Evaluation of Tractor Fuel Efficiency using Dynamometer and Baler Operation Cycle

Lee, Dae-Hyun
Department of Biosystems Machinery Engineering, Chungnam National University

Choi, Chang-Hyun
Department of Bio-mechatronic Engineering, Sungkyunkwan University

Chung, Sun-Ok
Department of Biosystems Machinery Engineering, Chungnam National University

Kim, Yong-Joo
Department of Biosystems Machinery Engineering, Chungnam National University

他

https://doi.org/10.5109/1564100

出版情報：九州大学大学院農学研究院紀要. 61 (1), pp.173-182, 2016-02-29. Faculty of Agriculture, Kyushu University
バージョン：

J. Fac. Agr., Kyushu Univ., **61** (1), 173–182 (2016)

Evaluation of Tractor Fuel Efficiency using Dynamometer and Baler Operation Cycle

Dae–Hyun Lee[1], Chang–Hyun Choi[2], Sun–Ok Chung[1], Yong–Joo Kim[1]*, Eiji Inoue and Takashi Okayasu

Laboratory of Agricultural Machinery and Production Systems Design, Division of Bioproduction Environmental Sciences, Department of Agro–environmental Sciences Faculty of Agriculture, Kyushu University, FuKuoka, 812–8581, Japan
(*Received November 11, 2015 and accepted November 19, 2015*)

The purpose of this study was to evaluate fuel efficiency of tractor using working cycle. First, baler operation was conducted in Italian ryegrass farmlands and engine torque and fuel consumption were measured as field data. Second, baler operation cycle was developed using the field data. The arbitrary working cycles were generated by randomly selected micro–trips, minimum working patterns. Some of the arbitrary working cycles were selected and baler operation cycle was determined considering sum of squared difference (SSD). The baler operation cycle was evaluated using performance value (PV) comparing with driving cycles. The results showed that PVs of the driving cycles were 67 ~ 109% of the baler operation cycle. Third, fuel efficiency of the baler operation was evaluated by dynamometer test using dynamometer system and the baler operation cycle. The fuel consumption and engine power were measured while the engine acted on the baler operation cycle and fuel efficiency was evaluated. The results of t–test showed no significant difference between fuel efficiency by the dynamometer test and fuel efficiency of each farmland by the field test. Considering all results of this study, the baler operation cycle is feasible to apply to evaluate fuel efficiency of tractor with dynamometer system.

Key words: agricultural tractor; baler operation; fuel efficiency; working cycle; performance evaluation; dynamometer

INTRODUCTION

The oil prices have been rising on geopolitical concerns and are expected to raise further (KAMICO and KSAM, 2012). High oil prices caused recession in most of the industries, and exhaust gas regulation was tightened up; as a result, the ways for improving fuel efficiency are needed in agricultural area (Park *et al.*, 2010a). Especially, the tractor uses 345,000 kL of oil which takes 48.5% of total oil consumption of agricultural machines, so interest in fuel efficiency of tractor is increased in this high–oil–price era (KAMICO and KSAM, 2012).

Generally, full load test which is one of the standard test method is used to evaluate fuel efficiency of tractor. Full load test measures fuel consumption per unit power. However, the full load test is hard to reflect actual tractor performance because it is not dynamic test using actual field load but static test using constant load (Lacour *et al.*, 2014). Therefore, various field tests are needed for optimizing tractor fuel efficiency. Several studies on the evaluation of the tractor fuel efficiency were conducted with field tests: analysis of fuel efficiency for major tractor works (Park *et al.*, 2010a), analysis of power requirement for major field operations (Kim *et al.*, 2011a), severeness analysis of tractor power take off (PTO) during rotary tillage (Kim *et al.*, 2011b). However, each study showed different results because each test was conducted under different field conditions and operators. Therefore, alternative methods are needed to replace expensive and time consuming field tests and to acquire reliable data.

For these reasons as an advanced test method for accurate evaluation of fuel efficiency during driving in the automotive industry, a reliable indoor test was conducted using a dynamometer and driving cycles to simulate actual driving patterns. Tamsanya *et al.* (2009) predicted fuel consumption and pollutant emissions of passenger cars using a chassis dynamometer. The test method predicted fuel consumption and pollutant emissions with an accuracy of 95%. Fontaras *et al.* (2008) simulated the fuel consumption of Toyota Prius and Honda Civic and showed that peak fuel consumption reduced by 60 and 40% compared to conventional vehicles. Ahlawat *et al.* (2012) proposed transmission in the loop simulation experiment to predict and analyze fuel economy, which was demonstrated successful emulation during indoor test. In agricultural research area, a few studies relating fuel efficiency measured indoor tests. Bietrasato *et al.* (2015) estimated BSFC (brake specific fuel consumption) of farm tractor engine indirectly using a PTO dynamometer. Lacour *et al.* (2014) evaluated fuel efficiency of tractor based on engine models. However, it is difficult to evaluate tractor fuel efficiency accurately with the indoor tests because these studies were conducted under full load test condition not real field load condition. Real field load should be considered in the indoor tests because tractors are operated under conditions of dramatic load changes which are different from conventional vehicles.

Tractor working cycle for field operation is needed

[1] Department of Biosystems Machinery Engineering, Chungnam National University, 99, Daehak–ro, Yuseong–gu, Daejeon–si, 305–764, Korea

[2] Department of Bio–mechatronic Engineering, Sungkyunkwan University, 2066, Seobu–ro, Jangan–gu, Suwon–si, 440–746, Korea

* Corresponding author (E–mail: babina@cnu.ac.kr)

in order to apply real field load to indoor test. However, there is no study on developing tractor working cycle, whereas there are many studies on driving cycles of conventional vehicles. Especially, driving cycles of conventional vehicles are test standards that were developed through measurement of various driving patterns in highway, urban, sub–urban and so on. Ergeneman *et al.* (1997) developed a driving cycle for predicting fuel consumption. Andre *et al.* (2006) developed a driving cycle for measuring pollutant emissions. Esteves–Booth *et al.* (2001) developed the Edinburgh driving cycle using traffic flow index. Ho *et al.* (2014) developed the Singapore driving cycle for evaluating fuel consumption and emissions and reported that it showed better performance when compared with the new European driving cycle NEDC using comprehensive modal emission model. Therefore, development of the tractor working cycle reflecting real field operation is needed.

