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Simple and cost effective method for fuel consumption measurements of agricultural machinery

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Abstract. Energy saving objectives in agriculture have created a demand for energy consumption figures of single field operations and for total fuel consumption in farm level. Although the fuel consumption of field operations is quite well known in general level, the conditions in different locations and years result in variation between these figures. In order to create an energy analysis for a single farm, a way to measure the fuel consumption on site is needed.

The most useful unit for fuel consumption in most of the farming field operations is l ha^{-1}, since it enables the comparison between different farms and years. Using this unit also reduces the effect of uncontrollable factors, for example weather and soil conditions.

In this study, a simple and cost effective way to measure the fuel consumption of agriculture machinery in l ha^{-1} was tested. The fuel consumption was measured by the voltage signal of machine's own fuel level sensor. The signal was recorded with a voltage data logger, and movements of the machine were recorded with a simple personal GPS-tracker. Manual bookkeeping was also made to provide support for data analysis. A calibration curve was created for each machine to calculate the corresponding fuel level for each voltage reading. Measuring system was inexpensive, easy to install and did not require any modifications to the fuel system. It can also be installed to almost any tractor or other self propelled farm machine.

Results showed that this is a useful measuring method with certain restrictions. The measuring period has to be relatively long to obtain reliable results, and therefore the continuous working periods for each working phase has to be long enough. The conclusion was that this kind of measuring system can be used to provide average values for energy analysis and also to detect the critical points in the production system.

Keywords: agriculture, fuel consumption measurement, fuel level sensor, GPS, energy saving, farming, fuel consumption per hectare.

Introduction

Declining energy resources and the climate effects from the use of fossil fuels have resulted in energy saving objectives in all industry sectors. Although agriculture has a minor role in energy markets, representing ca. 2% of total fuel and 1% of electric energy consumption in Finland (Agrifood Research Finland, 2012) and correspondent 4% and 3% in Estonia (Statistics Estonia 2012), it has an obligation to reduce the use of energy as a part of non-emission trade sector. As the energy prices continue to rise, the energy consumption becomes also more and more important to the economy of farms.

To find ways to save energy, the energy use inside the system and its allocation in the sub-systems must be known. Energy analyses are used to receive this information. For this purpose, all the energy inputs and outputs crossing the system boundaries must be examined. One of the major energy inputs in arable farming is diesel fuel for field machinery. For example in barley production in Finland, diesel fuel represents ca. 30% of the total energy consumption (Mikkola & Ahokas, 2009). Considering only the direct energy used in arable farming, fuels for field operations and grain drying are the principal energy inputs.

Although the fuel consumption of agriculture machinery is quite well known in general level, the variation of the figures can be considerably large. For example fuel consumption figures for ploughing vary from 14 to 52 l ha^{-1}, depending on the soil type, working depth and timing of the operation (Kalk & Hulsbergen, 1999). Therefore there is a demand for an easy, simple and cost effective method to measure fuel consumption in real time. Other requirements for the system are the ability to large scale measurements to receive an average figure for each work task instead of a single test plot, and independent operation to avoid any excess stress to the driver.

Fuel consumption can be measured by several methods. The simplest way is manual bookkeeping of the consumed fuel and the work done. Even this simple method gives adequate accuracy in many cases, and it can be used as an information source for energy analysis. However, it requires extra effort and attention from the operator. On-line measurement can be done indirectly, for example from the exhaust gas temperature or injection needle lift duration of the machine, or directly using a fuel flow meter (McLaughlin et al., 1993).

Suitability of different measuring methods depends on the use of the data and the objectives of the study. Indirect methods have been used to create an efficiency monitor to guide the driver to use the machine efficiently. The efficiency of a tractor operation can be improved often by SUTB-approach (shift up, throttle back) when not working under full load conditions (Howard et al., 2011). For example Pang et al., (1985) investigated the possibility of monitoring tractor efficiency by measuring the fuel consumption indirectly via the exhaust gas temperature and using an electronic correction system. De Souza and Milanez (1988) used the same method to evaluate the torque of the engine.

