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Terra-Mechanical and Statistical Analyses of Four-Wheel Grapple Skidder Performance Data

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Skidding. (left: USDA Forest Service photo; right: USDA Forest Service photo by Forest Operations Research, courtesy of Bugwood.org)

Abstract

Studies of skidder productivity typically involve a range of conditions that support specific study objectives related to harvest system, terrain, forest attribute, or other aspects of the harvest. Skidder production models often fit the data well because cycle time and productivity are strongly related to load size and skid distance. Changes in skidder design over time have increased load capacity, potential machine speed, and operator comfort. Since the harvest system often limits the observed range in speed and load size, the tradeoffs between those factors have not been a primary focus of production studies. We analyzed 33 studies with 77 estimates of skidder productivity using a typical regression approach and an approach based on the Wismer and Luth terra-mechanical (TM) relationships. The regression approach resulted in a good fit of productivity but poorer fits of cycle and element times. Nonlinear models developed with the TM approach also fit but had larger values for mean square error (MSE) than the linear regressions. The use of 14 additional studies with 33 estimates as validation data produced a lower mean square prediction error (MSPE) for nonlinear TM models when compared to the linear regression models. The TM approach allowed for the tradeoff between speed and load size to be modeled explicitly. We developed a spreadsheet production model to demonstrate the effect of choices made by harvest planners, logging managers, and operators on specific production goals.

Keywords: Logging, models, productivity, skidder, terra-mechanics.

INTRODUCTION

Logging contractors' choices of grapple skidder attributes (engine power, weight, grapple configuration, and tire size) are made to optimize performance across the range of harvest and site conditions encountered. Those conditions typically include tree size, soil strength, slope, and terrain roughness. While skidder performance is partially determined by the interaction of the machine and site conditions, logging planning can manage performance through landing spacing, bunch size, and control of nonskidding activities (e.g., gate delimbing, landing maintenance, debris removal).

The impact of the operator on skidder performance is also significant and complex. Factors that determine performance include both the human-machine interaction (whole-body vibration [WBV], ease of operation, skill level) and performance expectations (self-regulated and imposed). Performance expectations may include achievement of a production goal or, conversely, avoidance of damage to the machine or negative outcomes to the site (tree or soil damage).

Production models have been valuable tools in weighing system tradeoffs to optimize production in specific settings. Prediction of skidder cycle time or productivity with regression equations is effective because most of the cycle time is spent in travel and the load size is positively related to several cycle elements (Tufts and others 1988). The unexplained variance in regression equations includes stochastic events and factors related to the system and terrain which are often too complex or too difficult to quantify.

Meta-analyses of production rates or terra-mechanical (TM) approaches to estimating skidder productivity are also feasible alternatives to regression. Mellgren (1990) developed a meta-analysis approach with the estimation of baseline load size and speed. Load size and speed are adjusted using surface roughness and slope parameters. Several authors (Iff and others 1984, Olsen and Gibbons 1983, Spong 2001) developed TM skidder models using the approach developed by Wismer and Luth (1974). Other TM approaches have also been applied to analyze skidder performance (Curro and Verani 1990, Phillips 1983, Sever 1990). The TM models estimate the total drawbar pull available and the total resistance and provide for an estimate of potential machine speed. The independent variables needed for the TM approach (machine size, load, and terrain) are similar to those used in the regression and meta-analysis approaches. The TM approach requires simplifying assumptions, and the adoption of the approach to estimate production has been limited due to the complexity. However, TM approaches have been applied to forest machine performance related to soil-machine interactions (Ala-Ilomäki 1993, Eichrodt and Heinimann 2001, Wasterlund 1994).

The advantage of the TM approach is the exploration of feasible combinations of machine speed (empty and loaded) and load size given terrain and machine parameters. Understanding load and speed tradeoffs may be important to managing machine productivity (t pmh^{-1}), fuel efficiency (t mJ^{-1}), (Manner and others 2016), and operator comfort (Wegscheid 1994). The objective of this analysis is to estimate TM parameters from published skidder production data and compare TM results to a traditional regression approach. We applied TM parameters to build a model for skidder performance which identified the likely performance envelope given machine, load, and terrain parameters.

MATERIALS AND METHODS

We searched for literature which included data for four-wheel, grapple skidder productivity in conference proceedings, technical reports, and theses and dissertations for publication dates from 1995 through 2019. The starting date was chosen as balance between including mostly modern machines considering engine power, weight, and operators' stations and achieving a sample number of 100. We searched systematically through report series, conference proceedings, and journals known for forestry production studies. That search was supplemented with keyword searches in Google Scholar, AGRICOLA (National Agricultural Library, U.S. Department of Agriculture), CAB (Centre for Agriculture and Bioscience International), and Treesearch (Forest Service, U.S. Department of Agriculture) databases. Criteria for inclusion were cycle time and element times, skid distance, load size, indicators of terrain (slope and soil strength), and machine make and model.

Assumptions for the TM approach were designed to yield conservative estimates of net traction and speed (table 1). Ashmore and others (1987) developed net traction relationships for skidder tires which are more conservative than Wismer and Luth (1974). Iff and others (1984) and Olsen and Gibbons (1983) used specific skidder and load dimensions to determine wheel loads and net traction efficiency. We developed assumptions for wheel loads and load transfer to account for unknowns in weight distribution. In practice, operators can manipulate grapple position to affect load weight distribution and machine performance. We assumed equal static weight distribution across the four wheels to generate the most conservative estimate of net traction efficiency.

