BENCHMARKING COSTS OF FIXED-FRAME, ARTICULATED, AND TRACKED TRACTORS

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ABSTRACT. *Recent changes in the agricultural equipment market have led to increased costs associated with tractor ownership and operation. A regression analysis produced a linear model for purchase price based on a tractor's power and configuration (fixed frame, articulated, tracked). Projected purchase price and other cost contributors including fuel, repair and maintenance, housing, taxes, and insurance were used to predict hourly ($/h) and specific cost ($/kWh). Tractor cost per hour is proportional to power rating with marginal hourly cost independent of configuration. Specific cost for fixed frame and tracked tractors decreased slightly with increased power rating. Specific cost for articulated tractors remained constant at $0.56/kWh. This cost estimation can be used to make decisions related to machinery sizing and selection and budgeting.*

Keywords. *Fuel consumption, Power, Price, Spreadsheet, Tractor cost.*

Costs associated with owning, operating, and maintaining farm machinery is a major portion of farm operating costs. For example, crop budgets show machinery operating costs to be approximately 26% of the total cost for producing corn in the Midwestern United States in 2010 (USDA, 2014). Understanding these costs is important when selecting new equipment, for setting rental and lease rates, and when determining pricing for custom operations (Beaton, 2003). Buckmaster (2003) presented a benchmarking analysis which included a simple, user-friendly spreadsheet for estimating the cost of ownership of various sized tractors based primarily on published ASABE equations. This spreadsheet allowed users to compare the cost of owning and operating various sized tractors and provided benchmark values for selection algorithms. Using the equations for fuel and oil consumption, operators could also compare the costs of these inputs based on tractor size. Significant changes in the tractor market and economic context over the past decade make that previous work obsolete.

Since 2003, the cost of owning and operating tractors has increased due to several factors; namely inflation, new technology, and increased fuel price. The increase in prices attributed to inflation calculated using the consumer price indices from 2003 and 2014 is 37.2% (BLS, 2014). Within the last decade, Tier IV exhaust regulations have come into play; these resulted in i) additional fluid expense in the form of diesel exhaust fluid; a urea solution injected into the fuel stream to reduce nitrogen emissions in diesel exhaust, ii) improved fuel economy, and iii) increased purchase price due to increased complexity of the engine and controls. Regardless of the tractor brand or Tier IV solution implemented, the new compliant equipment costs an average of 5% more than similar previous non-compliant models (Patrico, 2010). Although fuel consumption has improved with this technology, it is not enough to offset the increased initial cost. The third major contributor to increasing cost of tractor operations is fuel cost. Over the last ten years, diesel fuel prices have risen 160%, exceeding general inflation by a significant percentage (EIA, 2014). The enhanced refinement process of ultra-low sulfur diesel is expected to continue this upward trend (EPA, 2000).

Increasing prices are not the only changes occurring in the tractors and related agricultural equipment. The current trend in agricultural equipment has been to go bigger with three distinct configurations: fixed frame, articulated, and tracked.

While works related to machinery sizing (Edwards, 2007; Sumner and Williams, 2007; Buckmaster, 2009) contribute to improved machinery sizing and selection decisions, the economic aspects, i.e., costs of the operations must be known to truly optimize farming operations. To facilitate proper agricultural machinery economic studies (budgeting, sizing, decision making), the objective of this work was to bring together prices and simple models for fuel and other operational costs of tractors into a simple tool for determining tractor costs for fixed frame, articulated, and tracked tractors.

Submitted for review in November 2014 as manuscript number MS 11074; approved as a Technical Note for publication by the Machinery Systems Community of ASABE in July 2015.

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Vol. 31(5): 741-745 ISSN 0883-8542 DOI 10.13031/aea.31.11074

MATERIALS AND METHODS

Tractor prices were obtained by collecting price data from the manufacturer's websites for four popular agricultural equipment brands (Case IH, 2014; Challenger, 2014; John Deere, 2014; New Holland, 2014). Within each class, models were selected to cover a range of power ratings. Power ratings for the fixed-frame class are expressed in rated PTO power, whereas the power ratings for the articulated and tracked classes are stated in engine power. Prices for fixed-frame, mechanical front-wheel driven tractors were obtained for the range of 75 to 325 kW (PTO rating per Nebraska/OECD testing); all units were fitted with cabs, duals on both axles, and standard features according to the manufacturer. Articulated tractors were priced for the range of 269 to 522 kW (engine rating); duals on all axles were used. Tracked tractors were priced for the range of 276 to 522 kW (engine rating) with track specifications taken as the standard option by the manufacturer. Since the power input is PTO equivalent for fixed frame tractors and net engine equivalent for the others, the engine-to-PTO driveline efficiency is included as an input to facilitate more fair comparisons across configurations.