However, the most common way to fuel consumption measurement has been the use of flow meters. This method can provide a good accuracy and it can be used for wide variety of applications. When using flow meters, the return line from the injection pump has to be either measured separately or be returned to the inlet side of the transfer pump. This may require an external cooling for the fuel in the return line. For high accuracy measurements, the fuel temperature must also be recorded in order to calculate the correct mass flow. (Domsch et al., 1999; McLaughlin et al., 1993)

In modern machines the fuel consumption data can also be captured from the CAN-bus (controller area network) of the machine. CAN-bus is used for the communication of the several electronic controller units inside modern machines. The fuel consumption information can be collected from the bus data traffic with a suitable analyzer hardware and software. The advantages of this method are that no additional sensors are needed, and some other useful information can be collected simultaneously, for example the draught force of the three-point hitch link. (Schutte et al., 2004)

All the addressed measuring methods require high technical expertise or, in many cases, modifications to the fuel system, which may cause high expenses and reduce the reliability of the machines. In this study, a simple and cost effective method for measuring the fuel consumption was developed and tested. The principal idea was to use the voltage signal of the machine’s own fuel level sensor to define the fuel consumption. The aim was to create a system which was cheap, easy to install and move from one machine to another, do not affect the reliability of the machine and could work independently for relatively long periods of time. The system was intended to be used for receiving average fuel consumption figures for the energy analysis, so a high accuracy was not included in main targets.

Combining the fuel consumption measurements with GPS position information enables an effortless recording of the velocity and location of the machine. It can also be used to match the measured data to the correct field plots. (McLaughlin et al., 2008) This information is needed to calculate the fuel consumption in l ha^{-1}. Since there are several low-cost GPS receivers with a data logging feature on a market, the position information was also included as a part of this study. Using the velocity information from the GPS data also makes it possible to determine the working efficiency during the field work.

Materials and methods

Fuel sensor voltage measurement

In this study, the fuel consumption of agricultural machinery was detected by the voltage signal of machine’s own fuel level sensor. The fuel level sensor, or sensing unit, is usually built from a float and a potentiometer, forming a simple voltage divider. When the fuel level in fuel tank changes, the float moves changing the resistance of the potentiometer. This can be measured as a change in the output voltage of the sensor. When the voltage signal is recorded continuously during field works and location of the machine is recorded with a GPS-tracker, the fuel consumption for the processed area in l ha^{-1} can be calculated.

The voltage signal of the sensor was measured and recorded with a voltage data logger unit. Two types of data loggers were used: Tinytag TGPR-0704 and Madgetech Volt101A. Tinytag has an adjustable measuring range of 0–2.5/10/25 V, resolution of 10/40/100 mV respectively and memory capacity of 64.000 readings. Madgetech Volt101A has a measuring range of 0–30 V, 1.0 mV resolution and memory capacity of ca. 1 million readings. Logging interval for both devices was 30 s, which enabled ca. 22 days of continuous data recording with Tinytag and almost one year with Madgetech.

A calibration curve was created for each machine to resolve the corresponding fuel level for each voltage reading measured from the sensor. This was done by pumping the fuel tank empty and then filling it in parcels of 5, 10 or 20 liters, depending on the size of the tank. For each added parcel of fuel, the voltage reading was recorded until the tank was full. A second order trend function was fitted into the received plot in the Excel spreadsheet program, which gave the equation for calculating the fuel level from the measured voltage signal. Example of a calibration curve is shown in the fig. 1.

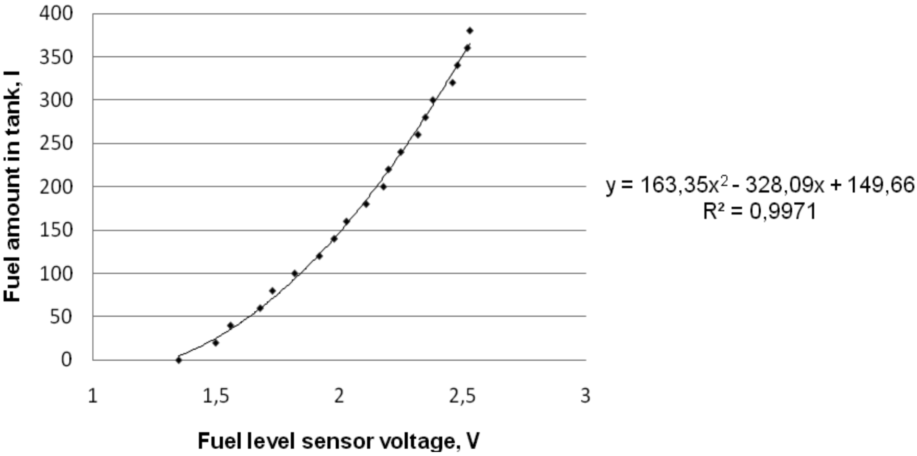

Fig. 1. Calibration curve for combine harvester and the equation for calculating the corresponding fuel level from the measured voltage.

Position information recording

The movements and velocity of the machines were recorded with low-cost personal GPS positioning devices. The measuring interval was the same 30 s as for the voltage data loggers, and the devices were selected to match the memory capacity of the voltage loggers as closely as possible.

With the Tinytag-logger, a Globalsat BT-338X GPS-tracker was used. It has the same 16 kB (ca. 60.000 readings) memory capacity as Tinytag. The accuracy according to the manufacturer is for velocity 0.1 m s^{-1} (95% probability) and for horizontal position 10 m with Navstar-GPS-signal and 5 m with WAAS/EGNOS-signal.

