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A Mathematical Model of Tractor PTO Power for Selecting Optimum Throttle Position for Best Fuel Economy

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ABSTRACT
A mathematical model was developed for tractor power take off (PTO) power that will help in selecting a suitable throttle position for carrying out farm operations. For model development, the PTO test was carried out at full throttle along with three part throttle positions using an eddy current dynamometer. PTO speed and PTO torque were recorded at each test point. Second order polynomial relation was fitted on test data with no load speed and speed droop as independent parameters. Analysis of variance (ANOVA) was done using Design-Expert® (V 7.0.0) of the Stat-Erase, Inc. and found that the model is highly significant at P value of 0.01. The coefficient of determination (R^2) value for the developed model was found close to 0.99 with the standard error of 0.9771. Coefficients of the model were determined and contours of PTO power were plotted. The power model was validated with the data collected at two other throttle positions and it was found that the model predicted the values with a maximum variation of -4.62%. The best throttle position can be selected for required power with the help of a contour plot. By running the tractor engine at low throttle, considerable fuel saving can be achieved, and at the same time by selecting higher gear, field capacity can also be maintained. Efficient use of fuel energy will reduce the overall production cost of agricultural products as well as help in controlling climate change.
Key words: PTO test, Mathematical power model, Gear up throttle down, Fuel saving, Climate change

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INTRODUCTION

Farmers have supplemented animate power (human and draught animal) with tractors, power tillers, diesel engines and electric motors during last few years of mechanization in agriculture. In 1960-61 major contribution (92.30%) in farm power was from animate power, whereas in 2009-10 the major share was that of mechanical and electrical power (86.85%). Mostly small size general-purpose tractors are manufactured in India, ranging from 15 kW to 37.5 kW for carrying out most of the farm operations. The current trend of the sale of different horsepower range of tractors indicates the highest share (46.2%) is of 31-40 hp tractors followed by 27.62% of 41-50 hp, 13.83% of 21-30 hp, 11.61% of above 51 hp and 0.75% of less than 20 hp tractors [6].

The primary purpose of agricultural tractors, especially those in the middle to high power range, is to perform drawbar work [7]. Tractor is a versatile machine which is used for a variety of farm operations ranging from low to high power requirement. The farmer cannot purchase different power units for these varieties of operations. So, it may happen that for some farm operations the power unit is oversized. For maximum operating efficiency, a tractor should be operated near its rated capacity, but many field operations do not require full tractor power. For these lighter operations, a considerable amount of fuel could be saved by shifting to higher gears while reducing the throttle position [4]. The majority of the farmers are operating their tractor at the higher engine speed, which causes the high specific fuel consumption which leads to high operating costs. Frictional losses can be reduced by running the engine at low speed that will help in fuel saving. At the same time by adopting the suitable gear, one can maintain the forward speed of tractor without compromising with field capacity. Past studies indicate that savings up to 20% on fuel consumption of tractor could be obtained with gear up throttle down concept [2, 5, 3]. During the last few years, there is a rapid hike in the prices of diesel fuel, which causes the high production cost of agricultural produce. So, there is a need to perform fuel efficient farm operations using the tractor as a power unit [1].

Tractor manufacturers are not providing adequate information about the selection of proper throttle position for a tractor operation under varying operating conditions. This lack of information makes farmer difficult to operate their tractor at its optimum working condition for better fuel saving. A mathematical model for tractor power is required to operate the tractor at maximum fuel efficiency. This mathematical model will help design engineers to mark optimum working conditions, thus enable them to make the decision for selecting proper throttle position for particular field operation. Hence, the need of the hour is to develop a mathematical model to predict tractor power. The model should be simple and efficient. Therefore, the primary objective of the present study was to develop an efficient mathematical model for tractor power.

