

REVIEW

Fuel Savings from an Operating Condition Indicator on Agricultural Tractors

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Abstract

In fundamental tests, we revealed that work power could be estimated based on measured values for engine speed and exhaust-gas temperature during the operation of an agricultural tractor. Based on these results, we developed a prototype which indicates the operating conditions to the operator to reduce the fuel consumption of agricultural tractors. This device employed five operating areas according to engine speed and work power and was designed to indicate changes in operating conditions (travel speed gear, PTO gear and engine speed) to ensure the tractor would operate within a region enabling high fuel efficiency and low exhaust-smoke density. The device was mounted on a 24 kW tractor, and indoor tests, rotary tillage tests, mole drainage tests, fertilizing tests and inter-row cultivating tests were all conducted. Consequently, by following the notification of the device, fuel consumption was reduced by approx. 15% at a power ratio of 55-65% (the ratio of work power to maximum PTO output), approx. 25-30% at a power ratio of 35-40% and approx. 35-45% at a power ratio of 20% with full throttle. Fuel consumption was also reduced by approx. 10% at a power ratio of 25-30% and approx. 10-25% at a power ratio of 10-15% with 50% throttle.

Discipline: Agricultural machinery

Additional key words: engine speed, exhaust-gas temperature, fuel consumption

Introduction

Since increased fuel is consumed when agricultural tractors (hereinafter referred to as “tractor”) engage in tillage and soil preparation tasks as part of farm work (Nishimura et al. 1997), saving energy during their operation is important. A tractor is a general-purpose device used for various works and with different loads. Under light- and medium-load operations, fuel consumption can be reduced by adjusting the operating conditions. Moving to a higher gear (Gotoh et al. 2009, Gotoh & Teshima 2009, Gotoh & Teshima 2010, Gotoh et al. 2010a, Grisso & Pitman 2001, Teshima & Gotoh 2010) and throttling down (Egami 1981, Gotoh et al. 2009, Gotoh & Teshima 2009, Gotoh & Teshima 2010, Gotoh et al. 2010a, Grisso & Pitman 2001, Sakai et al. 1989, Teshima & Gotoh 2010) allows fuel consumption to be reduced. Operation under excessive load conditions should also be avoided because the tractor is likely to operate unstably due to significant load fluctuation,

and exhaust concentration and carbon monoxide emissions tend to increase (Hiyoshi et al. 2009, Seki 2002).

The authors thus developed a prototype which indicates the operating conditions to the operator to reduce fuel consumption and exhaust-smoke concentration. In this report, we described basic tests conducted to estimate the work power based on engine speed and exhaust-gas temperature, a summary of the device, and the effects it achieved during the indoor tests, rotary tillage tests, mole drainage tests, fertilizing tests and inter-row cultivating tests.

Basic tests (Gotoh et al. 2010b)

1. Purpose of tests

To accurately indicate operating conditions to the operator, data on engine speed and load power during tractor work must be obtained. Consequently, we decided to examine the potential to estimate the power generated while work was ongoing (hereinafter referred to as “work power”) by detecting the engine speed and exhaust-gas temperature.

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2. Tractor and fuel under tests

For the tests, we used a riding tractor manufactured in Japan and equipped with a 24 kW 3-cylinder direct injection diesel engine (manufactured in 1999). Table 1 shows the major specifications. The fuel used was light diesel oil.

3. Test method and conditions

We conducted the following tests by fixing the tractor in the laboratory, shifting the PTO into first gear and connecting the PTO shaft to the electrical dynamometer (without driving the traveling section). We measured the PTO speed and power using the measurement-control section of the dynamometer, and calculated the engine speed based on the PTO speed and the speed reduction ratio from the engine to the PTO.

(1) Method and conditions of tests to detect the exhaust-gas temperature

To measure the exhaust-gas temperature of the tractor,

a sheath-type (K) thermocouple was attached to the engine exhaust manifold. The tests were conducted by dividing the engine speed without load into 18 stages (1,000-2,600 rpm at 100 rpm intervals plus 2,650 rpm with full throttle) and applying a certain load as a unit of 2 kW at each engine speed through the use of the dynamometer.