The price data obtained were used to develop a regression model to predict tractor cost using the rated power and tractor class. Various models were tested to assess the goodness of fit and although tractor brand had a significant effect on purchase price, it was not included in the model identified below. The spreadsheet implementation described below, by default uses the price model; however, a user can override this generic prediction with improved data (for example, an actual price quote for a unit with specific options).

Figure 1 is a replication of the nearly complete spreadsheet model; only the repair and maintenance calculations are not shown. Inputs include the tractor power rating and the tractor type which enable the price prediction. The anticipated length of ownership and annual usage determine the cumulative use and were used in the repair and maintenance estimates which are based on ASABE EP496.3 equations (*ASABE Standards,* 2014b). These estimates were adjusted for the time value of money at the interest rate provided. It is worth noting that Calcante et al. (2013) did find repair and maintenance to be nominally twice that predicted by the ASABE relationships up to cumulative usage of about 6000 h. Taxes, insurance, and housing were modeled as a proportion of purchase price as in Buckmaster (2003).

Abbrev.	*Detailed description*	*Scenario 1*	*Scenario 2*	*Units*	*Documentation notes*
Inputs					
Pkw	tractor power	260	303	kW	
Ctt	code for tractor type	Fixed Fram	Articulated	1, fixed frame, 2 articulated, 3 track	
Ny	length of time to keep the tractor	6	6	years	
H	use of tractor each year	600	600	hours	
i	interest or discount rate	0.050	0.050	decimal/y	
Pf	price of fuel	1.01	1.01	$/l	
Pd	price of diesel exhaust fluid	1.00	1.00	$/l	
TIH	taxes, insurance, and housing	2.00	2.00	% of price/y	
Pp	operating power as a percent of rated power	80	80	%	affects fuel consumption
Sp	operating speed as a percent of rated speed	90	90	%	affects fuel consumption
Afc	Adjustment to fuel consumption due to technology	97	97	%	fuel consumption compared to tractors of 1980-2000
Epto	Efficiency of the driveline from engine to PTO	90	90	%	ASABE D497 suggests 90%
Intermediate					
P	list purchase price of tractor	317300	304870	$	(1030*Pkw) + IF(Ctt=1,49500,IF(Ctt=2,-7500,96400))
PkWpto	tractor power, PTO equivalent	260	273	kW	IF(Ctt=1,Pkw,Pkw*Epto/100)
RV	remaining value of tractor at end of period	40.7	40.7	%	D497 fn | 100*IF(PkWpto>112,(0.976-0.119*Ny^0.5-0.0019*H^0.5)^2,(0.942-0.1*Ny^0.5-0.0008*H^0.5)^2)
SV	salvage value in Ny years	129143	124084	$	RV/100*P
PV	present value of price less SV	220931	212277	$, today	LP-SV/(1+i)^Ny
RM	repair & maintenance cost	7129	6850	$, today	sum from cumulative table below
PTM	partial throttle multiplier	0.95	0.95	--	D497 fn | 1 - (Sp/100-1)*(0.45*Pp/100-0.877)
F	average fuel consumption	65.1	68.3	l/h	D497 fn | PkWpto*(Pp/100)*(0.22+0.096/(Pp/100))*PTM*Afc/100
L	lubrication consumption	0.175	0.183	l/h	D497 fn | 0.00059*PkWpto+0.02169
D	diesel exhaust fluid consumption	1.30	1.37	l/h	.02*F
FC	fuel cost	39539	41507	$/y	F*H*Pf
PL	price of lubricant	4.05	4.05	$/l	4*Pf, assumed
LC	lubricant cost	426	444	$/y	L*H*PL
DC	diesel exhaust fluid cost	781	819	$/y	D*Pd*H
TIHa	taxes, insurance, and housing	6346	6097	$/y	TIH*P/100
Output					
AC	cost for the tractor, without fuel, DEF, & lube	51,278	49,269	$/y	PMT(i,Ny,-PV-RM)+TIHa
FLC	fuel, DEF, and lubricant cost	40,745	42,771	$/y	FC+LC
HCtot	hourly cost for the tractor	153.4	153.4	$/hour	(AC+FLC)/H
HCnf	hourly cost for the tractor, no fuel & lube	85.5	82.1	$/hour	AC/H
SCtot	**specific cost for tractor power (PTO power basis)**	**0.590**	**0.562**	**$/kWh**	**HCtot/PkWpto**
SCnf	**specific cost for tractor power, no fuel & lube (PTO power basis)**	**0.329**	**0.301**	**$/kWh**	**HCnf/PkWpto**

Figure 1. Spreadsheet implementation of the benchmarking model comparing similar cost fixed-frame and articulated tractors.