Table 1—Model assumptions for terra-mechanical estimates

Variable	Formula	Units	Source[a]
Adverse slope	I	degrees	Citation
Skidder weight	S	N	OEM or citation
Skid load	L	N	Citation
Gross engine power	E	kW	OEM or citation
Static load transfer to skidder	$T = (0.6)(L)$	N	Hassan and Sirois (1983)
Tire width and diameter	b, d	cm	TRA (2000)
Tire rated load	W_r	N	TRA (2000)
Wheel slip	$V = 0.20$ (loaded), 0.10 (empty)	N/A	—
Cone index	CI	N cm^{-2}	—
Static wheel load	$W = 0.25(T + S)$	N	—
Wheel numeric	$C_n = (CIbd)W^{-1}$	N/A	Wismer and Luth (1974)
Skidding coefficient	$R_c = 0.78$ (delimbed), 0.72 (limbs)	N/A	Hassan and Gustafson (1983)
Pull for skidding resistance	$R = (L - T)R_c$	N	Hassan and Gustafson (1983)
Net traction	$PW^{-1} = 0.47\,(1 - e^{-0.2C_nV}) + 0.38(WW_r^{-1}) - 0.22(C_n^{-1}) + 0.20$	N/A	Ashmore and others (1987)
Towed force	$TFW^{-1} = -0.10(WW_r^{-1}) + 0.22(C_n^{-1}) + 0.20$	N/A	Ashmore and others (1987)
Grade resistance	$G = \sin I(W + L - T)$	N	—
Maximum speed	$L_{max} = 1000\{E\}\{0.85\}\{4[TF] + R + G\}^{-1}$	m s^{-1}	—

[a] Sources for data are either the original equipment manufacturer (OEM) or the published article (citation). The sources for formulas are presented by author and year of publication.
— = Engineering formula (no attribution).

We classified soil conditions as wet, moist, or dry based on available evidence from the study and assigned cone index values of 88, 120, and 200 N cm^{-2}, respectively (Burger 1994). We used a slip estimate of 0.10 and 0.20 for empty and loaded travel since the observed values for forest machines in working conditions have been <0.20 (Ala-Ilomäki 1993, Fernandes and others 2008, Ringdahl and others 2012, Saarilahti and Ala-Ilomäki 1997).

Coefficients of weight transfer and skidding resistance were from Hassan and Sirois (1983) and Hassan and Gustafson (1983), respectively. For studies that reported load size and productivity in volume, we converted load volume to mass using specific gravity and average green moisture content from Miles and Smith (2009) for most species and from Skolmen (1983) for eucalyptus. The conversions did not consider expected variation in density and moisture content due to genetics, site, and silvicultural treatments. In many studies, determining whether load size was merchantable volume to a small-end diameter or whole-tree mass or volume was difficult. In the regression approach, we added a dummy variable of 0 where the volume or mass estimate appeared to include only roundwood to a merchantable top or 1 where the volume or mass estimate appeared to include merchantable volume, branches, and tops. Statistical significance was set at $\alpha = 0.1$.

RESULTS

We found 33 publications which included data for 77 cycle time means that met our criteria and 14 publications missing data for model building but useful for model validation. References and sample attributes from publications for model building are included in the appendix. Most publications were from operations in North America. For the model building dataset, there was an average of 73 cycles per mean. The tire size data were included in eight studies, and operator experience was specifically discussed in seven studies. Most cycle time means (67) were from full-tree systems, and just eight were from systems with chainsaw felling. Forty-seven means were exclusively from clearcuts, and the rest were either from thinnings, partial cuts, or a combination of clearcuts and partial cuts. Few publications included the machine age, and machine models are typically produced for several years. As an indicator of machine age, the median publishing year was 2007 with a range from 1995 through 2019. The data from the original equipment manufacturer (OEM) for gross engine power and mass are presented in figure 1, with median values of 140 kW and 14.7 t, respectively. The machines included in this dataset and those from Tufts and others (1988) are included for

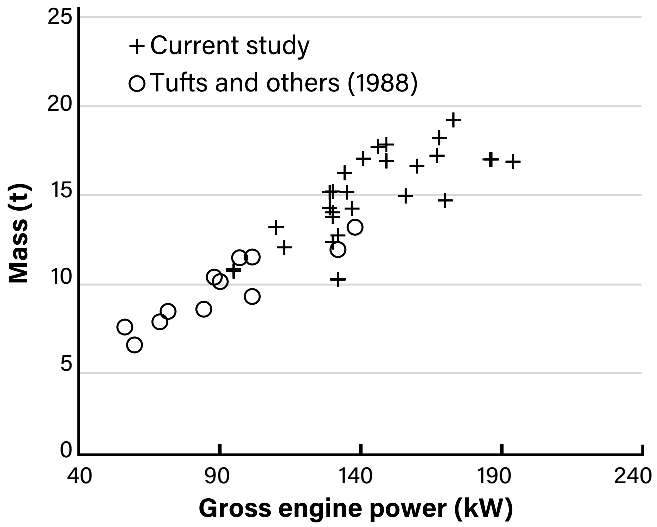

Figure 1—Machine mass and gross engine power from the current study and those from Tufts and others (1988).

comparison. Transmission type was seldom included in the study narrative, so those data were not included.