The final goal of this study was to evaluate fuel efficiency of tractor using working cycle. For doing this, this study was conducted as follow: 1) conducting field tests of baler operation which is one of the major tractor works, 2) developing baler operation cycle using the measured field data, 3) evaluating fuel efficiency of tractor using a dynamometer and the baler operation cycle.

MATERIALS AND METHODS

Working cycle

In this study, the tractor working cycle was developed using a driving cycle development method for conventional vehicles. The working cycle is torque–time profile of tractor operation in a farmland and developed using obtained field data collection. It can represent load characteristic of tractor operation through synthesized repeated working patterns in a farmland. The working cycle can provide the load variation with time as test code for indoor test, evaluating performance such as fuel efficiency, durability, shifting quality, and emissions (Hung *et al.*, 2007). The development process of the working cycle is composed of field data collection, working cycle generation, and working cycle determination (Hung *et al.*, 2007). First, field data were measured during baler operation and classified into micro–trips. Micro trip means minimum working pattern which is one among the repeated working patterns of working cycle. It is defined as torque–time profile during consecutive period of a working pattern, and indicates period to produce a bale in baler operation. The longer the period of micro trip, the longer working time for producing a bale. Arbitrary working cycles were generated by randomly selected micro–trips, and some of the arbitrary working cycles were selected by assessing absolute percentage error. Last, baler operation cycle was determined among the selected working cycles considering sum of squared difference (SSD) and compared using performance value (PV). The working cycle of tractor was developed with factors of torque and torque variations while the driving cycle of conventional vehicle was developed with factors of speed and acceleration (Tamsanya *et al.*, 2009; Tong *et al.*, 2011; Kamble *et al.*, 2009; Gong *et al.*, 2011) because agricultural tractors are affected by work load instead of vehicle speed.

Data collection

Recently, demands of tractors for baler operation continue to rise (KAMICO and KSAM, 2012). In this study, a tractor (L7040, LSMtron, Korea), the most popular model for baler operation in Korea, was used to collect field data. Specifications of the tractor were dimensions of 4,000(L) × 2,677(W) × 2,640(H) mm, total weight of 3,260 kg, and 4–wheel drive. The tractor was equipped with a mechanical engine of 71 kW power, maximum torque of 400 Nm at 1,300 rpm of engine speed. It also had a synchro–mesh type manual transmission composed of 2 direction–gears, 4 main–gears, and 4 sub–gears, which made total 32 gear combination settings (16 forward and 16 backward). And the PTO rotational speeds of the tractor at P1, P2, and P3 were 540 rpm, 750 rpm, and 1,000 rpm, respectively. The tractor had main and auxiliary hydraulic pumps: The main hydraulic pump used for controlling the implements and hitch, and the auxiliary hydraulic pump used for steering and lubrication. The maximum pressure and volumetric efficiency of each hydraulic pumps were both 20.6 MPa and 95%. Its displacement was 20 cc/rev for main hydraulic pump and 10 cc/rev for auxiliary hydraulic pump. A round baler (F55, McHale, USA) was equipped on the tractor for baler operation, and specifications of the baler were 15 blades, 60 kW required rated power, dimensions of 4,050(L) × 2,550(W) × 2,450(H) mm, and total weight of 3,500 kg. The baler produced bales of 1.25 m of diameter.

Working cycle is developed using tractor engine torque; therefore, the torques applied to the transmission input shaft, PTO input shaft, main and auxiliary hydraulic pumps were measured, and the total sum was used as an engine torque. The engine torque was calculated using the sum of each component power because torque of hydraulic pump was hard to measure directly. The power of input shafts were calculated as in eq. 1 (Ryu, 2004) using the measured torque and engine rotational speed which was the same with input shaft speed. The engine rotational speed was measured with a tachometer which was attached on the tractor engine. After the pressure of each hydraulic pump was measured, the power was calculated as in eq. 2 (Kim, 2004).

$$P_{shaft} = \frac{2\pi \times T \times N}{60000} \tag{1}$$

Where, P_{shaft} is power of shaft (kW), T is torque (Nm), and N is rotational speed (rpm).

$$P_{pump} = \frac{p \times Q}{104081 \times \eta} \tag{2}$$

Where, P_{pump} is power of hydraulic pump (kW), p is discharge pressure (MPa), Q is flow rate (cm^3/s), and η is volumetric efficiency.

Torque was measured on transmission and PTO input shafts which connected from engine crank shaft and flywheel to gearbox as in Fig. 1. The transmission input shaft torque was measured with four elements full–bridge strain–gauge (CEA–06–250US–350, Micro Measurement Co., USA) attached on outer of input shaft. A strain–gauge was mounted on 45 degree from the axial direction to minimize the influence of bending moment, and it detected the signals using radio telemetry I/O interfaces (R2, Manner, Germany). The radio telemetry system included two antennas and data receiver. A rotor antenna was installed on transmission input shaft, and a stator antenna was installed on the shaft case. For PTO torque measurement, a strain–gauge was installed on sleeve of flywheel, and a rotor antenna and a stator antenna were installed on flywheel and engine case, respectively. Pressures of main and auxiliary hydraulic pumps were measured with the discharged pressure by inserting pressure sensors (P6A, HBM, Germany) between hydraulic pump and hose as in Fig. 2.

In order to evaluate the fuel efficiency of baler operation using the working cycle, fuel consumption was measured with torque and pressure at the same time. The fuel efficiency was described as in eq. 3 using the measured fuel consumption and calculated engine power (Bietresato *et al.*, 2015).

$$E_{fuel} = \frac{C_{fuel}}{P_{engine}} \tag{3}$$

Where, E_{fuel} is fuel efficiency of engine (kg/kWh), C_{fuel} is fuel consumption of engine (kg/h), and P_{engine} is power of engine (kW).

Fig. 3(a) shows the cycle structure of tractor fuel supply. The fuel pump initiated fuel flow through the fuel supply line, connecting fuel filter and lift pump to the cylinder. The remaining fuel was released to the fuel tank through the fuel return line. The gear flow meter (M05, NURITECH, Korea) was fitted between the fuel tank and fuel filter to measure the precise fuel consumption during baler operation as shown in Fig. 3(b) (Park *et al.*, 2010b). The measuring range of the flow meter was 0.003~0.8 L/min, and it measured the tractor fuel consumption range of 0.15~40 kg/h considering specific gravity of diesel fuel (0.85 kg/L).

