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Consumed-Power and Load Characteristics of Potato Harvesting Operation in Dry Field

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건답에서 감자수확작업의 소요동력 및 부하특성

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ABSTRACT

This study analyzed the load and the consumed power characteristics of a potato harvesting operation in a dry field. The potato harvesting operation was performed using an underground crop harvester mounted on an agricultural tractor with a rated engine power of 23.7 kW. The rotational speeds and the torque of the engine output shaft, rear axle, and power take-off (PTO) shaft were measured under various working conditions. The load spectrum and the consumed power were analyzed using the measured data. The results show that the consumed power of the rear axle increased as the working speed increased, while that of the PTO shaft decreased. The consumed power of the engine output shaft showed a similar trend with that of the PTO shaft, but the torque deviation was larger in the load spectrum.

The results of previous studies were used to compare herein the consumed power and the load characteristics of the harvesting, rotary, and plow operations in a dry field. PTO and tractive power were highly consumed in the plow and rotary operations, respectively. The consumed power of the PTO shaft and the rear axle in the harvesting operation were 29–41% and 18–23% of the engine power, respectively. Compared to those in the rotary and plow operations, the engine power was relatively evenly distributed to the PTO shaft and rear axle in the harvesting operation.

Key words : Consumed-Power(소요동력), Load Characteristic(부하 특성), Load Spectrum(부하스펙트럼), Underground Crops Harvester(땅속작물수확기)

1. Introduction

The optimal design of a power transmission system is important in securing market competitiveness and

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improving the efficiency of domestic tractors. Therefore, the consumed power and the load characteristics of the power transmission system must be analyzed according to various operations.[1] The consumed power of a tractor is affected by the type of operation, soil conditions, and working speed, among others. Therefore, accurate and sufficient data under various working conditions are needed.[2]

The consumed power and load characteristics of the power transmission system have been previously studied. Kim et al. analyzed the consumed power and load characteristics of the plow and rotary operations in a dry field.[3] Wu et al. developed a torque load spectrum of the engine output shaft and the rear axle during a rotary operation in wet paddy fields.[4] Meanwhile, Kim et al. analyzed the consumed power of the plow, rotary, and loader operations.[5] Kim et al. also measured the torque load according to the power take-off (PTO) transmission stages and evaluated the severeness of the PTO shaft during a rotary operation.[6] Furthermore, they analyzed the consumed power of the rear axle, PTO shaft, and hydraulic system during a baler operation.[7] Most studies on the consumed power and load characteristics were conducted for plow and rotary operations. Other major agricultural operations, such as the harvesting operation, have rarely been studied. Most studies involving the harvesting operation were conducted to analyze the consumed power of the harvester without the PTO power.[2,8]

Load measurement and analysis for various harvesters are required to identify the consumed power and load characteristics of the harvesting operation. Most potato farmers in Chuncheon, Gangwon-do in South Korea use an underground crop harvester attached to a tractor. Potatoes are pulled onto the conveyor with traction. The conveyor is rotated using PTO power to carry, discharge, and dedust the potatoes. Therefore, the harvesting operation that uses an underground crop harvester requires traction and PTO power in a complex manner.

This study analyzes the consumed power and investigates the load characteristics of a potato harvesting operation in a dry field. The rotational speed and the torque load of the engine output shaft, rear axle, and PTO shaft are measured during harvesting operations with an underground crop harvester. Based on the measurement results, the load spectrums are then constructed, and the consumed power are analyzed.

2. Materials and Methods

2.1 Test equipment

2.1.1 Tractor

Figure 1 and Table 1 show the shape and specifications, respectively, of the tractor used in the test. The tractor had four main transmission gears (i.e., 1, 2, 3, and 4) and three sub-gears (i.e., L, M, and H). The rated engine output power was 23.7 kW. The rated rotational speed was 2600 rpm. Compared to other tractors with a similar engine output power, the tractor used herein was suitable for dry field operations because it was small in size and had high ground clearance.