Statistics for cycles and elements and parameters for the cycle, load, and machine are presented in table 2. Maneuver time included grapple and maneuver elements and all other nontravel elements in the woods. Some studies had times for travel between grapple and maneuver elements (intermediate travel) which added an average of 0.12 min cycle^{-1} to maneuver time. Unloading elements and all landing activities including gate delimbing were summed in landing. Fifty-two samples included productive delay time, and the average delay was 1.22 min cycle^{-1}. Only two studies indicated that the skid distance given was the straight-line distance; we applied a wander factor of 1.12 from Ackerman and others (2014) to estimate traveled distance. Estimates indicated as round-trip distances were divided equally into travel loaded and travel empty distances. The productivity estimate (t pmh^{-1}) in the studies might be a function of cycle time and load size or from other concurrent data like a gross production study. The cycle time calculated by dividing productivity by average load size yielded a cycle time of 4.15 minutes compared to a mean cycle time of 5.8 minutes. The cycle times were similar at 4.65 and 4.49 minutes, when estimated using median productivity and load size and median cycle time, respectively.

The Pearson correlation coefficients showed many of the expected significant correlations among dependent variables (productivity, cycle, and element times) and independent site and machine variables (table 3). Machine mass had significant correlations ($p < 0.10$) with element times, cycle time, and productivity. Engine power was significantly correlated with load mass and productivity. Tire size largely came from OEM data and tire contact area was significantly correlated to machine mass and engine power. Tire contact area and load mass were the only independent variables significantly correlated with maneuver time. The relationships which might reveal confounding factors include significant correlations between travel distance with tree size and tree number per load. The range in loaded travel distance was well distributed among skidder sizes, ranging from 40 to 400 m.

Application of the TM approach provides for the estimation of gross and net traction and potential loaded and empty travel speeds. Source of potential error in these estimates included the estimation of slope, soil conditions, and load transfer and load distribution by axle. Errors due to incorrect tire size were probably small since most tire size options listed by the manufacturers produced only a small difference (<5%) in wheel numeric. Finally, the assumption of wheel slip at 0.20 for loaded conditions and 0.10 for empty conditions could lead to a conservative estimate of speed and an overestimate of net traction.

Due to the potential for error in assumptions, we removed outliers based on a regression of observed speed versus estimated maximum loaded and empty travel speeds. Four observed values from three studies with studentized residuals >2.0 (or -2.0) were removed as outliers. In these observations, residuals for both loaded and empty speeds exceeded the threshold, so assumptions for machine, skidding, or terrain parameters were likely incorrect.

Table 2—Element and cycle time statistics and statistics for parameters for the cycle, load, and machine

Class	Attribute	Average	Median	10th percentile	90th percentile	Number of samples
Time (min)	Travel empty	1.44	1.23	0.63	2.58	77
	Travel loaded	1.85	1.74	0.78	3.07	77
	Maneuver	1.37	0.88	0.40	2.70	77
	Maneuver (with travel)	1.50	0.95	0.40	2.83	77
	Landing	0.81	0.71	0.11	1.49	77
	Delay	1.22	0.52	0.04	2.75	52
	Cycle time (delay-free)	5.80	4.49	2.37	9.71	77
Parameters	Loaded skid distance (m)	178	150	70	310	77
	Load size (t)	2.9	2.7	1.5	4.5	77
	Tree size (kg)	379	287	110	806	73
	Trees per load	12.3	8.8	3.7	24.9	73
	Productivity (t pmh^{-1})	41.9	34.8	12.5	70.7	77
	Slope (%)	7	5	3	15	77
	Engine power (kW)	140	132	110	170	77
	Machine mass (t)	14.7	15.2	10.3	17.8	77
	Tire contact area (m^2)	1.55	1.60	1.31	1.77	77

Table 3—Correlation (Pearson) coefficients for variables including cycle and element times, production, and harvest, load, and machine variables

Variables	Cycle time	Loaded travel	Empty travel	Maneuver	Maneuver with travel	Landing	Tree size	Tree number/ load	Load mass	Mean slope	Loaded travel distance	Productivity	Engine power	Machine mass
Loaded travel	0.60[a]													
Empty travel	0.58[a]	0.76[a]												
Maneuver	0.87[a]	0.32[a]	0.26[b]											
Maneuver with travel	0.89[a]	0.36[a]	0.31[a]	0.97[a]										
Landing	0.64[a]	0.08	0.11	0.57[a]	0.56[a]									
Tree size	-0.01	-0.15	-0.06	0.00	-0.04	0.14								
Tree number/load	-0.13	0.05	-0.02	-0.11	-0.06	-0.28[b]	-0.54[a]							
Load mass	-0.21[c]	0.00	-0.03	-0.25[b]	-0.22[c]	-0.20[c]	0.16	0.27[b]						
Mean slope	-0.01	0.03[c]	0.26[b]	-0.09	-0.11	0.03	0.05	-0.20[c]	-0.13					
Loaded travel distance	0.31[a]	0.72[a]	0.49[a]	0.08	0.12	-0.15	-0.33[a]	0.32[a]	0.18	-0.05				
Productivity	-0.53[a]	-0.40[a]	-0.46[a]	-0.42[a]	-0.43[a]	-0.34[a]	0.22[c]	0.13	0.72[a]	-0.07	-0.14			
Engine power	-0.20[c]	-0.03	-0.07	0.06	-0.08	0.10	-0.03	0.09	0.47[a]	0.07	0.09	0.35[a]		
Machine mass	-0.30[a]	-0.30[a]	-0.22[c]	-0.09	-0.15	-0.05	0.13	0.03	0.31[a]	0.21[c]	-0.15	0.29[b]	0.69[a]	1
Tire contact area	-0.24[b]	-0.14	0.00	-0.32[a]	-0.26[b]	-0.11	0.00	-0.02	0.33[a]	0.14	-0.03	0.25[b]	0.44[a]	0.24[b]