The fuel flowing through the fuel pump was injected into the cylinder, and then the remaining fuel was returned to the fuel tank at the existing fuel cycle structure. For this reason it was difficult to measure the exact amount of fuel used in real time. Thus, a fuel return con-

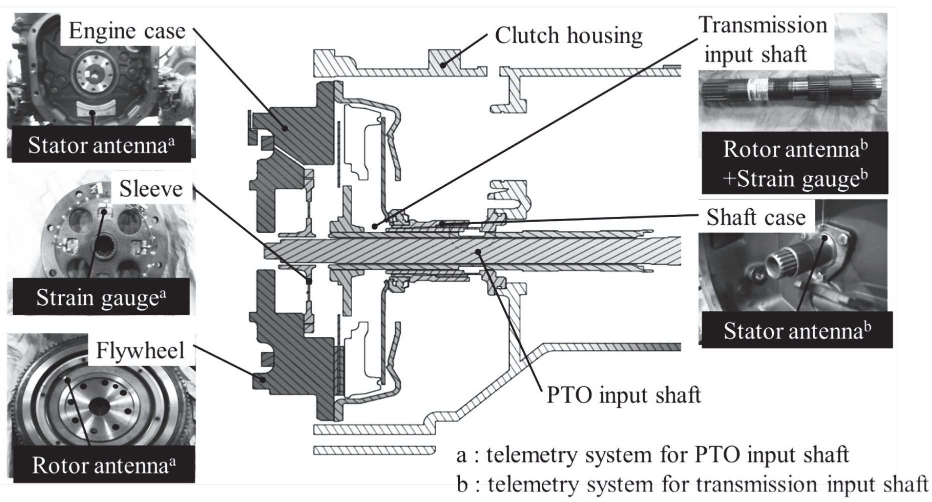


Fig. 1. Telemetry systems for torque measurement of transmission and PTO input shafts.

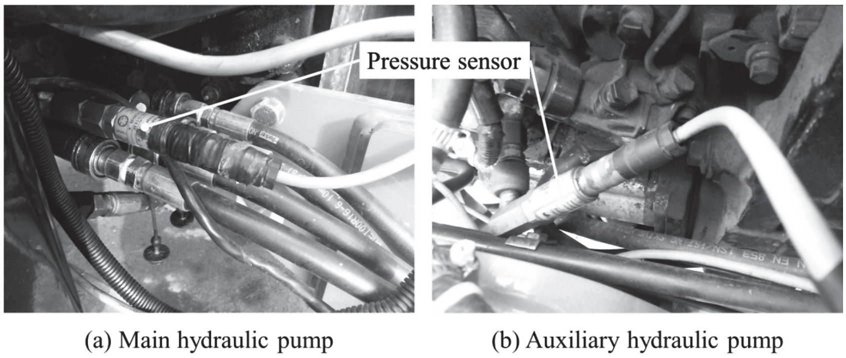
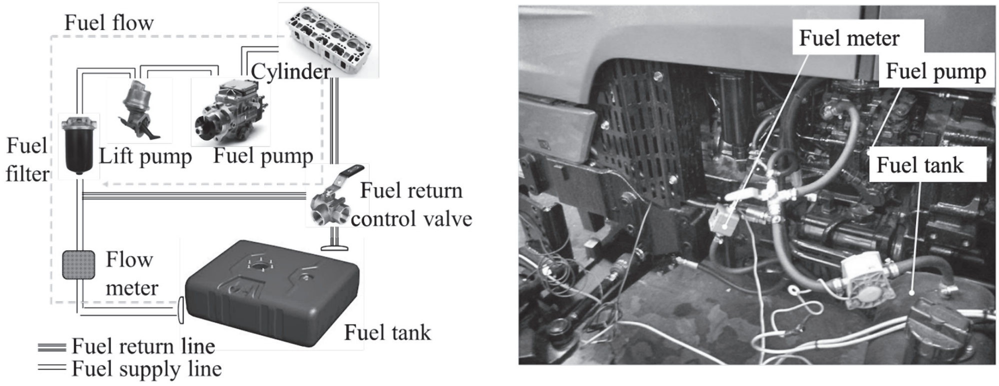


Fig. 2. Pressure sensors for measurement of pump pressure.



(a) Cycle structure of tractor fuel supply (b) Installation of flowmeter

Fig. 3. Measurement system of fuel consumption.

trol valve was mounted on the fuel return line to send the remaining fuel into the fuel supply line, which made the exact measurement of fuel consumption (Green *et al.*, 1983). The amount of consumed fuel was calculated by subtracting the returned fuel trough the control valve from the total fuel circulated through the fuel supply line.

A 24–bit resolution data acquisition system with 8 channels for analogue and digital signals (QuantumX MX840, HBM, Germany) was installed to acquire the signals from transmission and PTO input torques, main and auxiliary hydraulic pump pressures, and fuel consumption. A 24–bit analogue input channel with a sampling rate of 19.2 kHz per channel was used to acquire the torque and pressure signals, and a digital input channel with a sampling rate of 1 MHz per channel was used to measure the rising edge signals for the fuel consumption. The measured signals were transmitted to a lab notebook with a Firewire, and a measurement program was developed using Catman (version 3.1, HBM, Germany) to link the data acquisition system.

Baler operation was conducted in Italian ryegrass fields with similar sizes (3,000 m^2 : 100 m × 30 m) at Hampyeong–gun, JeollaNamdo province (latitude: 35.160668–35.161589, longitude: 126.613811–126.617695) on October, 2013 for one month. Reliability was improved by making an experienced operator conduct the baler operation, and transmission gear setting was determined to L3 (sub gear: L, main gear: 3) through the interview and testing with the operator. The ground speed of the tractor at L3 was 3.8 km/h, and seven bales were produced from one farmland. The baler operation was conducted at ten farmlands whose total size was 30,000 m^2, and field data were collected during 70 bales producing. Half of the measured data were used to develop baler operation cycle as calibration set and the rest of them were used to evaluate fuel efficiency as validation set. Before the field test conducting, soil characteristics such as texture, moisture content, and the cone penetration index and moisture content of Italian ryegrass were measured. Soil texture and moisture content were analyzed following USDA standards. Measurement of the cone penetration index was repeated three times using soil compaction meter (SC900, Spectrum Technology, E Plainfield, USA) (ASABE, 2011a; ASABE, 2011b). Soil texture, average moisture content, and cone penetration index were sand, 20.1%, and 1,379 kPa, respectively. The moisture content of Italian ryegrass was measured using ten samples from each farmland, and was expressed as averaged moisture content for each farmland.