(2) Method and conditions of fluctuating load tests

To grasp the propensity of the exhaust-gas temperature to follow the fluctuating load, we observed time-dependent change in the PTO power and exhaust-gas temperature.

4. Test results and review

(1) Results of tests to detect the exhaust-gas temperature

Figure 1 shows the relationship among engine speed, PTO power and exhaust-gas temperature. The exhaust-gas temperature was 79°C at an engine speed of 1,000 rpm without load. With increasing engine speed and PTO power, the exhaust-gas temperature rose accordingly and reached 630°C with PTO power of 23 kW and full throttle.

Table 2 shows the regression formulas and determination coefficients for the thermocouple output voltage (exhaust-gas temperature) and PTO power at each engine speed when the data were grouped according to engine

Table 1. Main tractor specifications

Type	4 wheel drive
Length×width×height	320 ×150×199.5 cm
Wheelbase	180 cm
Tread	Front: 123 cm, Rear: 115 cm
Total mass, front weight	1,570 kg, 20 kg×5
Tire	Front: 8-18-4PR, Rear: 3.6-26-4PR
Type of engine	Four-stroke cycle, 3 cylinders Diesel
Engine power, capacity	24 kW/2600 RPM, 1,642 ml
Type of injectors	Direct injection
Forward travel speed	0.21 - 26.7km/h (20 gears)
PTO speed	556, 787, 994, 1300 RPM

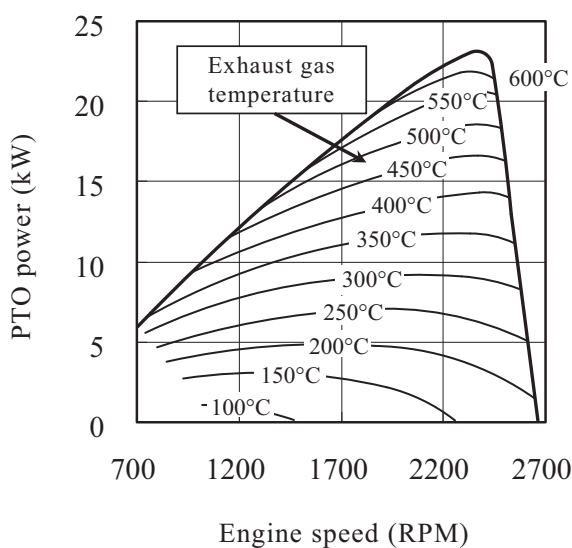


Fig. 1. Relation among engine speed, PTO power and exhaust-gas temperature

Table 2. Regression formulas and coefficient of determinations between output voltage of a thermocouple and PTO power

Engine speed (RPM)	Regression formulas*	Determination coefficients R^2
800 - 900	$y = 0.0033x^2 + 0.559x - 0.802$	0.9998
900 - 1000	$y = -0.0138x^2 + 0.952x - 2.372$	0.9999
1000 - 1100	$y = -0.0148x^2 + 0.971x - 2.193$	0.9993
1100 - 1200	$y = -0.0174x^2 + 1.081x - 2.660$	0.9995
1200 - 1300	$y = -0.0181x^2 + 1.163x - 3.079$	0.9992
1300 - 1400	$y = -0.0183x^2 + 1.229x - 3.310$	0.9992
1400 - 1500	$y = -0.0199x^2 + 1.304x - 3.664$	0.9997
1500 - 1600	$y = -0.0240x^2 + 1.429x - 4.281$	0.9996
1600 - 1700	$y = -0.0214x^2 + 1.446x - 4.572$	0.9994
1700 - 1800	$y = -0.0243x^2 + 1.554x - 5.155$	0.9994
1800 - 1900	$y = -0.0242x^2 + 1.603x - 5.539$	0.9997
1900 - 2000	$y = -0.0244x^2 + 1.669x - 6.108$	0.9995
2000 - 2100	$y = -0.0235x^2 + 1.684x - 6.493$	0.9993
2100 - 2200	$y = -0.0211x^2 + 1.666x - 6.868$	0.9995
2200 - 2300	$y = -0.0260x^2 + 1.884x - 8.800$	0.9991
2300 - 2400	$y = -0.0274x^2 + 1.987x - 9.909$	0.9996
2400 - 2500	$y = -0.0284x^2 + 2.021x - 10.409$	0.9994
2500 - 2600	$y = 0.0029x^2 + 1.460x - 8.577$	0.9986
2600 - 2650	$y = 0.0670x^2 + 0.679x - 6.793$	0.9957

x : Output voltage of a thermocouple (mV)

y : PTO power (kW)