Fig. 1 A view of tractor used

Table 1 Specifications of a prime mover tractor

Item	Specification
Model/Company/Nation	C320/Tongyang Moolsan/Korea
Weight (kN)	14.2
Weight distribution ratio (front axle : rear axle, %)	43.2:56.8
Length×Width×Height (mm)	3010×1390×2560
Minimum ground clearance (mm)	345
Rated engine power (kW) /speed (rpm)	23.7/2600

Fig. 2 A view of the underground crop harvester used

Table 2 A view of the underground crop harvester used

Item	Specification
Model/Company/Nation	GWN-1400 / Gangwon Agricultural Machinery / Korea
Weight (kN)	5.3
Length×Width×Height (mm)	1900×1670×1150
Nominal tilling width (mm)	1400
Applicable crops	potato, tumeric, lilium bulb etc.

2.1.2 Underground crop harvester

Most farmers in Chuncheon, South Korea use an underground crop harvester that could gather potatoes from both sides. The crop discharge direction could be controlled using hydraulic pressure. The harvester can be used for various crops, such as potatoes, turmeric, and lilies. Figure 2 and Table 2 present the shape and the specifications, respectively, of the underground crop harvester used in the test.

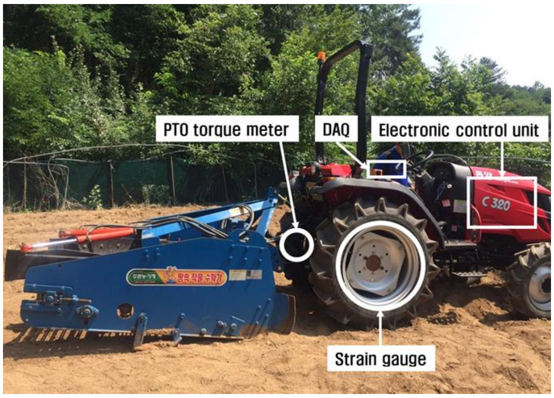


Fig. 3 A view of measuring instruments on tractor

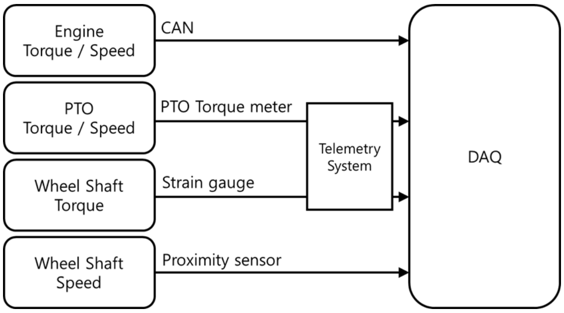


Fig. 4 Schematic diagram of data logging system

2.2 Measuring system

The torque load generated from the power transmission system of the tractor must be measured and analyzed to analyze the consumed power and load characteristics of the harvesting operation using the underground crop harvester. Therefore, a measurement system for measuring the consumed power and the torque of the engine output shaft, rear axle, and PTO shaft was constructed. Figures 3 and 4 show the overall configuration of a measuring system mounted on a tractor.

The rear axle torque was determined by the sum of the measured left and right rear wheel torques. The rear wheel torque was measured by attaching a

