Comparing Productivity and Costs of Three Subgrading Machines

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ABSTRACT

Production rates and costs of three forest road construction machines (Ford County 1164 tractor, D4D and D6D Caterpillar bulldozers) were analysed and compared. Results showed that differences in production rates were attributed mainly by the type and the size of the machine, driver's working experience and the nature of the terrain side slope.

Compared to other subgrade productivity studies, machine production rates found in this study were considered to be reasonably high. The mean production rates for the D6D, D4D and the County tractor were 129.0 m^3/h, 41.0 m^3/h and 28.1 m^3/h respectively. High productive time, easily workable soils and few obstacles encountered during earthworks operation were the major factors which contributed to high machine production rates.

Cost analysis showed that the higher the machine production rate the lower the subgrading cost and vice versa. The mean production costs for the D6D, D4D and the County were estimated to be US$ 0.49/m^3, US$0.79/$m^3$ and US$0.76/$m^3$ respectively. The estimated machine production costs were more or less the same as those estimated elsewhere.

Although low machine production cost is usually the criterion used in choosing the machine to be used for road construction works, this paper recommends that other factors be considered.

Key words. *subgrading, earthwork movements, road cross-section, production rate, production cost.*

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INTRODUCTION

Subgrading or the process of preparing the road subgrade constitutes a major cost in road construction works. Road construction studies show that about 30-50% of the total road construction costs fall under subgrade preparation [1,2,3,8]

The process of forming the subgrade varies depending on the definition of what constitutes subgrading. While in one place subgrading could be a mere removal of the topsoil, in some places it involves several work operations like grubbing, blasting, ditching and installation of drainage structures [8].

Traditionally, bulldozer machines have been used for constructing forest roads. However, due to environmental damage and lack of capital to purchase and operate these heavy and expensive machines, other road construction machines have been used in the forests. Such machines include hydraulic backhoes, line shovels, hydraulic shovels [9] and industrial tractors with front dozer blades [1]. Despite the fact that these machines cause minimum damage to the environment and have other advantages, bulldozers are still being used for road construction works due to their high mobility and ability to work in steep and difficult terrains [8].

The ability of a bulldozer machine to excavate and push soil materials depends on its weight and engine power, terrain side slope, coefficient of traction and the type of dozer blade [4]. Productivity studies show that in addition to these factors, subgrading productivity is also influenced by the number of stumps, stones and boulders along the roadline and the skills of the machine operator [8,9].

This paper, which is based on studies carried out in one of the forest plantations in Tanzania, analyses and compares productivity and costs of three earthmoving machines used in preparing a subgrade for a secondary forest access road.

MATERIALS AND METHOD

Study Site

Two subgrading studies were conducted at the Sokoine University of Agriculture Training Forest (SUATF) near Arusha between 1984 - 1988. The 840 ha forest planted mainly with Cupressus lusitanica and Pinus patula lies on the slopes of Mount Meru between 1,740 and 2,300 m above sea level [Fig. 1]. The terrain side slopes are moderately steep (10 - 40%) while the soils of the are volcanic sandy clay type.

The new road under construction was an extension of an existing one-lane, all-weather secondary access road [Fig.1]. The design specifications for the existing road were the ones adopted for the new 3.2 km study road. The roadway width was 6.5 m, while the design speed was 40 kmh. The ruling and maximum gradients were 5% and 8% respectively. All trees within the right of way were felled and skidded while stumps along the roadway were uprooted the first 1.3 km only before subgrading operation started.