* A suitable equation is chosen in the computer program according to the measured engine speed.

speed differences equal to or less than 100 rpm. As far as the data on engine speed difference equal to or less than 100 rpm is concerned, the determination coefficients for the quadratic regression formulas are always 0.99 or more, and it was confirmed that the work power could be estimated with high accuracy.

(2) Results of fluctuating load tests

Figure 2 shows the time-dependent change in PTO power and exhaust-gas temperature, which occurred when the dynamometer load changed from 10 to 20 kW in approx. 80 seconds. When the PTO power changed by approx. 10 kW, it took about 20-30 seconds before the exhaust-gas temperature stabilized. However, when the PTO power changed by approx. 2 kW, the response of the exhaust-gas temperature lagged behind by approx. 5 seconds. Thus, we found practically no problem in its propensity to follow the fluctuating load.

(3) Consideration

The plural regression formulas applicable in each engine speed range showed that work power could be estimated with sufficient accuracy from exhaust-gas temperature. Moreover, when the PTO power changes by approx. 2 kW, there is practically no problem in its propensity to follow the fluctuating load.

Based on these results, we determined the feasibility of estimating work power by detecting engine speed and exhaust-gas temperature in the absence of any abrupt load change in normal work conducted without frequently changing the settings of the travel speed gear, PTO gear or engine speed.

Outline of the device, which mainly comprises a notebook computer indicating to the operator (Gotoh et al. 2010b)

Based on the basic test results, we developed a prototype which indicates operating conditions allowing good fuel efficiency and reduces exhaust-smoke concentration to the operator. The outline is as described below.

1. Entire device configuration and features

The prototype consists of an electromagnetic rotation sensor to detect engine speed mounted on the tractor under tests, a K-type sheath thermocouple attached to the engine exhaust manifold and a notebook computer. In accordance with the operating status (engine speed and work power), the device indicates the operating conditions allowing the tractor to be driven facilitating good fuel efficiency and reduced exhaust-smoke concentration to the operator via audio and character messages issued by the computer.

2. How to estimate the engine speed and work power

In response to the basic test results, we aimed to esti-

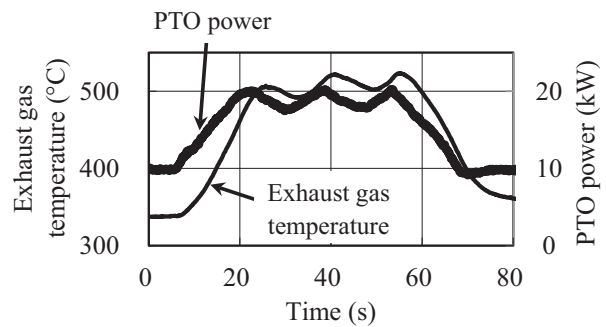


Fig. 2. Response of exhaust-gas temperature to variable load

mate the engine speed and work power based on the outputs of a rotation sensor and thermocouple, to detect the engine speed and exhaust-gas temperature respectively. To estimate the work power, we used regression formulas (Table 2) which were found based on data on the thermocouple output with around 100 rpm difference in engine speed and work power.

3. Configuration of the determination and notification of operating conditions

Referring to data in previous papers (Gotoh et al. 2009, Gotoh & Teshima 2009, Gotoh & Teshima 2010, Gotoh et al. 2010a, Hiyoshi et al. 2009, Seki 2002, Teshima & Gotoh 2010), we designated the 5 areas: A (Area with high exhaust-smoke concentration), B (Area facilitating good fuel efficiency), C (Area with relatively poor fuel efficiency), D (Area with poor fuel efficiency) and E (Area with extremely poor fuel efficiency) (Fig. 3) in accordance with the engine speed and work power, and ensured that the operator would be notified to change to operating conditions facilitating good fuel efficiency when working in one of areas C, D or E, and change to operating conditions facilitating good fuel efficiency and low exhaust-smoke concentration when working in area A. To maintain work accuracy, we ensured that the travel speed and PTO speed would remain almost unchanged before and after the notifications, except those to lower the exhaust-smoke concentration. However, the operator would be notified to adjust the engine speed to 1,200 rpm for a calculated value under 1,200 rpm, since otherwise the engine may stall due to the excessive load with excessively low engine speed.