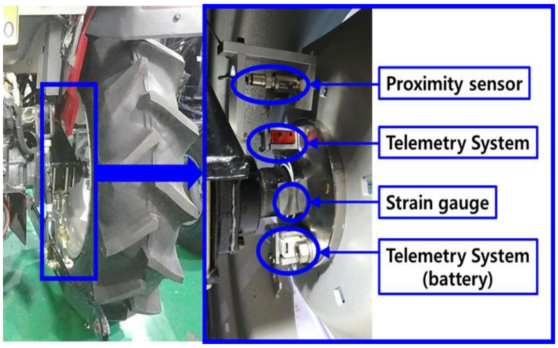


Fig. 5 Measuring system of rear wheel

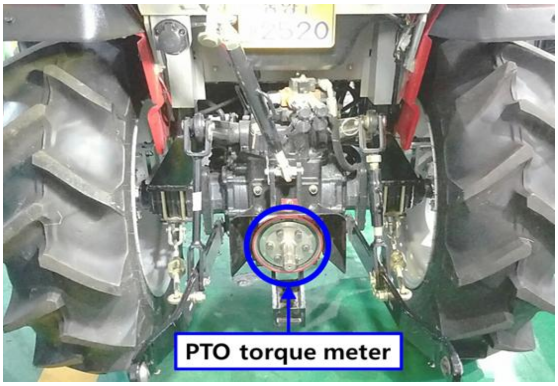


Fig. 6 A view of Torque meter mounted on the PTO shaft

Table 3 Specifications of the Torque meter

Item	Specification
Model/Company/Nation	MW_B_2kNm/Manner Sensortelemetrie /Germany
Linearity deviation (%)	0.2
Integrated speed acquisition (pulses/turn)	120
Temperature range (℃)	-10 ~ 85

two-element 90° rosette strain gauge (CEA-06-062UV-350, Micro-Measurements Co., USA) to the rear axle and configuring it as a full bridge. The strain gauge signal was calibrated using a torsion tester (215.45C, MTS Inc., USA) similar to that used by Nam et al.[3] in a calibration range

Fig. 7 Radar sensor for actual working speed measurement.

Table 4 Specifications of the radar sensor

Item	Specification
Model/Company/Nation	RADARⅡ /DICKEY-john/USA
Velocity range (km/h)	0.53～96.6
Accuracy (%)	5
Mounting angle (°)	35±5
Mounting height (mm)	610 ～ 2,438

of －100 kgf · m to 100 kgf · m. The rotational speed of the rear wheel was measured by attaching a proximity sensor (MP-981, Ono Sokki Co., Japan) to the rear axle. The strain gauge signals were transmitted to a data acquisition device (DAQ) through a telemetry system. The signals from the proximity sensor were then sent to the DAQ through wired cables. Figure 5 shows the measuring system of the rear wheel.

The PTO torque and the rotational speed were measured by attaching a torque meter to the PTO shaft. The signals from the torque meter were collected using a telemetry system. Figure 6 and Table 3 show the shape and the specifications, respectively, of the torque meter mounted on the PTO shaft. The data sampling frequency of the torque meter signal was set to 100 Hz.

A radar sensor was attached to the front of the tractor to measure the actual working speed. Figure 7 and Table 4 present the shape and the specifications, respectively, of the radar sensor used in the test.

2.3 Work conditions

The potatoes in the test site (Seo-myeon, Chuncheon, Gangwon-do, South Korea) were cultivated for harvest in July. The soil strength of the test site was measured using a soil cone penetrometer for hard soil (SC 900, Spectrum Technology, E Plainfield, USA) defined in the American Society of Agricultural Engineers (ASAE) S313.3 standard.[9] The soil strength measurements were performed up to 25 cm in 5 cm intervals at nine random points in the range of 34-2100 kPa (Table 5) according to the specified test method (ASAE EP542)[10].

There were four test conditions, as determined in Table 4. The transmission gears and the PTO stages were determined by considering the actual working speed of local farmers. The engine rotational speed was fixed at the rated rotational speed. The working length during an operation was 30-50 m. Figure 8 shows the actual view of the field operation using the potato harvester. The harvesting operation was repeated thrice under each working condition. The data were analyzed using averaged values.