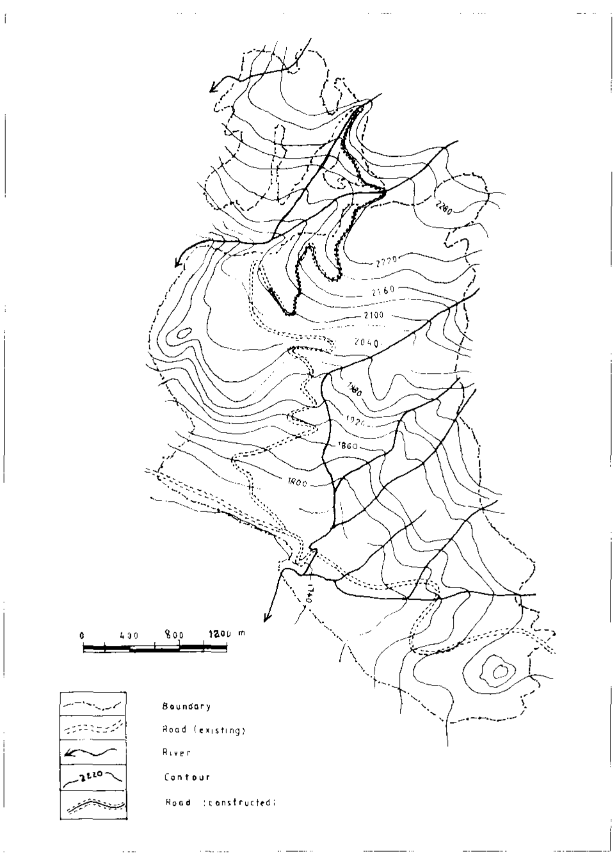

Figure 1. Location of the study road in the SUATF, near Arusha.

Although the three earthmoving machines worked at different road sections at different times, the terrain working conditions were almost the same and within machines capabilities. All three machines were fitted with "Straight" type dozer blades for cutting and moving the soils. The 4W-drive Ford County 1164 tractor subgraded road section I (the first 520 m) while road section II (the next 780 m) was subgraded by a D4D Caterpillar bulldozer. The last 1,900 m (section III) were subgraded by a D6D, Caterpillar bulldozer. The first two road sections were constructed and studied in 1984 [1] while road section III was constructed in 1988.

Data Collection

At each working site, time study data and earthworks data were collected and recorded without interfering or altering the normal working procedures. Detailed time study was carried out in each work operation using a time study watch. Each machine formed an operating unit and the total time spent on the site per day (shift) was referred to as *Work place time*. Work place time was segregated into effective machine working time, necessary and unnecessary delay times and lunch time. Effective machine working time and necessary delay time formed *Productive working time*.

To be able to determine the amount of earthwork volume cut or filled per area per day, cross-sectional road profiles after every 20 m (on tangent sections) and 10 m (on curve sections) were taken before and after the day's task or operation. Cross-sectional road profiles were later plotted and their cross-sectional end areas determined [1].

Estimating Earthworks Volume

To estimate the volume of soil cut or filled per road section, the *average end area method* was used [1]. Equation (1) which estimates the amount of earthworks excavated or filled in two adjacent stations was the one used in estimating the earthworks volume:

$$V_{i,i+1} = 0.5(A_i + A_{i+1})L_{i,i+1} \qquad (1)$$

where

$V_{i,i+1}$ = Volume of soil cut/filled between road station i and the next station (i+1), m^3

A_i and A_{i+1} = Cross-sectional end area of road station i and the next station (i+1), m^2.

$L_{i,i+1}$ = The distance between road station i and the next station (i+1), m.

When computing the fill volume, a shrinkage factor of 0.8 was used in order to compensate for soil compaction and loss of soil when moving soil materials from cut areas to fill areas [1].

Estimating Production Rates and Costs

Productive working time was the unit of time used in computing machine production rates and costs. Production rates were estimated by computing the length of subgrade prepared per hour and the volume of soil excavated or cut and filled per hour. The cost of subgrading a metre of road and the cost of cutting/filling one cubic metre of soil were used as unit measures of machine production cost.

In order to be able to make realistic cost comparisons and to eliminate the problem of devaluation and price differences between the two study periods, all prices and costs used in machine cost calculations in this study are based on 1992 prices. The standard machine cost formula used in estimating the value of the various components of a machine was used in computing the fixed and the variable machine costs [7].

Besides time and earthworks data, information on the general terrain slope, stand conditions and operators working experience were also collected. To find out if there was any relationship between the amount of earthworks and the length of subgrade prepared per unit time, both earthworks data and subgrade length data were subjected to analysis of variance and regression analysis.

RESULTS AND DISCUSSION

Table 1 summarizes time study data and earthwork statistics during subgrade preparation for the three earth moving machines.

Table 1. Summary statistics for the time study data and earthworks volume per day for the three earth moving machines.