[a] $p < 0.01$ [b] $p < 0.05$ [c] $p < 0.10$

Regression Approach

The stepwise models for elements, cycle time, and productivity were highly significant ($p < 0.01$) (table 4). We forced machine mass into the stepwise models for empty and loaded travel time, cycle time, and productivity to represent machine size. Machine mass was significantly correlated with more dependent variables than engine power (table 3). The maneuver and landing element models had relatively low R^2 values at <0.20. The maneuver model included aspects of machine size (tire contact area and power) and the cycle (skid distance and load). The landing model included skid distance and tree number. The machine mass parameter estimate was significantly different from 0 ($p < 0.10$) in the cycle time and observed productivity models but not in the travel models. An interaction with machine size was included in loaded travel (power) and cycle time (mass) models. Model significance values and correlation coefficients were typical of skidder models considering productivity and travel time models. The low F value and R^2 for the cycle time model were unusual. Individual parameter estimates demonstrated mostly expected results considering skid distance and load size. It was notable that slope was significant in the empty but not the loaded travel model. The positive parameter estimate for biomass in the productivity model may indicate more measured mass per cycle considering the stems, limbs, and tops.

We estimated times and productivity with the stepwise models using mean machine, load, and site values from Tufts and others (1988) and the current data. We assumed the average tire size in Tufts and others (1988) was a 28L-26

Table 4—Stepwise model results with entry and exit probabilities ≤0.10 for major elements, cycle time, and observed and estimated productivity

Variable	Code	Model
Maneuver	*V*	3.52 — 1.651(*a*) + 0.0000586(*p*)(*ed*) — 0.00193(*w*)(*ed*)
Landing	*L*	0.975 — 0.0000527(*n*)(*ld*)
Empty travel (min)	*ET*	0.204 — 0.00412(*m*) + 0.00591(*ed*) + 3.51(*s*) + 0.124(*w*) — 0.00114(*n*)(*m*)
Loaded travel (min)	*LT*	1.25 — 0.043(*m*) + 0.00584(*ld*) — 0.0000737(*n*)(*ld*) + 0.0000198(*p*)(*ed*)
Cycle time (min)	*CT*	9.52 — 0.387(*m*) — 0.0934(*n*) — 0.0014(*m*)(*ed*)
Productivity (cycle time – t pmh^{-1})	*PC*	2.96 — 0.641(*m*) + 21.2(*w*) + 0.0151(*w*)(*ed*) — 0.0527(*w*)(*ld*)
Productivity (observed – t pmh^{-1}) [a]	*PO*	14.25 — 1.64(*m*) + 22.41(*w*) — 0.0369(*w*)(*ed*) + 9.26(*b*)

Variable	Code	Tufts [b]	Current [b]	R^2	F	MSE	df
Maneuver (min)	*V*	1.76	1.48	0.18	4.81	2.0006	68
Landing (min)	*L*	0.89	0.86	0.08	5.49	0.4443	68
Empty travel (min)	*ET*	1.46	1.52	0.64	22.32	0.2782	68
Loaded travel (min)	*LT*	2.05	1.95	0.65	29.09	0.3798	68
Cycle time (min)	*CT*	7.09	6.01	0.30	9.25	10.362	68
Productivity (cycle time – t pmh^{-1})	*PC*	20.3	37.1	0.73	43.45	229.30	68
Productivity (observed – t pmh^{-1})	*PO*	23.6	37.0	0.71	39.03	202.03	68

Variable	Code	Tufts [b]	Current [b]
Engine power (kW)	*p*	91	140
Machine mass (t)	*m*	9.77	14.7
Loaded distance (m)	*ld*	178	178
Empty distance (m)	*ed*	163	163
Round-trip distance (m)	*rd*	341	341
Slope (%)	*s*	7	7
Trees per load	*n*	9.3	12.2
Load mass (t)	*w*	1.55	2.85
Tire contact area (m^2)	*a*	1.3	1.5
Biomass	*b*	0 [a]	0 [a]

[a] The value for the dummy variable for biomass (*b*) is 0 when only merchantable volume is in measured load mass (*w*).
[b] Models estimated element, cycle time, and productivity values with either average machine values and cycle values from Tufts and others (1988) or from the current average values.

for estimation of the tire contact area. For the 1988 skidders, the smaller machines and load sizes resulted in predictions of slightly longer element times and considerably longer cycle times and lower productivity. The full-tree skidding cycle time model from Tufts and others (1988) for assumptions in table 4 estimated the productivity at 23 t pmh^{-1} which compares to estimates of about 20–23 t pmh^{-1} from the current regression models. The R^2 values in Tufts and others (1988) were in general higher than those for the current data, but there were no other model statistics to compare.

Terra-Mechanical Approach

We displayed the ratio of total resistance (sum of towed force, grade resistance, and skidding resistance) to the gross pull estimated during the loaded element in figure 2. The ratios were mostly between 0.25 and 0.60 and were unrelated to machine weight (fig. 2). Since there was excess gross pull in nearly all cases, we might have solved for a slip that produced a specific traction efficiency. However, the lack of standard methods for determining average slope and soil strength reduced the feasibility of that approach.

The empty speed chosen may represent the operator's tradeoff between ride quality and achieving production expectations. That tradeoff could be influenced by training and individual preferences. A kernel analysis with empty speed and the ratio of empty to loaded speed showed that 80% of the observations had a ratio of empty to loaded speed <1.5 and a range in empty speeds from 0.74 m s^{-1} to 4.1 m s^{-1}. However, the greatest density of observations occurred at empty speeds <3.0 m s^{-1}.