Fig. 8 A view of actual harvesting operations

Table 5 Soil strength for field test

	Soil strength by depth (kPa)				
Location	5 cm	10 cm	15 cm	20 cm	25 cm
1	103	241	448	897	1138
2	69	138	172	207	724
3	34	69	207	207	483
4	138	241	276	1242	2070
5	34	241	207	310	1276
6	172	241	552	793	1138
7	34	241	310	655	2100
8	207	207	517	966	1932
9	69	138	655	1000	1173

Table 6 Work conditions for field test

Gear of Tractor/PTO	Rated working speed (km/h)
M1/1	2.57
M1/2	2.57
M2/1	3.53
M2/2	3.53

2.4 Analysis of load data

The measured data of the time-load diagram included the high-frequency noise components caused by ununiformed soil, working type, explosion stroke of the engine, etc. Therefore, filtering was performed through the moving average method. The number of averaged data was set to 10. The filtered data were used to construct the load spectrum and determine the consumed power of the power transmission system during the harvesting operation.

The consumed power was analyzed by considering the torque load, rotational speed, and working speed. Using the measured rotational speed and torque, the consumed power of the engine output shaft, rear axle, and PTO shaft was determined in Eq. (1).

$$P_r = \frac{2\pi \times T \times N}{60 \times 1000} \tag{1}$$

where,

P_r = Consumed power (kW)

T = Torque (N·m)

N = Rotational speed (rpm)

The load spectrum refers to the expressed amplitude of the loads as a function of frequency. The loads were measured over time; thus, the number of times a certain load is generated should be counted accurately and expressed in the frequency domain. The loads generated during the harvesting operation were analyzed using the rainflow-counting method because the loads were aperiodic and irregular. The maximum value of the measured load was divided into 32 bins. The number of cycles in each bin was counted. The amplitude and the average of the loads for all the load cycles included in the measured data are calculated if the rainflow-counting method is applied to the data in the time-load diagram. The Smith-Watson-Topper equation was applied [Eq. (2)] to convert the measured load to the equivalent and completely reversed load using the calculated amplitude and the load average.[11]

$$P_e = \sqrt{P_a(P_a + P_m)} \tag{2}$$

where,

P_e = Equivalent completely reversed load (Nm)

P_a = Average load (Nm)

P_m = Load amplitude (Nm)

In analyzing the torque load generated from the power transmission system, the relative value is more important than the absolute value.[12,13] Therefore, the load spectrum of the engine output shaft, rear axle, and PTO shaft was constructed herein using the measured torque-to-the-rated torque ratio. The rated torque of the engine output shaft was derived using Eq. (3), whereas those of the rear axle and the PTO shaft were obtained using Eq. (4).

$$T_e = \frac{P_e \times 60 \times 1000}{2\pi \times N_e} \tag{3}$$

Where,

T_e = Rated torque of engine output shaft (Nm)

P_e = Rated power of engine output shaft (kW)

N_e = Rated rotational speed of engine output shaft (rpm)

$$T_r = T_e \bullet \rho \tag{4}$$

Where,

T_r = Rated torque of rear axle (or PTO shaft) (Nm)

T_e = Rated torque of engine output shaft (Nm)

ρ = Gear ratio of engine to rear axle (or PTO shaft)

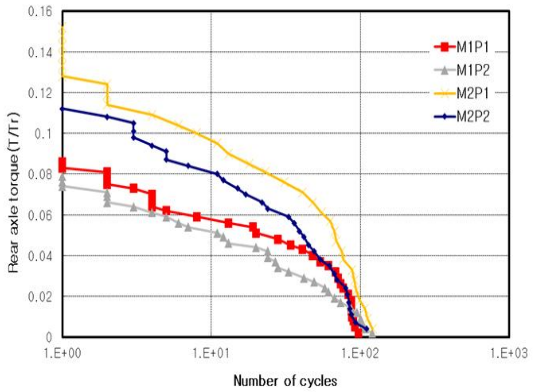
3. Results and Discussion

The actual working speed measured by the radar sensor ranged from 1.88 to 2.29 km/h under each working condition. The working speed varied with the transmission gear and decreased as the PTO rotating speed increased. The PTO rotating speed increased the load of the rear-mounted harvester, thereby causing a large wheel slip. Table 7 shows the actual working speed, consumed power of the engine shaft, rear axle, and PTO shaft, and ratios of the PTO power to the engine power and the rear axle power to the engine power under each working condition. Figures 9-11 illustrate the consumed power and the load spectrum of the rear axle, PTO shaft, and engine output shaft according to the working conditions.