4. Details of notifications

Figure 4 shows an example screen display from the device. The top right of the screen shows a diagram of the determination area shown in Figure 3, featuring the current operating status (engine speed and work power) which are circled. Underneath is a notification to change to operating conditions facilitating good fuel efficiency and low exhaust-smoke concentration.

The upper part of Figure 4 shows the screen displayed

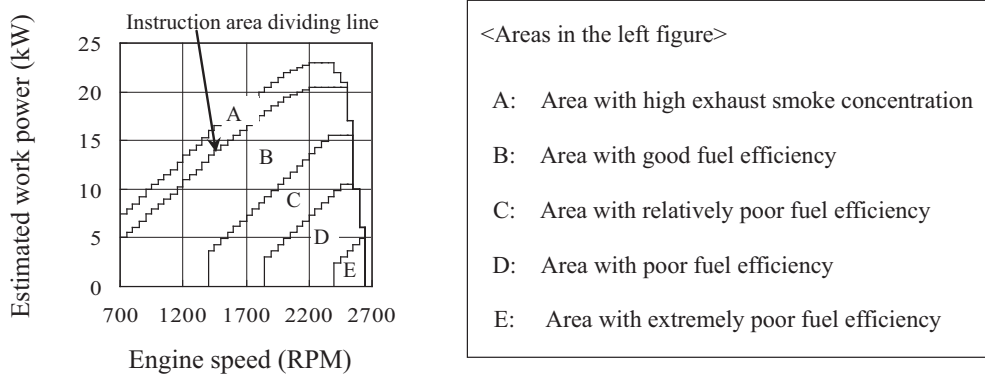


Fig. 3. Decision areas (upper) and notification example of operating conditions (lower)

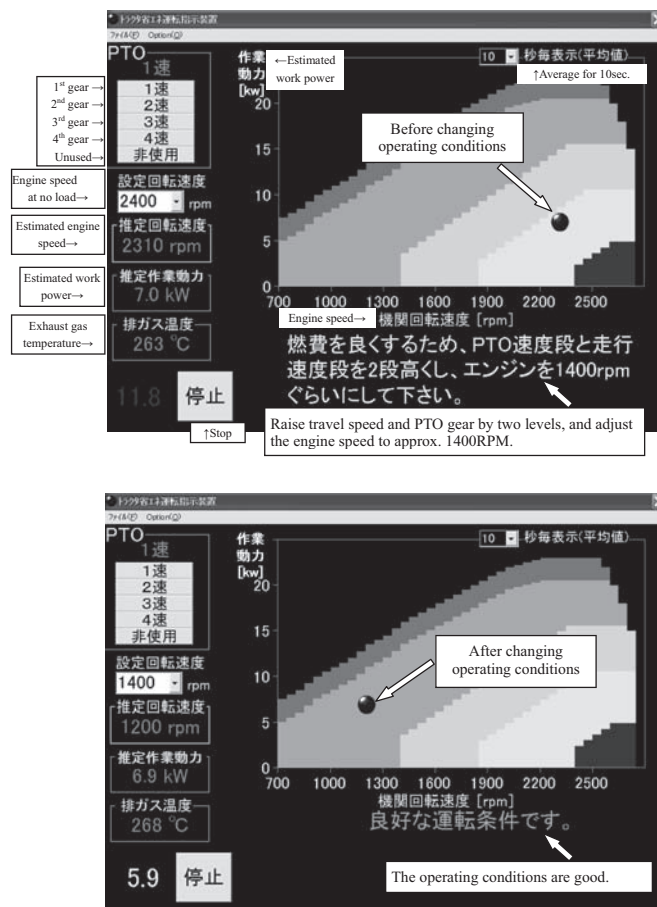


Fig. 4. Displays of prototype system (upper: before changing operating conditions, lower: after changing operating conditions)

for the operation in Area D before the operating conditions are changed and the message “To improve fuel efficiency, raise the travel speed and PTO gears by two levels and adjust the engine speed to approx. 1,400 rpm.” is shown. The lower part of Figure 4 shows the screen displayed after the operating conditions are changed in accordance with the notification. After the operating conditions are changed, the operation is conducted in Area B and the message “The operating conditions are good” is shown.