Cycle generation

Baler operation repeated baling, tying, and discharging to produce a bale; therefore, a minimum pattern of baler operation, micro–trip, was determined from the starting point of the baling to terminating point of discharging. The engine torque data during baler operation were classified into micro–trips. The number of micro–trips that constituting a working cycle was determined based on the number of the produced bales at a farmland. Seven micro–trips were used for working cycle generation because average produced bales were seven at a farmland. Therefore, the calibration set was classified into 35 micro–trips at five farmlands. The arbitrary working cycles were generated by combining arbitrary micro–trips among 35 micro–trips as in eq. 4 (Kamble *et al.*, 2009; Tong and Hung, 2010; Dong *et al.*, 2012). The generated working cycles were selected less than 5% absolute percentage error between calibration set and generated arbitrary cycle as in eq. 5 (Tong *et al.*, 1999), when maximum, minimum and means of torque and torque variation were the factors. Also, mean micro–trip duration was selected as an additional factor. This is because increased time consumption indicated low work efficiency, or abnormal work conditions such as re–selection of gear stage, failure, and so on. Therefore, total of seven factors were used in assessment criteria for working cycle selection.

$$C_i = \{x_1, x_2 \cdots, x_j, \cdots x_n\} \qquad \forall\, x_j \in D_c \tag{4}$$

Where, D_c : calibration set, C_i : the ith generated working cycle, x_j : the jth sequence of torque data constituting a micro–trip.

$$\bar{d}_i = \left| \frac{\bar{\theta}_c - \bar{\theta}_i}{\bar{\theta}_c} \right| \quad (5)$$

Where, $\bar{d}_i$: vector consisting of absolute percentage errors of the ith generated working cycle, $\bar{\theta}_c$: vector consisting of the assessment criteria value of the calibration set, $\bar{\theta}_i$: vector consisting of the assessment criteria value of the ith generated working cycle.

Cycle determination

The selected working cycle having the lowest SSD was determined as the baler operation cycle (Andre, 2004; Nesamani and Subramanian, 2011), and its performance was compared using PV. The SSD was calculated using torque–torque variation probability distribution indicating working patterns as in eq. 6 (Tong *et al*., 2011). Torque was equally divided from 0 to 400 Nm considering maximum torque of tractor engine with an interval of 10 Nm because torque of less than 10 Nm might be occurred by noises such as tractor vibration, wheel slip and so on (Nguyen and Inaba, 2011). Torque variation was equally divided from –200 to 200 Nm/s with an interval of 10 Nm/s considering torque range because tractor torque changed to bi–direction with increasing (positive) and decreasing (negative). And then the frequency of occurrence time of each torque–torque variation pair was calculated and converted to a percentage of the baler operation cycle duration. The LabVIEW (version 2012, National Instrument, USA) was used for torque torque–variation probability distribution creation and SSD calculation. Performance of the baler operation cycle was compared through PV comparing with international standards driving cycles because there is no research on the working cycle of tractors. PV was calculated by the sum of the weighted absolute errors of the assessment criteria (maximum, minimum, average values of each torque and torque variation, and micro–trip duration) as in eq. 7 (Hung *et al*., 2007). The performance of the baler operation cycle was expressed as a ratio of PV of the developed driving cycles to PV of the baler operation cycle. It indicates that the working cycle had better performance with lower PV.

$$SSD = \sum_{i=1}^{N_t} \sum_{j=1}^{N_{tv}} (p_{ij} - q_{ij})^2 \quad (6)$$

Where, N_t : the number of torque classes, N_{tv} : the number of torque variation classes, p_{ij} : ith torque class of the calibration set – probability distribution of jth torque variation class, q_{ij} : ith torque class of working cycle – probability distribution of jth torque variation class.

$$PV = |\bar{\theta}_c - \bar{\theta}_i| \cdot W^T \quad (7)$$

Where, W^T : the transposed row vector of weight vector.

Evaluation of fuel efficiency

Fuel efficiency of the baler operation was evaluated by dynamometer test using a dynamometer system and baler operation cycle. The dynamometer system was composed of a tractor diesel engine of 71 kW rated power, an engine dynamometer (dynoload, AVL, Austria) of 200 kW rated power, and fuel conditioning equipment (735C, AVL, Austria) as shown in Fig. 4. AC drive type engine dynamometer had 600 Nm rated torque, therefore, baler operation cycle to engine could be generated in real time variables. The fuel conditioning equipment supplied fuel to engine and regulated fuel conditions such as temperature and pressure. To reduce vibration of the engine, the dynamometer system was installed on the surface bed which had four air dampers to adjust horizontality for the system. In order to transmit torque to the engine, the flywheel of the tractor diesel engine was connected to output flange shaft of the engine dynamometer through universal shaft. The developed baler operation cycle using calibration set was converted to excel form of torque profile and applied to operating system. The operating system (PUMA, AVL Austria) controlled rotational speed of output flange shaft of the engine dynamometer to control engine torque following input baler operation cycle with 10 Hz control speed.

For reliability of the dynamometer test, the engine warmed up for one hour under rated engine speed in

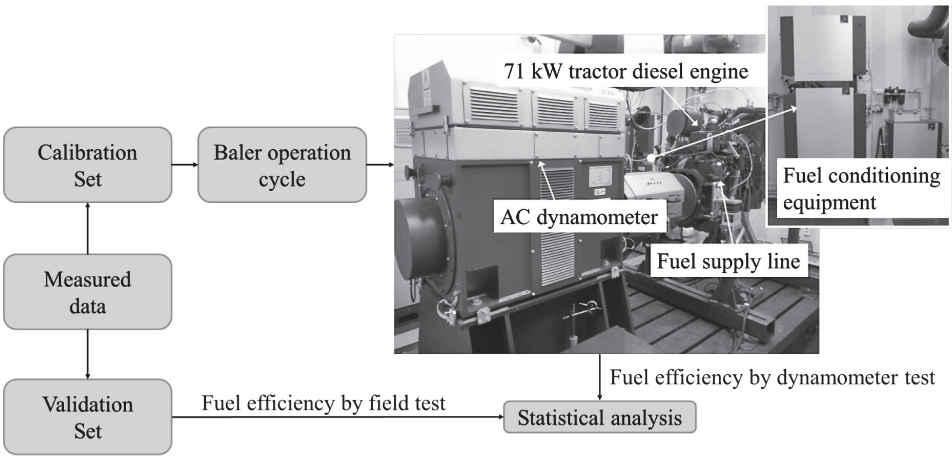


Fig. 4. Fuel efficiency evaluation using dynamometer system and baler operation cycle.

non–load condition. After the warming up, the fuel consumption and engine power were measured while the engine acted on the baler operation cycle in real time. And fuel efficiency was evaluated at the same time as in eq. 3. F–test was conducted using fuel efficiency of the dynamometer test, and the fuel efficiency of each micro–trip constituting the baler operation cycle were compared each other. And then, t–test was performed to compare the fuel efficiency by the dynamometer test and the fuel efficiency of validation set by the field test. The statistical analysis was performed within a significance level of 0.05 using the SAS (version 9.1, SAS Institute, Cary, USA), and repeated five times.