We conducted a bivariate kernel analysis of the ratio of observed to maximum loaded speed (workload ratio) and the ratio of load mass to machine mass (load ratio). We found most (80%) of the values were between a workload ratio of 0.43 and 1.12 and a load ratio between 0.12 and 0.35. The greatest density of values occurred at workload ratios <0.9 and load ratios <0.24. Half of the observed values were between load ratios of 0.14 and 0.26 and workload ratios of 0.45 and 0.81. Selection of load and speed combinations were mostly independent of engine power since neither was highly correlated at 0.18 and 0.12, respectively.

We developed two approaches for a TM model, both using skid distance and load size as inputs to calculate productivity from delay-free cycle time. Machine, load size, and terrain parameters were used to estimate maximum speed for loaded and empty travel. For the first TM model (P_{TM1}), we used average parameters from the dataset including average speed ratios (E_r and L_r) and average combined maneuver ($\overline{V}$) and landing ($\overline{L}$) times. For each sample, we estimated maximum empty (E_{max}) and loaded speeds (L_{max}) from machine, load, and terrain parameters. The predicted productivity using this method resulted in an mean square prediction error (MSPE) of 1,151. The result compared unfavorably to the mean square error (MSE) of about 200 for the stepwise regression models.

For the second TM model (P_{TM2}), we developed a nonlinear equation where we avoided issues with the high correlation between loaded and empty travel speeds by estimating a parameter for round-trip skid distance ($ed + ld$). The estimated parameters were fitted in PROC NLIN (SAS-Institute 2016) and are presented in equation (2) where 0.984 (standard error 0.224) and 107.1 (standard error 20.4) were fitted parameters. The model statistics included an F value of 167.1 and MSE of 565.0. Since the estimated E_{max} was about 50% greater than L_{max}, the round-trip speed indicated by the model was significantly below the maximum speed but greater than the ratios used in used in equation (1). Fixed

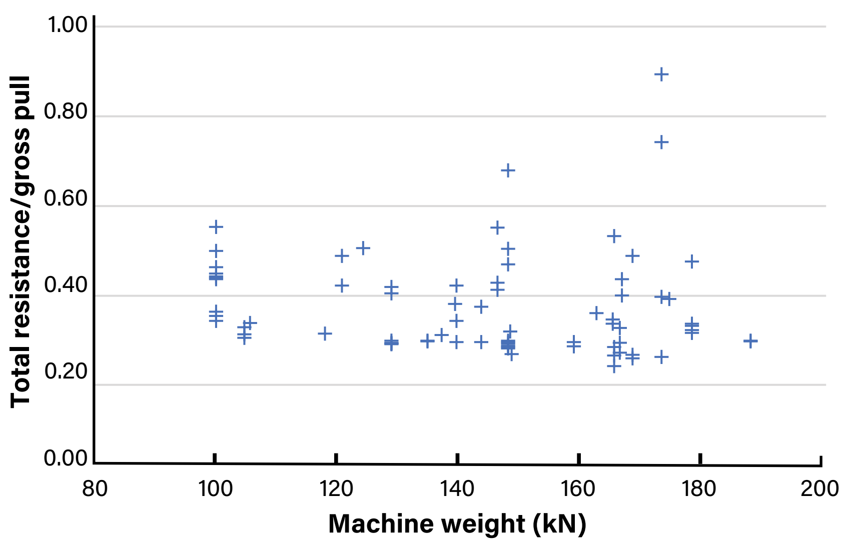

Figure 2—Estimates for the ratio of total resistance to gross pull for each skidder observation compared to machine weight.

time per cycle added 107.1 seconds to the cycle compared to the mean for maneuver and landing time of 154 seconds used in equation (1) and to the median values of 95 s cycle^{-1}.

$$P_{TM1} = w\,\{3600[(ed\{E_r\,E_{max}\}^{-1}) + (ld\{L_r\,L_{max}\}^{-1}) + \overline{V} + \overline{L}]^{-1}\} \quad (1)$$

where

$E_r = 0.50$
$L_r = 0.62$
$\overline{V} = 94$
$\overline{L} = 60$

$$P_{TM2} = w\,\{3600[(\{(ed + ld)\}\{0.984L_{max}\}^{-1}) + 107.1]^{-1}\} \quad (2)$$

We accumulated 14 studies that did not meet the criteria for inclusion in the first dataset because they were missing one or more components, typically element analysis. In total, we had 33 samples with a range in observed productivity from 8 to 153 t pmh^{-1} and engine power from 110 to 194 kW. The references for model validation are included in the appendix. We estimated an MSPE for the two regression models and the two TM models. The plot of residual values and predicted values for the two best models is presented in figure 3. Four of the 33 samples did not have enough parameters to fit the regression models. The linear regression models had an MSPE of 1,755 and 1,523 for the cycle time and observed models, respectively. The TM model based on mean values (eq. [1]) had even greater MSPE at 2,201. The nonlinear TM model (eq. [2]) had the lowest MSPE of the group at 769 compared to the model MSE of 565. There appeared to be some bias in all models with significant negative correlations between the residual and observed values. Only one observation had a residual value in excess of ± 50 for all four models. When that data point was removed, the MSPE for the linear regression equations dropped by 6% (observed) and 11% (cycle time) and by 25% (eq. [1]) and 33% (eq. [2]) for the TM models. With the outlier removed, the MSPE for the TM nonlinear model (eq. [2]) was 574 or nearly the same as the model MSE.