Effect confirmation tests with the use of the device (Gotoh et al. 2010c, Gotoh et al. 2010d)

1. Test method and conditions

(1) Device and fuel under tests

For tests to confirm the effect of the device, it was mounted on the same tractor used for the basic tests and the fuel used was light diesel oil.

(2) How to measure the fuel consumption, engine speed and work power

The fuel consumption was measured by attaching a flow detector and flow indicator to the tractor. Also, during the indoor tests, the engine speed and work power were measured using the measurement-control section of the dynamometer. Meanwhile, in the other tests conducted in the field, the engine speed and work power were measured by an electromagnetic rotation sensor attached to the tractor and the K-type sheath thermocouple attached to the engine exhaust manifold. Table 3 shows the field conditions for rotary tillage, mole drainage, fertilizing and inter-row cultivating tests.

(3) Indoor test methods

The tractor was fixed in the laboratory, the PTO gear was shifted into first gear and the PTO shaft was connected to the electrical dynamometer. Changing the engine speed and PTO power by some levels (Gotoh et al. 2010c), tests were conducted to check the notifications issued by the device, whereupon further tests were conducted by applying PTO loads equivalent to that applied before changing the tractor operating conditions (PTO gear and engine speed) as notified by the device.

(4) Rotary tillage test methods

The work power and other parameters were measured by attaching a rotary tiller with work width of 160 cm to the tractor, shifting the PTO gear to first gear and changing the travel speed gear and engine speed by some levels (Gotoh et al. 2010c) to conduct rotary tillage (target tillage depth: about 12 cm). When the device issued notifications to change the operating conditions, the works were repeated in accordance with the recommended operating conditions (The same procedure was adopted for tests conducted in the field as described below).

(5) Mole drainage tests

Table 3. Field conditions during rotary tillage, mole drainage, fertilizing and inter-row cultivating tests

	Rotary tillage	Mole drainage	Fertilizing, Inter-row cultivating
Field	Paddy field	Dry field	Dry field
Soil texture	Silty Clay	Clay Loam	Loam
Liquidity index	0.28	-0.12	0.58
Wet Bulk density (g/cm ³)	1.42	1.28	1.03
Dry Bulk density (g/cm ³)	0.96	0.95	0.57
Cone index (MPa)	0.62	0.33	0.30
	[0-10cm]	[0-10cm]	[0-5cm]
Cohesion (kPa)	37	24	16
Internal friction (°)	30	25	27

The work power and other parameters were measured by attaching a vibrating subsoiler with a mole to the tractor and changing the PTO gear, travel speed gear and engine speed by some levels (Gotoh et al. 2010c) to conduct the work (target work depth: about 35 cm).

(6) Fertilizing tests

The work power and other parameters were measured by attaching a broadcaster to the tractor and changing the PTO gear, travel speed gear and engine speed by some levels (Gotoh et al. 2010d) to conduct the work.

(7) Inter-row cultivating tests

The work power and other parameters were measured by attaching a triple rotary inter-row cultivator to the tractor and changing the PTO gear, travel speed gear and engine speed by some levels (Gotoh et al. 2010d) to conduct the work (target work depth: approx. 5 cm).

2. Test results

(1) Results of the indoor tests (Gotoh et al. 2010c)

In the 7 tests, where notifications on the change in operating conditions (PTO gear, engine speed) to reduce fuel consumption were issued, the results for the fuel consumption reduction rates per hour (hereinafter referred to as “fuel consumption reduction rate”) were as described below. It should be noted that notifications on the change in operating conditions to reduce the exhaust-smoke concentration were issued in 4 tests.