RESULTS AND DISCUSSION

Moisture content of Italian ryegrass

Table 1 shows the averaged moisture contents of Italian ryegrass for each farmland. Moisture content for each farmland had ranges of 11.7 to 12.5% for calibration and 11.9 to 17.2% for validation set, respectively. Most of moisture content showed similar ranges except farmland number 2 for validation which had the highest moisture content of 17.2%.

Baler operation cycle

Data collection and micro–trip

Fig. 5 shows the representative measured data from the micro–trip of transmission and PTO input shafts, the pressures of main and auxiliary hydraulics, and the calculated engine torque. The process of baler operation was as follows: the tractor picked up and chopped the forage at baling period, the tractor stopped to tie a bale when the chamber was filled with the forage at tying period, and the tractor open the chamber to discharge the bale at discharging period. The working routes of the baler follow the forage paths in order to pick up the forage on the field. Torque of transmission input shaft increased rapidly at the initial point of baling due to maximum static friction force, and the range of the torque was 50~130 Nm in most of baling operation. After baling period, torque of transmission input shaft decreased below 20 Nm consistently because the tractor stopped for tying a bale and discharging it. The measured torque of PTO input shaft increased gradually as the amount of collected the forage increased in the baling period and decreased with stopping the forage collecting in the tying period. After tying the bale, the torque increased rapidly to discharge it. The PTO input shaft reached maximum torque about 200 Nm at the end of baling period. The pressure of main hydraulic was maintained constantly about 4.5 MPa level during baling period, however, it increased up to 9~15 MPa at several points in the ranges of 0~20 and 30~50 s because the operator controlled the 3–point hitch due to the tractor load condition. At the end of the tying period, the pressure increased over 18 MPa due to the opening of the baling chamber and then decreased to 4 MPa as opening of the bailing chamber is completed. In the discharging period, the pressure of main hydraulic increased up to 16 MPa rapidly due to the closing of the baling chamber and then decreased to 2 MPa. The pressure of auxiliary hydraulic showed torque range of 4~8 Nm with some fluctuations according to forage paths, and it increased rapidly up to 16 MPa at the initial point of baling period while steering the tractor to set to the first direction. Engine torque showed similar curves with the PTO input shaft torque during entire period because most of the torque was generated from the PTO. And it increased by traction force in the baling period, and some fluctuations were observed according to the variations of the hydraulic system in controlling baler chamber and steering the tractor. The maximum engine torque was up to about 270 Nm.

Cycle determination

Fig. 6 shows the determined baler operation cycle which had the lowest SSD of 1262.19 and PV of 89.55. The baler operation cycle was developed seven micro–trips because seven bales were produced in a farmland. The length of working time was about 600 s in a farmland (100 m × 30 m) and each micro–trip was similar with the representative measured data as shown in Fig. 5.

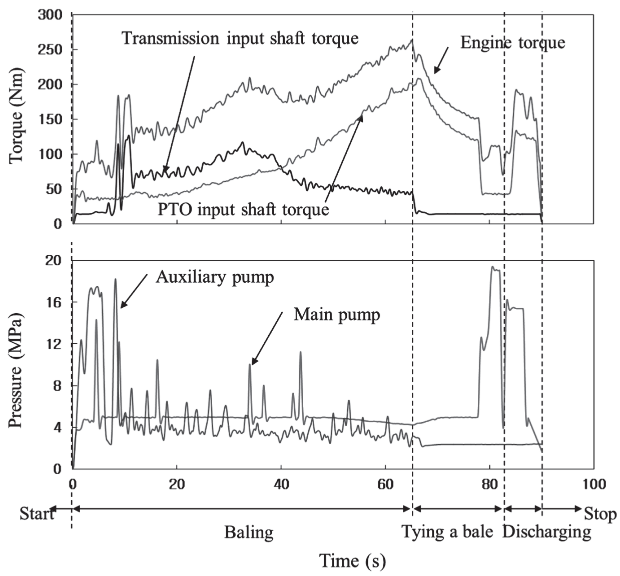


Fig. 5. Representative measured data and micro–trip of baler operation.

Table 1. Averaged moisture contents of Italian ryegrass for each farmland

Farmland No	Calibration set					Validation set				
	1	2	3	4	5	1	2	3	4	5
Moisture content (%)	11.7	12.0	12.4	12.1	12.5	12.3	17.2	11.9	12.4	13.0

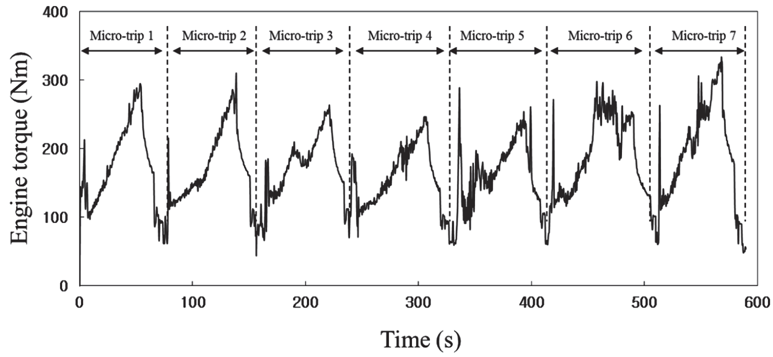


Fig. 6. Determined baler operation cycle in a farmland (30 m × 100 m).

Table 2. Comparison of assessment parameters of the baler operation cycle using the calibration set and the validation set

Assessment criteria	Validation set	Baler operation Cycle using Calibration set	Absolute percentage error (%)
Max. torque (Nm)	334.2	331.3	0.9
Min. torque (Nm)	32.6	34.2	4.9
Mean torque (Nm)	172.1	176.2	2.4
Max. torque–variation (Nm/s)	210.3	207.9	1.1
Min. torque–variation (Nm/s)	–209.0	–204.5	2.2
Mean torque–variation (Nm/s)	0.060	0.058	3.3
Mean micro–trip duration (s)	91.8	89.3	2.7

The baler operation cycle had repetitive patterns of gradual increases and sharp decreases depending on baling and bale discharging. The maximum engine torque range was from 250 to 320 Nm.