DISCUSSION

Ghaffariyan (2021) recently reviewed skidder production studies and found that independent variables affecting productivity are fairly consistent and silvicultural and system interactions are an important determinant in machine productivity. The relationships identified in this study are consistent with other studies in regard to the simple statistics, correlations, and stepwise regression. Even the predicted values from the current equations are not much different from those predicted by a model from more than 30 years earlier (Tufts and others 1988). While the newer machines are significantly larger, the basic relationships were robust because they rely mostly on skid distance and load size. In interpreting the predicted values, the 95% confidence intervals for the predicted values were quite large, limiting the utility of interpretation of subtle differences in inputs.

Aspects of the terrain data were estimated with various levels of certainty. Soil conditions were derived from clues in the text about time of year, precipitation, soil type, rutting, etc. Slope data were sometimes given directly and other times as a qualitative description (e.g., flat, gently sloping, etc.). We do not have a great deal of confidence in those data, which could be a source of significant error in the TM estimates. Additionally, we would expect roughness to be a factor in machine productivity, but there was limited quantitative or qualitative information across the studies. Production differences due to slope can be detected at the extremes, but the effects of smaller changes are more difficult to detect (Diniz and others 2019). Mellgren (1990) also suggested that extreme values of slope and roughness affect machine speed.

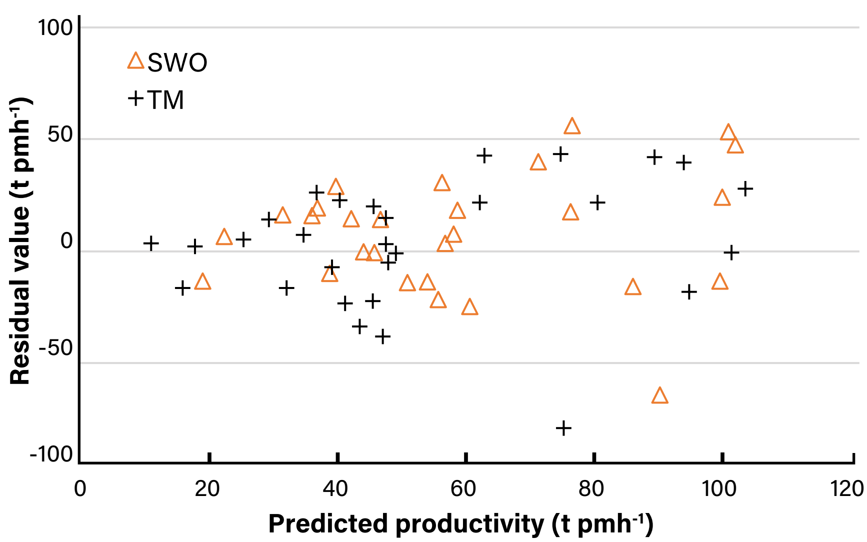

Figure 3—Predicted and residual values from the validation data from the linear stepwise regression (SWO) model with observed productivity and the nonlinear terra-mechanical (TM) model.

Productivity is likely to decline with lower soil strength as operators accommodate the conditions and attempt to avoid rutting by reducing load size to reduce sinkage and avoid wheel slip (Ala-Ilomäki 1993). In these data, the range in soil conditions was limited to mostly firm soil conditions.

Operators respond to multiple influences to determine both load size and speed. The load size that operators choose is influenced by grapple limitations, critical points in the path, or limitations in bunch or tree selection. The precise load size is only partially within the skidder operator's direct control, although crew-based tradeoffs for whole-system productivity could be considered in balancing system performance (Gingras 1988). Gingras (1988) suggested that accumulating larger loads is more important at longer skid distances since maneuver time becomes a smaller proportion of cycle time. In these data, the correlation with skid distance was significant for tree number per load but not load mass.

Few of the observations were near what other studies had estimated as the skidder optimal load size considering the tradeoff between speed and load size. Curro and Verani (1990) estimated an optimal load which would have been 50% of machine mass for the skidder tested. Colton and Brink (1999) estimated optimal loads of 45% to 75% of machine mass on nearly level ground using the approaches from Curro and Verani (1990) and three other methods. In operational data, they found loads were about 60% of the estimated optimum or 30% to 45% of machine mass. The skid load masses in Tufts and others (1988) were all <20% of machine mass.

Load building from more than one bunch requires an operator to make an initial decision about the collection of the first bunch and then dependent decisions about whether to accumulate other bunches. The time per cycle increased when skidders accumulated more than one bunch (Jernigan and others 2016, Tufts and others 1988) in order to maintain or increase the load per cycle when dealing with less than optimal bunch size. In Klepac and Mitchell (2016), increases in bunch number and load mass caused by feller buncher type (rubber-tired to tracked) did not result in increased productivity. While bunch and load size have been observed and modeled (Hiesl and others 2015, She and others 2018), how operators approach the tradeoffs is important. For any skid cycle, the penalty for overloading (losing a part of the load or loss of trafficability) is probably greater than for underloading (low productivity).

STMM MODEL

We used the nonlinear TM model (eq. [2]) to develop a spreadsheet-based production model called the Skidder Terra-Mechanical Model (STMM) to estimate productivity given the machine, terrain, and load parameters. The model approach estimates a value based on the fitted parameters for equation (2) and productivity for the range in observed values of workload and load ratio. We assumed that the most important factor determining operator behavior was the expectation for shift-level production. Since shift-level production is somewhat stable due to the harvest system constraints, operator behavior might conform to production expectations. The model results for mean productivity and a range of ± 10% are estimated, and those results are highlighted. Additionally, the model estimates productivity for most of the observed values from the dataset, with a range that includes 80% of the observations and another range that includes 50% the observations. The results are expressed as productive hours per shift and miles traveled per shift. Combinations of load size and speed that fail to meet at least 90% of the shift production goal are not shown.