The fuel consumption reduction rates achieved when the operations were underway with full throttle were 14% at a 53% ratio of PTO power to maximum PTO output (hereinafter referred to as “power ratio”), 28% at a power ratio of 36% and 46% at a power ratio of 18% respectively. Also, the fuel consumption reduction rates achieved when the operations were underway with approx. 75% throttle were 12% at a power ratio of 35% and 31% at a power ratio of

Table 4. Working conditions and results of indoor and rotary tillage tests

		Indoor						Rotary tillage			
Throttle opening rate (%)		100			75		50		100		
Power ratio (%)		53	36	18	35	18	27	9	65	60	40
Estimated PTO power (kW)		12.0	7.9	4.0	8.0	4.1	6.0	2.0	14.2	13.4	8.9
Fuel consumption (mL/kWh)	Before indication	366	451	690	382	553	378	735	389	390	464
	After indication	314	326	375	335	384	344	653	339	333	346
Fuel consumption reduction rate (%)		14	28	46	12	31	9	11	13	15	25

Table 5. Working conditions and results of mole drainage, fertilizing and inter-row cultivating tests

		Mole drainage				Fertilizing			Inter-row cultivating			
Throttle opening rate (%)		100	85	75	50	100	85	50	100	75	50	
Power ratio (%)		20	39	12	15	21	33	28	19	17	24	13
Estimated PTO power (kW)		4.7	8.9	2.9	3.5	5.0	7.8	6.9	4.0	3.7	5.6	2.8
Fuel consumption (mL/kWh)	Before indication	721	481	814	529	708	508	432	830	789	481	683
	After indication	459	401	578	429	394	423	388	474	481	435	525
Fuel consumption reduction rate (%)		36	17	29	19	44	17	10	43	39	10	23

18% respectively. Furthermore, the fuel consumption reduction rates achieved when the operations were underway with approx. 50% throttle were 9% at a power ratio of 27% and 11% at a power ratio of 9% respectively.

(2) Results of the rotary tillage tests (Gotoh et al. 2010c)

The fuel consumption reduction rates in the 3 tests were 13 to 15% at a power ratio of approx. 60-65% and 25% at a power ratio of approx. 40% while the operations were underway with full throttle. It should be noted that the notifications on the change in operating conditions to reduce the exhaust-smoke concentration were only issued in 1 test.

Table 4 shows the working conditions and results of the indoor and rotary tillage tests.

(3) Results of the mole drainage tests (Gotoh et al. 2010c)

The fuel consumption reduction rates in the 4 tests were 36% at a power ratio of approx. 20% while the operations were underway with full throttle, 17% at a power ratio of approx. 39% and approx. 85% throttle, 29% at a power ratio of approx. 12% and approx. 75% throttle, and 19% at a power ratio of approx. 15% and approx. 50% throttle respectively.

(4) Results of the fertilizing tests (Gotoh et al. 2010d)

The fuel consumption reduction rates in the 3 tests were 44% at a power ratio of approx. 21% while the operations were underway with full throttle, 17% at a power ratio of approx. 33% and approx. 85% throttle, and 10% at a power ratio of approx. 28% and approx. 50% throttle.

(5) Results of the inter-row cultivating tests (Gotoh et al. 2010d)

The fuel consumption reduction rates in the 4 tests

were 43% at a power ratio of approx. 19% while the operations were underway with full throttle, 39% at a power ratio of approx. 17% and approx. 75% throttle, and 10 and 23% at power ratios of approx. 24 and 13% while the operations were underway with approx. 50% throttle.

Table 5 shows the working conditions and results of mole drainage, fertilizing and inter-row cultivating tests.

Conclusion

We developed a prototype which indicates the operating conditions (travel speed gear, PTO gear and engine speed) facilitating good fuel efficiency and low exhaust-smoke concentration for the operator. Attaching it to a 24 kW riding tractor, we confirmed that the device issued appropriate notifications by conducting indoor and field tests. Also, the fuel consumption reduction in tests when the device notified changes in operating conditions to reduce fuel consumption were approx. 15% at a power ratio of 55-65%, 25-30% at a power ratio of 35-40% and 35-45% at a power ratio of approx. 20% while the operations were underway with full throttle, approx. 10 and 30-40% at power ratios of approx. 35 and 10-20% with approx. 75% throttle, and approx. 10 and 10-25% at power ratios of approx. 25-30% and 10-15% with approx. 50% throttle.

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