Fuel and diesel exhaust fluid prices are needed to compute the cost of these items. Fuel consumption was modeled after Grisso (2004) which is consistent with ASABE D497.7 (*ASABE Standards,* 2014a). In order to estimate fuel consumption, both the load (as a percentage of rated) and the engine speed reduction (essentially throttle setting) must be stated. ASABE D497.7 and EP 496.3 (*ASABE Standards,* 2014a, b) could be used to estimate power requirement. Because the Grisso (2004) model was based on tractors prior to 2000 and there is plenty of evidence that recent Tier IV models are more efficient (Caterpillar, 2014 – 5%; Cummins, 2014 – 5%), an option to adjust fuel consumption was included in the model. Diesel exhaust fluid consumption was estimated at 2% of fuel consumption which is typical of the range (1-3%) reported by the manufacturers. Lubricant cost, albeit generally small, was estimated from lubricant use (ASABE D497.7) and lubricant price which was assumed to be four times the price of fuel.

The salvage value was determined from the ASABE D497.7 function for remaining value. Realizing that this function may not be applicable to recent models, the results from this equation were compared with the prices of used tractors listed for sale on commercial sites (www.tractorhouse.com and www.ironsearch.com). Although these test cases were not Tier IV models, they were recent models with age less than 10 years; 24 units were evaluated with 12 fixed frame, 7 articulated, and 5 tracked tractors of varying power ratings considered. As expected, the used resale prices varied greatly depending on condition, manufacturer, and model. For the 24 units considered, the ASABE salvage value model provided an estimate which was 20% below the purchase price of used tractors. Considering the difference between trade-in and re-sale prices, the function used to estimate salvage value was deemed adequate for this application.

Time value of money was considered in the annual tractor costs via the amortization of the purchase price, the future return of the salvage value, interest and adjustments to repair and maintenance costs. Hourly costs were determined simply by proportion both with and without fuel. To aid in evaluating units of varying power rating, costs were also computed on an energy basis ($/kWh) in addition to the hourly basis ($/h).

RESULTS AND DISCUSSION

A reasonable and simple regression model for tractor price as a function of power rating and classification was developed and is illustrated in figure 2:

$$Price_{\$} = 1030 * P_{kW} + 49500 * I_{fixed} - 7500 * I_{articulated} + 96400 * I_{tracked} \quad (1)$$

$$(R^2 = 0.91)$$

where

$Price_{\$}$ = list price based on 2014 manufacturer website values;

P_{kW} = advertised power rating of the tractor (PTO for fixed frame, engine for articulated and track);

I_{fixed} = 1 for fixed frame tractors, 0 otherwise;

$I_{articulated}$ = 1 for articulated tractors, 0 otherwise;

$I_{tracked}$ = 1 for rubber-tracked tractors, 0 otherwise.

There were significant ($p<0.05$) brand effects, however tractor brand was not included in the model for this publication; users interested in this level of detail should override the price model in the worksheet (fig. 1) with actual price data. Figure 2 indicates the typical price variability in the market. Although the price model was, at worst, 44% high or 32% low, most of the extreme differences were due to brand differences. This price model should be satisfactory for most machinery sizing decisions and partial budget analysis on cropping systems; this price model is not likely accurate enough for specific model lease or buy, or replacement decisions.

The scenarios depicted in figure 1 illustrate some utility of the model with a fixed frame tractor compared to a seemingly larger articulated model. Realizing the articulated model was based on engine power and the fixed frame model was based on PTO ratings, the articulated model can still be larger to yield the same hourly cost, including fuel. If intended operations were such that either chassis would suffice, the larger articulated model appears better due to the lower purchase price. Even though fuel cost will be higher (because it is putting out more power and doing more work), the per hour cost of the two tractors is equal. On a work or energy basis, the larger articulated tractor is 5% more economical with a cost of $0.562/kWh rather than $0.590/kWh. However, with the larger tractor, presumably the work could be done in less time, thereby also reducing labor cost; the impact of reduced labor and improved timeliness is not evaluated here.