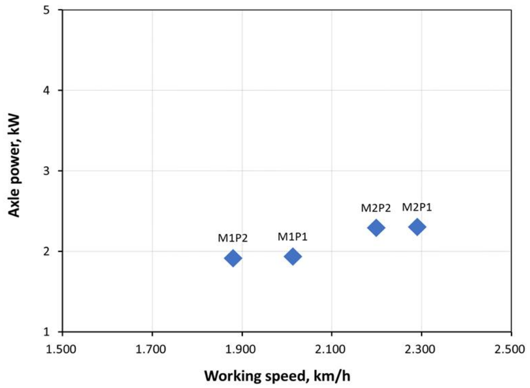
The consumed power of the rear axle increased as the working speed increased. The torque load of the rear axle also increased as the working speed increased through the load spectrum of the rear axle. If the traction load increased according to the working speed, the rear axle torque also increased because of the soil thrust that supports the tractive force.[14] The increasing consumed power of the rear axle came from the traction load. The PTO was an independent power transmission system that did not affect the consumed power of the rear axle (Fig. 9).

Table 7 Consumed power and actual working speed for harvesting operation

Working Condition	Working speed (km/h)	EG power (kW)	Axle power (kW)	PTO power (kW)	PTO power / Engine power	Rear axle power / Engine power
M1/PTO1	2.01	10.087	1.935	3.709	0.319	0.194
M1/PTO2	1.88	10.482	1.916	4.368	0.418	0.183
M2/PTO1	2.29	8.882	2.304	2.613	0.296	0.258
M2/PTO2	2.20	9.835	2.291	3.692	0.377	0.233