Variable	Statistic	County tractor	D4D Cat.	D6D Cat.
No. of observations (days)	Total	26	11	7
Work Place time (h)	Mean	5.63	8.05	7.03
	Minimum	3.41	3.65	5.58
	Maximum	8.90	9.68	7.92
	Std. dev.	1.28	2.16	0.96
Productive time (h)	Mean	4.85	7.30	6.43
	Minimum	2.83	3.17	5.01
	Maximum	7.60	9.36	7.43
	Std. dev.	1.17	2.04	0.89
Lunch time (h)	Mean	0.78	0.59	0.60
	Minimum	0.50	0.50	0.33
	Maximum	1.68	1.14	1.20
	Std. dev.	0.29	0.19	0.33
Earthworks Volume (m^3)	Mean	136.34	299.27	829.43
	Minimum	58.60	91.40	423.00
	Maximum	240.00	485.20	1089.00
	Std. dev.	46.11	106.19	253.28
Length of subgrade prepared (m)	Mean	73.85	133.64	274.28
	Minimum	40.00	80.00	180.00
	Maximum	140.00	180.00	360.00
	Std. dev.	26.09	37.49	63.99

Since the percentage of productive working time to Work place time for the three machines ranged between 86-91% it implied that machine utilization was high. The percentage of unnecessary delay time was significantly low due to close supervision and good working conditions of the machines during the study periods. Under normal field working conditions, the productive working time would most likely be lower than what was recorded in this study. The road being a climbing type, most parts of the road required cutting rather than filling. Where a section of a road had excess cut materials, the excavated materials were either side cast or moved to road sections requiring fill materials. In road section I, only 19% of the excavated material was hauled to areas requiring filling while the rest was side cast. In road sections II and III, about 38 and 44% of the excavated material were used as fill materials while the rest were side cast respectively. From Table 1 it is clear that as more of the excavated materials is hauled and used as fill material, the higher the subgrading operation, i.e., earthworks volume and the length of subgrade prepared per day.

The type of terrain cross-sections being excavated appeared to have influenced the machine production rates. In road section I, which was a typical *cut through section*, the machine production rate was lower than in road sections II and III which were *cut/fill sections*. Unlike in cut/fill sections where the excavated materials from one side of the road were used as fill materials on the embankment side of the road, in cut through sections all the excavated materials had to be moved long distances before they could be side cast or used as fill material. This means therefore to achieve high machine productivity, as far as possible road planning or road alignment should aim at having a roadline with more cut/fill sections as opposed to more cut through or fill sections.

Table 2 shows machine specifications, driver's working experience and mean production rates of the three machines.

Table 2 indicates that production rates both in terms of the length of subgrade prepared and amount of earthwork volume worked per hour depend on the type and the size of the machine. While the rubber tired County tractor showed low production rates, the two tracked machines (with low centre of gravity and high traction powers) had relatively higher production rates. On the other hand the D6, whose engine power was double that of a D4, was found to be three times more productive than the D4. Experience and skills of the machine operators also seemed to have contributed to machine productivity. As has been found elsewhere [9], the County tractor operated by a driver with no experience on road construction works had lower production rates than the two Caterpillar machines operated by experienced drivers.

Through analysis of variance and regression analysis, the correlation between the amount of earthwork volume excavated and subgrade length prepared per unit time were found. Table 3 shows regression analysis data and equations for predicting earthworks volume from subgrade length prepared per day.

Table 3 indicates that for road sections I and II, there was a linear relationship between the amount of earthworks volume and the length of the subgrade prepared per day. Through analysis of variance it was also found that in these two road sections the length of the subgrade prepared per day had a significant influence on the total amount of earth volume excavated per day. On the other hand, in road section III there was no linear relationship between the length of the subgrade and the amount of earthworks and neither was the earthworks volume influenced by the length of the subgrade prepared per day. Relatively deep cuttings in some parts (3.0 m^3/m) and more time spent on uprooting

Table 2. Machine specifications and production rates.

Type of machine	Engine power (kw)	Age of machine (Years)	Operators experience (Years)	Depth of cut m^3/m	Production rate m^3/h	Production rate m/h
County	85	5	-	1.8	28.1	15.6
D4D	56	10	9	2.2	41.0	18.3
D6D	104	5	8	3.0	129.0	42.6

Table 3. Correlation between subgrade length and the amount of earthworks volume during subgrading operation.

Variable	Road section I	Road section II	Road section III
Null hypothesis H_0: $b_1=b_2=0$	Rejected	Rejected	Accepted
Test of significance	Very significant	Significant	Not significant
Correlation coeff. R^2	0.33	0.37	0.17
Predicting vol. (Y) from subgrade lenght (X)	Y = 61.5 + 0X	Y = 69.8 + 1.7X	Y = 376.7 + 1.6X

Table 4. Machine Costing in US dollar ($) based on 1992 prices.