The baler operation cycle was determined among selected working cycles which are satisfied all the criteria by less than absolute percentage error 5% to the calibration set. Also, it was satisfied all the criteria by less than 5% absolute percentage error to the validation set with range of 0.9 to 4.9% as in Table 2. The maximum, minimum, and mean torques of the baler operation cycle were 331.3, 34.2, and 176.2 Nm, respectively, and each had 0.9, 4.9, and 2.4% of absolute percentage error to the validation set. The maximum, minimum, and mean torque variations of the baler operation cycle were 207.9, –204.5, and 0.058 Nm/s, respectively, and each had 1.1, 2.2, and 3.3% of absolute percentage error to the validation set. The micro–trip duration was 89.3 s, and the absolute percentage error was 2.7% to the validation set. The absolute percentage errors of minimum torque and mean torque–variation had higher errors than other assessment parameters. This is because amplitudes of minimum torque and mean torque–variation were lower than other assessment parameters. Maximum and mean torques of baler operation required about 83 and 44% of engine maximum torque, respectively. Also, load variation of the baler operation changed dramatically such an extent that increased or decreased nearly 50%/s at the maximum engine torque of 400 Nm.

The results indicate that the developed baler operation cycle could be a possible representative of actual baler operation because the absolute percentage error between the baler operation cycle and both of the calibration and validation sets were less than 5%.

Fig. 7 shows the torque–torque variation probability distribution of the baler operation cycle and the validation set. Two graphs showed similar shapes and ranges, however, probability distribution of the baler operation cycle was dispersed more than the one of the validation set due to the small number of sample. Most of the probability distribution of the validation set was in the torque range of 50~250 Nm and torque variation range of –40 ~ 40 Nm/s, and the one of the baler operation cycle was in the torque range of 40~260 Nm and torque variation range of –50~50 Nm/s. Probability distribution of the torque was dispersed more than the one of the torque variation at both baler operation cycle and validation set. Because most torque of the baler operation was continuously increased and decreased from 50 to 270 Nm with low torque variation below 50 Nm/s in baling and tying a bale periods, respectively. The peak probabilities of the baler operation cycle and the validation set were about 2.0 and 2.5% in same torque and torque variation range.

When compared with SSD of sub–unban driving cycle (697.04) from Hung *et al*. (2007), the SSD of the baler operation cycle (1262.19) showed lower performance. However, it showed difference of 10% to the ones of urban (1213.65) and highway driving cycle (1144.08) from the

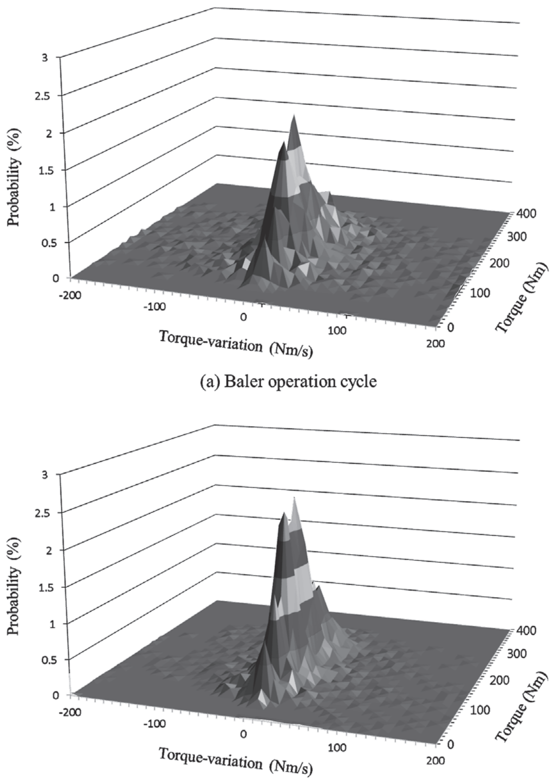


Fig. 7. Results of torque-torque variation probability distribution for the validation set and determined baler operation cycle.

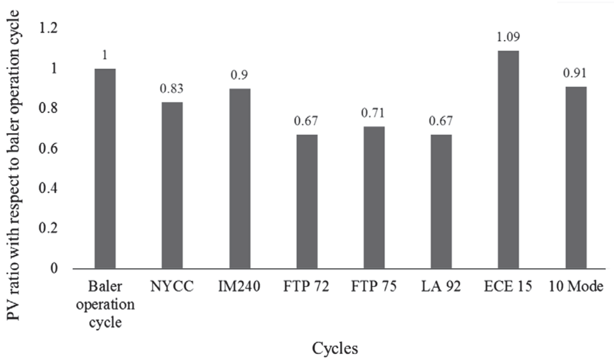


Fig. 8. Evaluation result of baler operation cycle.

same research. In addition, the baler operation cycle was compared with the international standard driving cycles of conventional vehicle with PV values, and it was expressed as a ratio of PV of each driving cycle to PV of baler operation cycle. PVs of the commonly used driving cycle were 67~109% of the baler operation cycle as in Fig. 8, and FTP 72 and LA 92 were the lowest to 67% of the baler operation cycle. The ECE 15 and 10 Mode were the closest to the baler operation cycle within 10% difference, especially PV of the ECE 15 was 109% higher than the baler operation cycle. The results showed that the baler operation cycle had higher performance than the ECE 15, however, some of the driving cycles had 67~71% of it. The determined baler operation cycle is feasible to emulate load condition in field test. However, to use as standard cycle, the additional research such as acquiring more field data in various environmental conditions, applying more assessment criteria factors, and developing working cycle construction method are needed.