Model users can select a skidder from the dataset or directly input gross engine power and mass. Once engine power is selected, the input for mass is limited by the range in observed data (fig. 1). When users select tire size, a warning is displayed if the static load approaches or exceeds the rated load for the tire with the likely range in load size. An example for a specific set of inputs and basic assumptions and the results of the calculations are displayed in table 5. From those inputs, the estimated productivity of 48.4 t pmh^{-1} required 4.7 machine hours to achieve the production goal of 225 t $shift^{-1}$.

Users can allow metric units to be shown in the interface, but the model results are displayed in imperial units which are more commonly used in the United States. Using the inputs from table 5, an example for productive hours per shift is shown in figure 4. The full range of results represents 80% of observations of workload (observed loaded speed:maximum loaded speed) and range in load size. Load size is estimated from machine mass and the observed range in load ratio (load mass:machine mass). The TM model estimate and ± 10% is highlighted in green. The bordered range in the center includes 50% of the bivariate range of observations in workload and load ratio. Results that exceed the productivity estimate from the TM model have blue background, and those which are less have a yellow background. If the combinations of workload and load ratio do not achieve at least 90% of the shift production goal, the values are not displayed.

The effect of load size is evident in miles traveled per shift (fig. 5). The range in miles traveled for 50% bivariate distribution ranged from 9 to 16 miles traveled per shift. The two measures (hours and miles traveled) provide skidder efficiency metrics indicating that relatively small changes in load size can maintain productivity while reducing machine speed and controlling operating hours.

Table 5—Assumptions and example calculations for the Skidder Terra-Mechanical Model (STMM)

Variable	Value	Units	Source
Shift-level production	225	t $shift^{-1}$	Input
Productive delay	5%	—	Input
Machine mass	18.423	t	Input
Engine power	149	kW	Input
Tire contact area	2.00	m^2	Input
Skid distance (one way)	148	m	Input
Slope (adverse - loaded)	5%	—	Input
Cone index (*CI*)	128	N cm^{-2}	Input
Load transfer (ratio)	0.6	—	Assumption
Wheel load (*W*)	45.14	kN	Equation (see table 1)
Wheel numeric (C_n)	56.48	—	Equation (see table 1)
Wheel slip (*V*)	0.20	—	Equation (see table 1)
Pull at wheel slip (*P*)	76.04	kN	Equation (see table 1)
Rolling resistance (*RR*)	5.90	kN $wheel^{-1}$	Equation (see table 1)
Grade resistance (*GR*)	9.67	kN	Equation (see table 1)
Skidding resistance (*SR*)	10.27	kN	Equation (see table 1)
Total resistance (*TR*)	10.89	kN $wheel^{-1}$	Equation (see table 1)
Ratio (*TR:P*)	0.57	—	Equation (see table 1)
Maximum speed (L_{max})	2.33	m s^{-1}	Equation (see table 1)
Model production rate (with delay)	48.4	t pmh^{-1}	Equation (see table 1)
Travel time	2.4	min $cycle^{-1}$	Equation (see table 1)
Productive machine hours (*pmh*)	4.7	pmh $shift^{-1}$	Calculation
Cycle time	4.2	min $cycle^{-1}$	Calculation
Total travel time	2.68	hr $shift^{-1}$	Calculation
Total maneuver and landing time	2.03	hr $shift^{-1}$	Calculation
Productive delay time	0.23	hr $shift^{-1}$	Calculation
Nonoperating time	4.31	hr $shift^{-1}$	Calculation
Estimated travel speed	2.08	m s^{-1}	Calculation

Productive hours per shift

Workload (% of engine power)		30%	40%	50%	60%	70%	80%	90%
	6.1	5.3	4.0	3.2	2.7	2.3	2.0	1.8
	5.7	5.5	4.1	3.3	2.8	2.4	2.1	1.9
	5.3	5.8	4.3	3.5	2.9	2.5	2.2	1.9
	4.9	6.1	4.6	3.6	3.0	2.6	2.3	2.0
	4.5	6.4	4.8	3.9	3.2	2.8	2.4	2.2
Range in load size (tons)	4.1	6.8	5.1	4.1	3.4	2.9	2.6	2.3
	3.6	7.3	5.5	4.4	3.7	3.2	2.8	2.5
	3.2	7.5	6.0	4.8	4.0	3.4	3.0	2.7
	2.8		6.6	5.3	4.4	3.8	3.3	3.0
	2.4		7.4	6.0	5.0	4.3	3.7	3.3
	2.0			6.9	5.7	4.9	4.3	3.9

Figure 4—Productive hours per shift from Skidder Terra-Mechanical Model (STMM) results for the inputs and assumptions in table 5. Values shaded in green are within 10% of the model-predicted value. The values displayed represent 80% of the observations, and the bordered region contains 50% of the observations.

Miles traveled per shift

Workload (% of gross power)		30%	40%	50%	60%	70%	80%	90%
	6.1	7.6	7.6	7.6	7.6	7.6	7.6	7.6
	5.7	8.1	8.1	8.1	8.1	8.1	8.1	8.1
	5.3	8.8	8.8	8.8	8.8	8.8	8.8	8.8
	4.9	9.5	9.5	9.5	9.5	9.5	9.5	9.5
	4.5	10.3	10.3	10.3	10.3	10.3	10.3	10.3
Range in load size (tons)	4.1	11.4	11.4	11.4	11.4	11.4	11.4	11.4
	3.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
	3.2	13.4	14.2	14.2	14.2	14.2	14.2	14.2
	2.8		16.3	16.3	16.3	16.3	16.3	16.3
	2.4		19.0	19.0	19.0	19.0	19.0	19.0
	2.0			22.8	22.8	22.8	22.8	22.8

Figure 5—Miles traveled per shift from Skidder Terra-Mechanical Model (STMM) results for the inputs and assumptions in table 5. Values shaded in green are within 10% of the model-predicted value. The values displayed represent 80% of the observations, and the bordered region contains 50% of the observations.