Type of Machine	County	D4D	D6D
General information:			
Delivered price (US$)	56 000	90 000	170 000
Depreciation period (yr)	8	8	8
Annual usage (h)	1 000	1 000	1 000
Salvage value (10%)	5 600	9 000	17 000
Average Annual Investment (60% of Delivered price)	33 600	54 000	102 000
Machine fixed cost:			
Depreciation cost ($/h)	6.30	10.13	19.13
Interest: 10% of AAI ($/h)	3.36	5.40	10.20
Insurance and taxes: 5% of AAI	1.68	2.70	5.10
Machine running cost:			
Maintenance and repair (100% of depreciation cost)	6.30	10.13	19.13
Fuel cost (0.33$/1)	2.74	2.97	8.50
Oil & lubricants (2.0$/1)	0.46	0.50	0.84
Driver ($/h)	0.33	0.40	0.40
Helper ($/h)	0.15	0.25	0.25
Hourly machine cost (US$/h)	21.32	32.48	63.51
Machine production cost (US$/m³)	0.76	0.79	0.49

stumps in road section III could have contributed to there being no correlation between the earthworks volume and the length of the subgrade prepared per day.

The ratios of m^3/m found in this study are low when compared to 6.12 m^3/m found in Canada when using a D8H Caterpillar [3]. This signifies that the depth of excavation or cutting in this study was not very extensive.

When compared to other subgrade preparation studies carried out elsewhere, the production rates found in this study appear to be slightly higher than those found in other countries. For example, when using a D4 for subgrade preparation, studies on production rates in the Philippines [5] and Iran [6] found production rates to be 25 m^3/h and 27 m^3/h respectively. Although the type of a machine used was much bigger, a similar study carried out in Canada using a D8 Caterpillar found a production rate of about 132.9 m^3/h [9]. In Sweden, where excavator machines were used for subgrading a forest road, the average length of subgrade prepared was 12.7 m/h [8]

When compared to Caterpillar machine production figures, the production rates found in this study appear to be within the acceptable range. For instance, for an average dozing distance of 30 m, the production rates (after adjusting for various correction factors) for D4 and D6 Caterpillar machines are estimated to be 54.4 m^3 and 122.3 m^3 per hour respectively [4].

The relatively high machine production rates found in this study could be due to a high percentage of productive working time resulting from good working conditions of the machines and constant supervision, easily workable soil and few obstacles (rocks, boulders and stumps) encountered along the roadline.

Table 4 shows the cost of owning and running the three road construction machines. As already stated, the 1992 market prices rather than the actual prices which prevailed during the construction time have been used so as to be able to compare the production costs of these machines.

The cost of owning and running the D6, D4 and County per hour as indicated on Table 4 are US$ 63.51, US$ 32.48 and US$ 21.32 respectively. By dividing these costs with hourly machine production rates, subgrading production costs were found to be US$ 0.49/m^3, US$ 0.79/m^3 and US$ 0.76/m^3 for D6, D4 and County respectively. Despite D6 being the most expensive machine to buy and run, it was found to be a reasonably cheap machine for subgrading roads in this study. Relatively low machine production rates appear to have contributed to high subgrading costs when using D4 and the County machines. By improving machine productivity through training of machine operators and proper road planning, machine production costs could be reduced quite considerably.

In relation to other subgrading cost studies, the earthworks costs found in this study do not differ significantly from those found in Canada where the earthwork costs were Can$ 0.46/m^3, Can$ 0.44/m^3 and Can$ 0.95/m^3 for D8H Caterpillar bulldozer, 235 hydraulic backhoe and hydraulic shovel respectively in 1978 [9].

CONCLUSIONS

The production rate of the County tractor was relatively lower than the production rates of the D4 and D6 Caterpillar machines. Operators' long working experience, low machine centre of gravity, high traction power and the type of terrain cross-section (cut/fill section) on which the Caterpillar machines operated contributed to production rates of the D4 and D6 being higher than the County.

Compared to other subgrading studies, machine production rates found in this study were relatively higher due to high productive working time, easily workable soils and few obstacles encountered along the roadline.

Despite the costs of owning and running the County and the D4 being low, relatively low machine production rates made them relatively more expensive earthmoving machines than D6. This means therefore cheap machines to own and run are not necessarily the most economical machines to use for road construction works. Before one decides on which type of earthmoving machine to buy for road construction works, it is important that one bears this in mind.

The size or the length of the road project and the amount of money available to purchase and run a machine can influence the choice of the machine to buy. For instance where the road project is only few kilometres and there is a constraint of money, the

County tractor, though a relatively more expensive earthmoving machine than the D6 Caterpillar, could still be the most appropriate machine to use because of low capital investment and possibility of using it for other forest operations like skidding and log hauling.

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