Evaluation of fuel efficiency

Fuel consumption and fuel efficiency were evaluated while the dynamometer acted on baler operation cycle as shown in Fig. 9. The fuel consumption showed similar trend to the measured torque of the baler operation cycle which showed repeated patterns of gradual increases and rapid decreases with the range of 7~16 kg/h at seven micro–trips. However, the fuel efficiency showed reverse trend to the fuel consumption because it was expressed in fuel consumption per unit power. This is because the fuel efficiency could increase although the fuel consumption increased in the case that power consumption increased more than fuel consumption. The fuel efficiency during baling period was low to 0.5 kg/kWh mostly, except initial point. The rapid increasing at the initial point was due to maximum static friction force. On the contrary, the fuel efficiencies at tying and discharging periods were up to 0.5 kg/kWh, and maximum values were in the range from 0.75 to 1.35 kg/kWh, approximately. Therefore, the fuel efficiency of the baling period was the lowest because it has not only higher consumed engine power but also higher fuel consumption than other peri-

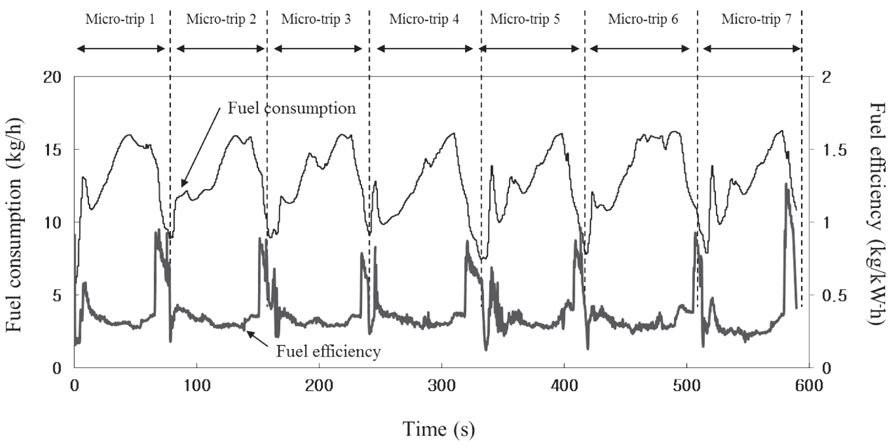


Fig. 9. Evaluation results of fuel consumption and efficiency using baler operation cycle.

Table 3. Comparison the averaged fuel efficiency of each micro trip constituting baler operation cycle by dynamometer test

Number of Micro–trip	Fuel efficiency by dynamometer test (kg/kWh)	F–value
1	0.37±0.121[1)]	
2	0.37±0.116	
3	0.35±0.119	
4	0.36±0.132	1.25[2)]
5	0.37±0.126	
6	0.36±0.131	
7	0.39±0.140	

1) Mean±std.
2) $p>0.05$

ods.

Fuel efficiency by the dynamometer test was expressed as averaged value of each micro trip constituting baler operation cycle. Table 3 shows the averaged fuel efficiency of each micro trip. The averaged fuel efficiencies of micro–trips were 0.37, 0.37, 0.35, 0.36, 0.37, 0.36, and 0.39 kg/kWh, respectively. The results of F–test showed no significant difference between each micro–trip constituting baler operation cycle although maximum difference had 0.04 kg/kWh. The fuel efficiency of each micro trip constituting the baler operation cycle which was evaluated by the dynamometer test showed similar patterns; therefore, it can be stated that micro trips of the baler operation cycle have the similarity each other.

Fuel efficiency by the dynamometer test was compared with the fuel efficiency of each farmland in the validation set by field test. Fuel efficiency by the dynamometer test was expressed as averaged fuel efficiency, and the fuel efficiency of each farmland in the validation set were expressed as averaged fuel efficiency for each farmland. Table 4 shows comparison between the averaged fuel efficiency of dynamometer test data and the ones of field test data. The averaged fuel efficiencies by field test were 0.39, 0.52, 0.38, 0.39, and 0.40 kg/kWh at each farmland, respectively, and the averaged fuel efficiency by dynamometer test was 0.37 kg/kWh. The results of t–test showed that there was no significant difference between fuel efficiency of the dynamometer test and fuel efficiency of the field test except one farmland. In the case

Table 4. Comparison the averaged fuel efficiency of dynamometer test data and field test data by each farmland

Farmland No. of validation set	Fuel efficiency Field test	Dynamometer test	t–value
1	0.39±0.109[1)]		1.50
2	0.52±0.111		3.31[2)]
3	0.38±0.121	0.37±0.141	1.29
4	0.39±0.118		1.77
5	0.40±0.130		1.95

1) Mean±std.
2) $p<0.05$

of farmland number 2, moisture content of Italian ryegrass was highest among the other farmlands, which can give an increase in fuel efficiency.

Therefore, the baler operation cycle was available to evaluate the fuel efficiency using dynamometer. However, to improve reliability of fuel efficiency evaluation more accurate baler operation cycle should be developed, which reflects actual working through considering various environmental condition factors such as forage characteristics.

SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate fuel efficiency of tractor using working cycle. For doing this, this study conducted field tests of baler operation, developing baler operation cycle using the measured field data, and evaluating fuel efficiency of tractor using a dynamometer and the baler operation cycle. The results of the study are as follows:

Torque data of baler operation were measured by installing a load measurement system on transmission input shaft, PTO input shaft, main and auxiliary hydraulics, and fuel consumption was measured by mounting a flow meter on fuel supply line. Baler operation was conducted in total ten of Italian ryegrass farmlands with similar sizes (3,000 m^2:100 m × 30 m) and the soil and forage characteristics of the each farmland were analyzed. Total 70 number of field data was measured. Half of the measured data were used to develop the baler operation cycle as calibration set and rest of them were used to evaluate fuel efficiency as validation set. The baler operation cycle was developed using the calibration set, and performance of it was evaluated through comparing the validation set. The developed baler operation cycle satisfied all the criteria by less than absolute percentage error 5 % to the calibration set. Also, it satisfied all the criteria by less than 5% absolute percentage error to the validation set with range of 0.9 to 4.9%. PV of the baler operation cycle and the international standard driving cycles of conventional vehicles were compared for performance evaluation of the baler operation cycle. The evaluation results showed that PVs of the commonly used driving cycle were 67~109% of the baler operation cycle. The ECE 15 and 10 Mode were closest to the baler operation cycle within 10% difference, especially PV of the ECE 15 was 109% higher than the baler operation cycle. Fuel efficiency of the baler operation was evaluated using a dynamometer system and baler operation cycle. The dynamometer system was composed of a tractor diesel engine, an engine dynamometer, and fuel conditioning equipment. The fuel consumption and engine power were measured while the engine acted on the baler operation cycle in real time, and fuel efficiency was evaluated at the same time. The statistical analysis was performed for analysis of fuel efficiency evaluation using the dynamometer and baler operation cycle. The results of t–test showed that there was no significant difference between fuel efficiency of the dynamometer test and fuel efficiency of the field test except one farmland. This is because moisture content of Italian ryegrass was highest among the other farmlands, which can give an increase in fuel efficiency.