CONCLUSION

The model results indicate opportunities to increase machine productivity and reduce machine travel speed by increasing load size. The majority of previous grapple skidder studies appear to show underutilized load capacity. Colton and Brink (1999) demonstrated an average load ratio of 30% to 45% was possible with cable skidding. That ratio was greater than most of the grapple skidder observations. However, optimizing load size in grapple skidding might face a number of practical limits like load-building efficiency of the skidder or bunch-size constraints from the feller-buncher (Gingras 1988). In addition to simply increasing productivity, trading bigger load sizes for slower loaded speeds would appear to have a number of benefits like reduced site traffic, reduced fuel consumption per unit volume, and potentially reduced WBV exposure on the operator. The relationship between higher WBV and speed seems likely (Eger and others 2011, Marin and others 2016), but a quantitative relationship is needed for skidders. Most operators choose or are directed to drive speeds and shift lengths that subject them to WBV exposure that could have cumulative health effects (Lynch 2017, Neitzel and Yost 2002, Wegscheid 1994).

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APPENDIX

References and attributes for model building and model validation datasets

Model building

Reference	Region	Number of samples	Number of cycles
Ackerman and others (2014)	South Africa	1	34
Andersson and Evans (1996)	Alberta, Canada	11	560
Brinker and others (1996)	Southern United States	4	106
Diniz and others (2019)	Brazil	3	378
Folegatti (2004)	Southern United States	6	297
Ghaffariyan (2013)	Western Australia	1	56
Ghaffariyan and others (2011a)	Western Australia	1	108
Ghaffariyan and others (2012)	Western Australia	1	58
Klepac and Mitchell (2016)	Southern United States	4	139
Klepac and Mitchell (2018)	Eastern United States	1	30
Klepac and Rummer (2000)	Southern United States	2	67
Klepac and Rummer (2004)	Western United States	1	20
Klepac and others (2001)	Southern United States	3	98
Klepac and others (2011)	Southern United States	1	30
Kosicki (2003)	British Columbia, Canada	3	234
Kosicki (2005)	British Columbia, Canada	1	384
Kulak and others (2017)	Poland	3	326
Lanford and Stokes (1996)	Southern United States	1	20
Lopes and others (2007)	Brazil	2	203
Mousavi and others (2012)	Iran	1	58
Mousavi and others (2013)	Iran	1	48
Nishio (2010)	British Columbia, Canada	2	90
Pereira and others (2015)	Brazil	3	NA
Phillips (1997)	Saskatchewan, Canada	1	86
Plamondon and Brais (2000)	Quebec, Canada	2	NA
Renzie (2006)	British Columbia, Canada	3	1,066
Sambo (2003)	British Columbia, Canada	1	130
Smidt and McDaniel (2012)	Southern United States	1	77
Spinelli and Hartsough (1999)	Western United States	1	154
Strandgard and others (2019)	Western Australia	3	NA
Thibodeau and others (1996)	British Columbia, Canada	3	453
Vitorelo and others (2011)	Western United States	4	128
Wang and others (2004)	Eastern United States	1	150

Model validation

Reference	Region	Number of samples	Number of cycles
Bolding and others (2009)	Western United States	1	120
Ghaffariyan and others (2011b)	Western Australia	1	NA
Ghaffariyan and others (2013)	Western Australia	2	21
Gingras (2006)	New Brunswick, Canada	2	NA
Gingras and Godin (2001)	Ontario, Canada	2	NA
Halbrook and Han (2005)	Western United States	1	88
Jernigan and others (2016)	Southern United States	1	59
Kosicki (2007)	British Columbia, Canada	4	289
Lopes and others (2014)	Brazil	2	370
Ngulube and others (2014)	Malawi	1	412
Reisinger and Gallagher (2001)	Eastern United States	2	28
Riopel and others (2000)	Quebec, Canada	2	NA
Sauder and MacIsaac (2004)	Alberta, Canada	11	NA
Visser and Stampfer (2003)	Eastern United States	1	29

NA = Data not available.

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Studies of skidder productivity typically involve a range of conditions that support specific study objectives related to harvest system, terrain, forest attribute, or other aspects of the harvest. Skidder production models often fit the data well because cycle time and productivity are strongly related to load size and skid distance. Changes in skidder design over time have increased load capacity, potential machine speed, and operator comfort. Since the harvest system often limits the observed range in speed and load size, the tradeoffs between those factors have not been a primary focus of production studies. We analyzed 33 studies with 77 estimates of skidder productivity using a typical regression approach and an approach based on the Wismer and Luth terra-mechanical (TM) relationships. The regression approach resulted in a good fit of productivity but poorer fits of cycle and element times. Nonlinear models developed with the TM approach also fit but had larger values for mean square error (MSE) than the linear regressions. The use of 14 additional studies with 33 estimates as validation data produced a lower mean square prediction error (MSPE) for nonlinear TM models when compared to the linear regression models. The TM approach allowed for the tradeoff between speed and load size to be modeled explicitly. We developed a spreadsheet production model to demonstrate the effect of choices made by harvest planners, logging managers, and operators on specific production goals.

Keywords: Logging, models, productivity, skidder, terra-mechanics.

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