(a) Torque ratio of rear axle

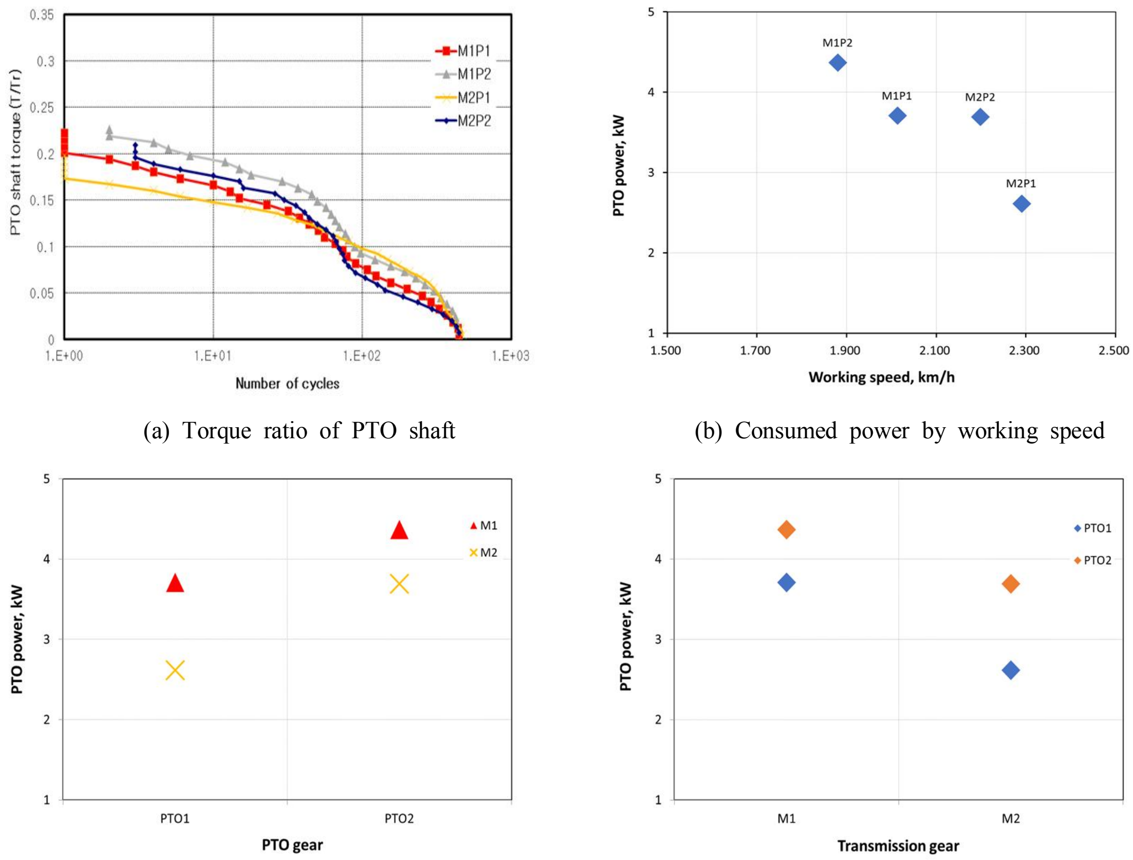


(b) Consumed power by working speed

(c) Consumed power by PTO gear

(d) Consumed power by transmission gear

Fig. 9 Consumed power and load spectrum of rear axle according to working condition.



(a) Torque ratio of PTO shaft

(b) Consumed power by working speed

(c) Consumed power by PTO gear

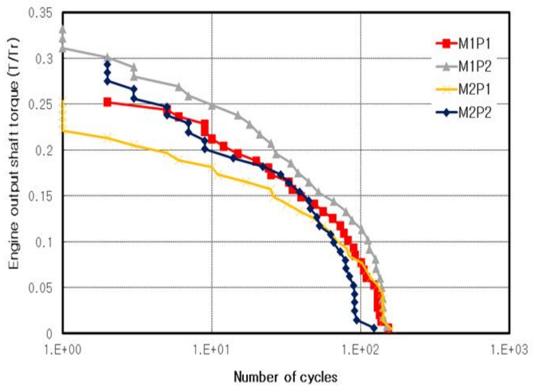
(d) Consumed power by transmission gear

Fig. 10 Consumed power and load spectrum of PTO shaft according to working condition.

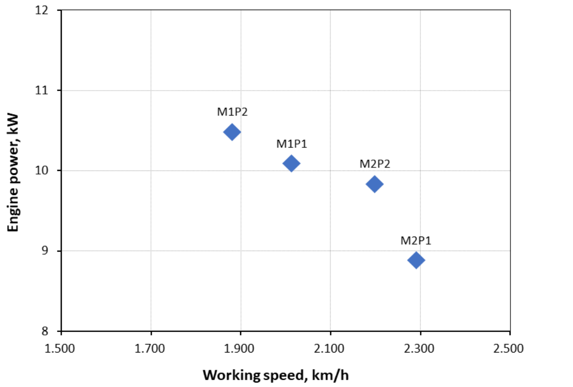
The consumed power of the PTO shaft tended to decrease as the working speed increased. The PTO was a power source for the conveyors that hauled the excavated potatoes up. The feeding speed of potatoes into the conveyor increased as the working speed increased, thereby shortening the time the potatoes pass through the conveyor and reducing the PTO shaft torque for moving the potatoes. Therefore, the consumed power and the torque load decreased as the working speed increased. In addition, the consumed power of the PTO shaft increased as the rotating speed of the PTO increased (Fig. 10).

The consumed power of the engine output shaft increased as the working speed decreased and as the rotating speed of the PTO shaft increased. According to the working conditions, the consumed power of the engine output shaft tended to be similar to that of the PTO shaft; however, the torque ratio was larger in the load spectrum. This result indicates that in the potato harvesting operation, the consumed power and the torque load of the PTO shaft were the main factors determining the consumed power and the torque load of the engine (Fig. 11).