Considering all results of this study, the developed baler operation cycle could be a possible representative of actual baler operation, and it evaluated the fuel efficiency using the dynamometer. The developed baler operation cycle in this study can solve the problems of field test such as inconveniences, low reliability, and high cost, and it will compensate for the difficulties of full load test that is hard to reflect actual tractor performance. In addition, it will be utilized for various tests of tractor performance evaluation. However, to improve reliability of indoor test more accurate baler operation cycle should be constructed through developing working cycle construction method with considering various environmental conditions and assessment criteria factors.

ACKNOWLEDGEMENTS

This work was supported by research fund of Chungnam National University.

REFERENCES

Ahlawat, R., S. Jiang, D. Medonza, and M. H. Smith 2012 On emulating engine and vehicle transient loads for transmission–in–the–loop experiments. *Mechatronics*, **22**(7): 989–996

Andre, M. 2004 The ARTEMIS European driving cycles for measuring car pollutant emissions. *Sci. Total Environ.*, **334–335** (1): 78–84

Andre, M., R. Joumard, R. Vidon, P. Tassel, and P. Perret 2006 Real–world European driving cycles, for measuring pollutant emissions from high– and low–powered cars. *Atmos. Environ.*, **40**(31): 5944–5953

ASABE 2011a Soil Cone Penetrometer. In: ASABE Standards S313.3. St. Joseph, Mich: ASABE publication.

ASABE 2011b Procedures for Using and Reporting Data Bbtained with the Soil Cone Penetrometer. In: ASABE Standards EP542. St. Joseph, Mich: ASABE publication.

Bietresato, M., A. Calcante, and F. Mazzetto 2015 A neural network approach for indirectly estimating farm tractors engine performances. *Fuel*, **143**: 144–154

Dong, S. H., W. C. Nak, L. C. Sung, S. Y. Jin, S. K. Kwang, S. Y. Wan, and H. J. Chung 2012 Characterization of driving patterns and development of a driving cycle in a military area. *Transp. Res. D Transp. Environ.*, **17**(7): 519–524

Ergeneman, M., C. Sorusbay, and A. Goktan 1997 Development of a driving cycle for the prediction of pollutant emissions and fuel consumption. *Int. J. of Veh. Des.*, **18**(3): 391–399

Esteves–Booth, A., T. Muneer, H. Kirby, J. Kubie, and J. Hunter 2001 The measurement of vehicular driving cycle within the city of Edinburgh. *Transp. Res. D Transp. Environ.*, **6**(3): 209–220

Fontaras, G., P. Pistikopoulos, and Z. Samaras 2008 Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real–world simulation driving cycles. *Atmos. Environ.*, **44**(18): 4023–4035

Gong, Q., S. Midlam–Mohler, V. Marano, and G. Rizzoni 2011 An iterative Markov chain approach for generating vehicle driving cycles. *SAE Int. J. Eng.*, **4**(1): 1035–1045

Green, M. K., B. A. Stout, and S. W. Searcy 1983 Instrumentation package for monitoring tractor performance. ASAE Paper No. 83–1562. ASABE, St. Joseph, Mich.

Ho, S. H., Y. D. Wong, and V. W. C. Chang 2014 Developing Singapore driving cycle for passenger cars to estimate fuel consumption and vehicular emissions. *Atmos. Environ.*, **97**(2014): 353–362

Hung, W. T., H. Y. Tong, C. P. Lee, K. Ha, and L. Y. Pao 2007 Development of a practical driving cycle construction methodology: A case study in Hong Kong. *Transp. Res. D Transp. Environ.*, **12**(2): 115–128

Kamble, S. H., T. V. Mathew, and G. K. Sharma 2009 Development of real–world driving cycle: Case study of Pune in India. *Transp. Res. D Transp. Environ.*, **14**(2): 132–140

KAMICO and KSAM 2012 Agricultural Machinery Yearbook in Republic of Korea. Suwon: Korea Agricultural Machinery Industry Cooperative and Korean Society for Agricultural Machinery

Kim, D. J. 2004 Hydraulic Engineering. Seoul: Bookshill

Kim, Y. J., S. O. Chung, S. J. Park, and C. H. Choi 2011a Analysis of power requirement of agricultural tractor by major field operation. *J Biosystem Eng.*, **36**(2): 79–88

Kim. Y. J., D. H. Lee, S. O. Chung, S. J. Park, and C. H. Choi 2011b Evaluation of tractor PTO severeness during rotary tillage operation. *J Biosystem Eng.*, **36**(3): 163–170

Lacour, S., C. Burgun, C. Perilhon, G. Doscombes, and V. Doyen 2014 A model to assess tractor operational efficiency from bench test data. *J. Terramechanics*, **54**: 1–18

Nesamani, K. S. and K. P. Subramanian 2011 Development of a driving cycle for intra–city buses in Chennai, India. *Atmos. Environ.*, **45**(31): 5469–5476

Nguyen, V. N. and S. Inaba 2011 Effects of tire inflation pressure and tractor velocity on dynamic wheel load and rear axle vibrations. *J. Terramechanics*, **48**(1): 3–16

Park, S. H., Y. J. Kim, D. H. Im, C. K. Kim, Y. Jang, and S. S. Kim 2010b Analysis of factors affecting fuel consumption of agricultural tractor. *J Biosystem Eng.*, **35**(3): 151–157

Park, S. H., Y. J. Kim, D. H. Im, C. K. Kim, S. C. Jung, H. J. Kim, Y. Jang, and S. S. Kim 2010a Development of eco driving system for agricultural tractor. *J Biosystem Eng.*, **35**(2): 77–84

Ryu, K. H. 2004 Tractor Engineering Principles. Seoul: Munundang

Tamsanya, S., S. Chungpaibulpatna, and B. Limmeechokchai 2009 Development of a driving cycle for the measurement of fuel consumption and exhaust emissions of automobiles in Bangkok during peak periods. *Int. J. of Automot. Technol.*, **10**(2): 251–264

Tong, H. Y. and W. T. Hung 2010 A framework for developing driving cycles with on–road driving data. Transp. Rev. A Transnatl. Transdiscipl. J., **30**(5): 589–615

Tong, H. Y., W. T. Hung, and C. S. Cheung 1999 Development of driving cycle for Hong Kong. Atmos. Environ., **33**(14): 2323–2335

Tong, H. Y., H. D. Tung, W. T. Hung, and H. V. Nguyen 2011 Development of driving cycles for motorcycles and light–duty vehicles in Vietnam. Atmos. Environ., **45**(29): 5191–5199