If anything, the estimates for hourly costs for tractors estimated by the relationships used in this work should be lower than actual due to the likely higher repair and maintenance cost (Calcante, 2013); however, most published tractor costs are substantially lower than this

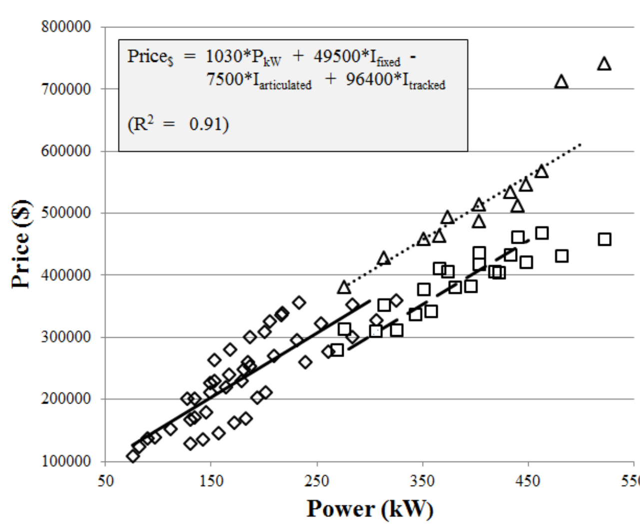

Figure 2. Prices of fixed-frame (diamond, solid), articulated (square, dashed), and tracked (triangle, dotted) tractors vs. power rating (lines represent regression model predictions).

work would estimate. Hourly rates computed using the methods described herein are higher than Midwestern state custom rates (ascertained via surveys) recently reported (Ward, 2012; Halich, 2013; Wilson, 2014) which suggest rates of approximately \$0.40/kWh. Beaton et al. (2003) evaluated survey data from Kansas that showed custom rates are 20% lower than the actual cost of owning and operating the equipment for various reasons. Shastri et al. (2010) included tractor costs in their model which were also lower than would be predicted by the tool in figure 1. Shastri et al. (2010) assumed \$33/h and \$84/h for 168 and 224 kW tractor, respectively while the work presented herein would estimate costs to be \$104/h and \$134/h, respectively. The magnitude of the differences point to the need to accurately reflect inputs identified in figure 1.

Figure 3 illustrates the sensitivity of hourly and specific costs to tractor power. The hourly cost (\$/h) increases with increased power and the marginal rate ($\$h^{-1}kW^{-1}$) is about the same for each tractor configuration. For the fixed frame and tracked units, the specific cost (\$/kWh) lowers as power rating increases; for the articulated units, specific cost (\$/kWh) is nearly constant over the power range considered.

Conclusions

A linear model for purchase price was developed based on a tractor's rated power and configuration (fixed frame, articulated, tracked). A fuel consumption model was revised to account for Tier IV emissions designs and implemented to predict fuel consumption with varying load and throttle position. Tractor costs per unit of use (\$/h and \$/kWh) were computed using the fixed cost of purchase (less salvage), fuel, diesel exhaust fluid, repair and maintenance, and taxes, insurance and housing (as a fixed percentage). Hourly costs (\$/h) increase linearly with power rating for all configurations. Specific cost (\$/kWh) decreases for fixed frame and tracked tractors and remains constant for articulated tractors. The tractor costs estimated by this tool are higher than costs published in comparable works. A simple spreadsheet tool which allows the user to use default functions (or alter them) was made available.

Availability: The spreadsheet of figure 1 is available for free download at: https://engineering.purdue.edu/~dbuckmas/research/tractor_cost.xlsx.

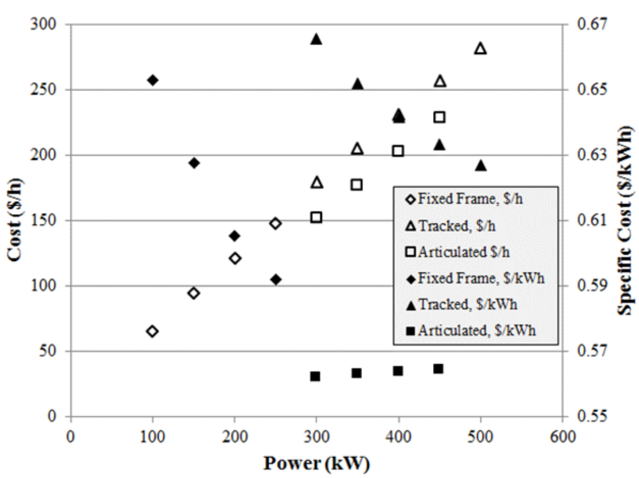

Figure 3. Hourly (open diamond, open triangle, and open square markers) and specific tractor costs (including fuel) (filled diamond, filled triangle, and filled square markers) for tractors of varying size (with assumptions as in figure 1 except for power and an operating speed of 90% of rated).

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