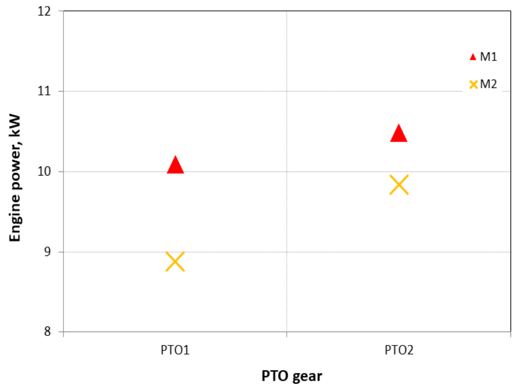
During the harvesting operation, the engine consumed 37-44% of the rated power; the PTO shaft consumed 29-41% of the engine power; and the rear axle consumed 18-23% of the engine power. The consumed power of the harvesting, rotary, and plow operations were compared to those in the previous studies performed in Chuncheon, which used the same tractor (Table 8).[12] The plow operation did not use the PTO power. Moreover, the consumed power of the rear axle was the highest at 41-51% due to the tractive force. In the rotary operation, the consumed power of the PTO shaft was the highest at 63-76%. Meanwhile, the rear axle consumed 2.4-3.4% of the engine power. In the harvesting operation, the consumed power of the PTO shaft and the rear axle was relatively evenly generated. Furthermore, the largest torque load occurred in the PTO shaft.



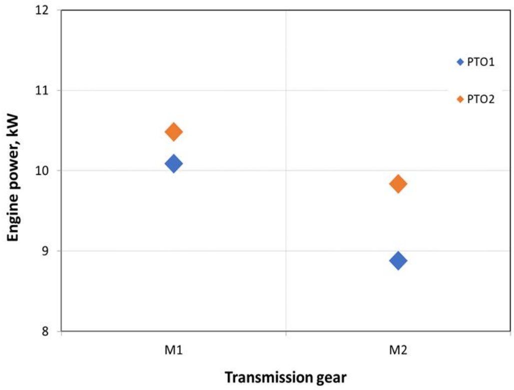
(a) Torque ratio of engine output shaft



(b) Consumed power by working speed



(c) Consumed power by PTO gear



(d) Consumed power by transmission gear

Fig. 11 Consumed power and load spectrum of engine output shaft according to working condition.

Table 8 Consumed power characteristics for three types of operation (Rotary tillage, Plow tillage, Harvesting)

Operation	Rotary tillage (%)	Plow tillage (%)	Harvesting (%)
Engine power / Rated engine power	72～95	37～84	37～44
PTO power / Engine power	63～76	-	29～41
Rear axle power / Engine power	2.4～3.4	41～51	18～23
Drawbar power / Engine power	-	27～40	-

4. Conclusions

This study derived the load and the consumed power characteristics during a potato harvesting operation in a dry field. The harvesting operation was performed using an underground crop harvester mounted on an agricultural tractor with a rated engine power of 23.7 kW. The working conditions were determined by considering the actual working environment of local farmers. The rotational speeds and torque of the engine output shaft, rear axle, and PTO shaft were measured. The load spectrum and the consumed power were analyzed using the measured data. The main results of this study are as follows:

1. The consumed power and torque of the rear axle increased as the working speed increased.
2. The consumed power of the PTO shaft tended to decrease as the working speed increased and increased as the rotating speed of the shaft increased.
3. The consumed power of the engine output shaft increased as the working speed decreased and as the rotating speed of the PTO shaft increased, thereby showing a similar trend to the PTO shaft, albeit with a larger torque ratio in the load spectrum.
4. The consumed power of the engine during the harvesting operation was 37-44% of the rated power, while those of the PTO shaft and the rear axle were 29-41% and 18-23% of the engine power, respectively.
5. The consumed power of the harvesting, rotary, and plow operations were compared to those in previous studies that used the same tractor. For the plow operation, the rear axle had the highest power consumption, while for the rotary operation, the PTO shaft ranked the highest. In the harvesting operation, the consumed power of the PTO shaft and the rear axle were relatively uniform, and the largest torque occurred in the PTO shaft.

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