweden.
- [10] TFK 1979. Massförflyttning vid anläggning- och byggnads- arbeten. Mängd-, tid- och kapacitetsbegrepp. Transport-forskningskommissionen, Rapport 1979:4.