MATERIAL AND METHODS

A 26 kW three cylinder four stroke tractor with a rated speed of 2100 rpm was selected for the study. The specifications of test tractor are given in Table 1. The full throttle and part throttle tests were done for determining the coefficients of mathematical model.While conducting these tests, recommendations of BIS code were adopted (Anonymous, 1995). Eddy current dynamometer was used to measure the PTO speed and equivalent crankshaft torque. To test the engine, it is generally necessary to use a dynamometer controller. It is usually an electronic unit which has the capability of controlling the load on the dynamometer and can measure the load and speed. The eddy current dynamometer which was used for PTO test is shown in Fig. 1.

Table1: Specifications of test tractor

Parameters	Values
Rated PTO power	26 kW
Rated engine speed	2100 rpm
High idle speed	2300 rpm
Low idle speed	800 rpm
Maximum engine torque	138 N-m
Engine speed at maximum torque	1300 rpm

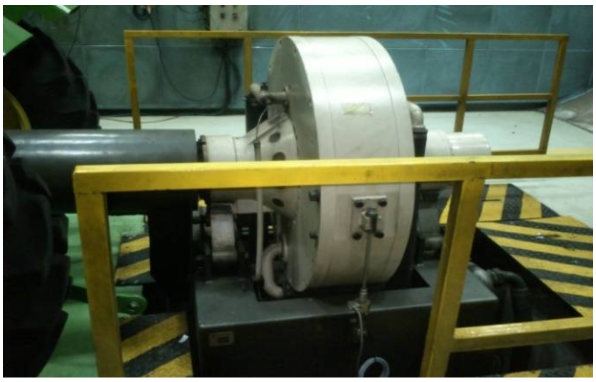

Fig. 1: Tractor PTO testing

For developing the power model, PTO test was done in the laboratory for four throttle positions which were represented by engine speed of 2300, 2000, 1700 and 1300 rpm at zero torque. Data of PTO speed and equivalent crankshaft torque at five points on each throttle position was taken, and then power was calculated at each test point by using equation (1).

$$P_{pto} = \frac{2\pi NT}{60000} \quad (1)$$

Where, Ppto is the PTO power (kW), T is the equivalent crankshaft torque (N-m) and N is the engine speed (rpm).

For the preliminary study, power was plotted against the engine speed. By observing the nature of graphs, polynomial equations were developed to predict the power of diesel engine. Finally, the coefficients involved in the models were determined by using the multiple nonlinear regression analysis for the best fit to the measured data points.

RESULTS AND DISCUSSION

The throttle position of engine can easily be defined by no load speed of the engine. It was observed that when the torque was applied to the engine then speed of engine started to fall below the engine no load speed. The difference between the engine no load speed and current engine speed is the engine speed droop. The engine speed droop is last up to the governor maximum point where governor started to supply the full fuel. If the torque is increased further, the engine starts to run along the full fuel line. The whole working range of engine consisted of an envelope which is surrounded by the full throttle governor line, full fuel line, minimum throttle governor line and zero torque line. After carrying out the preliminary work, it was found that power is a simple function of droop in engine speed below engine no load speed for any throttle position. The engine no load speed (S) and engine speed droop (D) was selected as the independent variables for developing the mathematical model. It was found that the second order polynomial for representing the power model is a good compromise to develop the simple equation. Power model is represented by the equation (2).

$$P = b_0 + b_1S + b_2D + b_3S^2 + b_4D^2 + b_5S.D \quad (2)$$

For determining the coefficients, data was recorded for four throttle positions with five points on each which include the test point at engine no load speed as well as at governor maximum point for each throttle position. These throttle positions were well distributed over the range of engine performance envelope and defined by engine speed of 2300, 2000, 1700 and 1300 rpm. The analysis of variance (ANOVA) was done using Design-Expert® (V 7.0.0) of the Stat-Erase, Inc. The significance of the model was judged at a probability level (p) of 0.01. The ANOVA result for the developed model is given in Table 2. F-value of 282.33 and P-value less than 0.01 from ANOVA result indicates that power model is highly significant. The R^2 value for the model was 0.9902 with the standard error of 0.9771. The variation of power with no load speed and speed droop was graphically presented in the contour plot as shown in Fig. 2.

Table 2: ANOVA and coefficients for power model

Source	Sum of squares	df	Mean square	F-value	P-value	
Model	1323.497	5	264.699	282.33	< 0.0001	significant
Residual	13.126	14	0.938			
Total	1336.623	19				

	b_0	b_1	b_2	b_3	b_4	b_5
Coefficients	-38.4196	0.044414	0.128238	-1.2E-05	-0.00053	4.9E-05

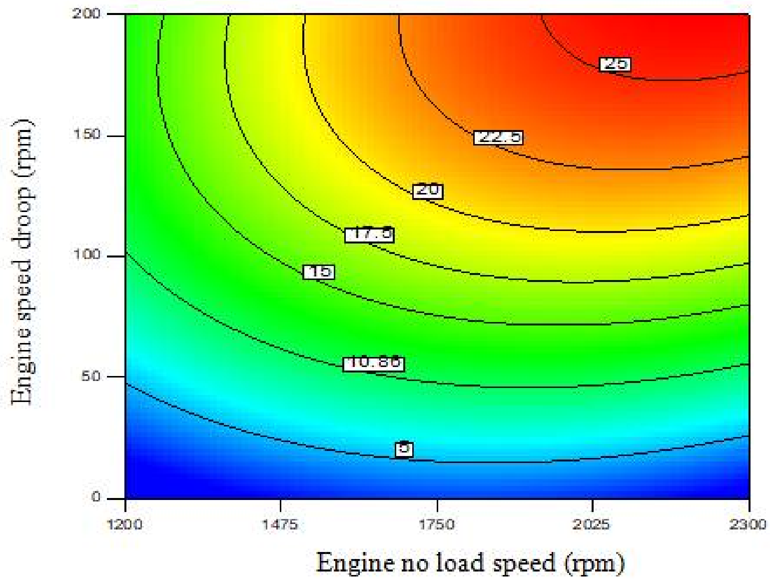

Fig. 2. Contours of power (kW) for test tractor engine

Power increases with increase in engine speed droop at all throttle positions of engine. Power is also increased with increase in throttle position for the same droop in engine speed. There is only one point of maximum power that is the point of rated power of engine. The developed mathematical model was validated with the data collected at two other throttle positions and results are presented in Table 3. From the predicted values, it was observed that developed model could predict the values of power very well within the engine performance envelope. The negative value of variations shows that model is under predicting the measured values. The developed model for power was predicting the values with a maximum variation of -4.62%.

Table 3: Validation of power model

No load speed (rpm)	Speed droop (rpm)	Predicted power (kW)	Measured power (kW)	Variation (%)
	50	9.45	9.59	-1.46
1500	100	15.54	15.88	-2.14
	151	19.00	19.92	-4.62
	51	11.56	11.83	-2.28
1800	101	18.34	18.72	-2.03
	151	22.44	23.17	-3.15

By using contour plot of power, one can determine the power developed by tractor engine for any combination of throttle position and engine speed droop within the performance envelope of the test engine. This plot will help in selecting the best throttle position for required power. If required power is available at any low throttle position, then a considerable amount of fuel energy could be saved by using gear up throttle down concept.

CONCLUSION

PTO test was conducted at different throttle positions and a mathematical model for PTO power of tractor was developed with coefficient of determination (R^2) close to 0.99 and standard error of 0.9771. The developed model is capable of predicting the PTO power with a maximum variation of -4.62%. Contour plot of power could be used to select the best throttle position in order to develop the required power at low throttle position and consideration amount of fuel could be saved. At the same time field capacity could be maintained by selecting higher transmission gear. The overall production cost of agricultural products could get reduced by using fuel energy efficiently.

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