A Qstarz CR-Q1100P GPS-tracker was used with the Madgetech voltage logger. It has a memory capacity of ca. 400.000 readings, but due to the vibration-controlled sleep mode, it can reach at least the same operation time as the Madgetech voltage logger. The accuracy for velocity is 0.1 m s^{-1} and for horizontal position 3 m (< 3 m 50% probability) and with the WAAS/EGNOS-signal 2.5 m (according to the manufacturer).

According to the European Space Agency ESA (2009), the EGNOS-signal reaches the accuracy of 1–2 m with 95% and 2–3 m with 99% probability for horizontal positioning in southern Finland. However, in this study the GPS position information was used only to match the measured data to the correct field plots, and therefore the accuracy of the position information was not crucial. The velocity information, on the other hand, is relatively accurate, and therefore it can be used as a reliable information source for calculating the working efficiency.

Calculation of fuel consumption

The field plot area used in the fuel consumption calculations was the official digitized area, which was received from the farm bookkeeping. With the aid of the GPS data, the measured fuel consumption was allocated to the correct field area. Since both the voltage readings and the GPS position information had a timestamp, and the trace of the machines could be seen on a map, it was possible to separate the fuel consumption for one specific field plot or several field plots together. When the distance between the farm and the field plots was short, few kilometers at maximum, and no additional jobs were done with the tractor between processing several field plots, the fuel consumption was calculated to all these field plots together and the transport from one field to another or to the farm centre was ignored. This improved the accuracy of the results, since the absolute error became relatively small as the data material increased. The amount of fuel consumed during the transport was assumed to be so small that it had no notable effect on the results when the distance was short.

The fuel consumption was calculated as the difference between the averages from the first and last 10 voltage readings from the start and end of the work. If the fuel tank was filled during the processing of the monitored area, the fuel consumption was calculated in same way for each refueling, and the total amount was received by summing these results. This was then divided by the processed area to obtain the result as liters per hectare. The calculation is described in equation (1).

$$x_S = \frac{1}{A}\left(\sum_{i-1}^{n} \Delta \bar{x}_i\right) \qquad (1)$$

x_s - work specific fuel consumption, l ha^{-1}

A - monitored area, ha (e.g. one or several field plots)

n - refueling times

$\Delta \bar{x} = \bar{x}_1 - \bar{x}_2$

$\bar{x}_1 = \frac{1}{10}\sum_{i=1}^{10} x_{1i}$ - fuel amount with full tank or in the beginning of work task, l

$\bar{x}_2 = \frac{1}{10}\sum_{i=1}^{10} x_{2i}$ - fuel amount before refueling or at the end of work task, l

Working efficiency

In agriculture field operations, the working efficiency describes how efficiently the time is used to do the effective work. Usually this is expressed as a relationship between the effective working time and total working time. Because of the headland turns, overlapping and possible interruptions, the working efficiency is always less than 100%. This information can be used, for example, to compare the efficiency of different driving patterns on a field.

Instead of the working time, the efficiency is here calculated based on the actual field plot area and theoretical area, which is received from the average velocity during the work and the working width. Average velocity and time spent on a particular field plot was received from the GPS information. The working efficiency was calculated with equation (2).

$$\eta = \frac{A}{\bar{v}wt}1000 \qquad (2)$$

η – working efficiency, %;
A – field plot actual area, ha;
$\bar{v}$ – average velocity, km h^{-1};
w – working width, m;
t – time, h.

Data processing

Data from the voltage- and GPS data loggers was uploaded to computer for analysis. This was done when the memory of the loggers was full or at least few times during the season to check whether the devices were working properly. Data was analyzed in the Excel spreadsheet program with the aid of the own software of the GPS loggers and the manual bookkeeping. The software provided with the GPS loggers enabled displaying the trace of the machine on a map. This information was used to connect the measured fuel consumption into a particular field plot (or several plots). Manual bookkeeping was used along with the GPS information and fuel consumption measurements to verify the correct field plots and the work that was done.

Results and discussion

Fuel consumption measurements

The proposed method for fuel consumption measurements was tested in various field operations on two farms in southern Finland during summers 2010 and 2011. The principal soil types in terms of soil texture on both farms were clay loam and sandy loam. The production orientation on the first farm is combined milk and crop production. The second farm is focused on pork production. This production structure enabled the measurements in most of the common agriculture field operations. The measurements took place in following tasks: harrowing, sowing, combine harvesting, ploughing, cutting grass, loader wagon operation and manure spreading. Some of the lightest tasks, like spraying and windrowing were not examined.

The table 1 shows examples of the average measured fuel consumption from all of the results of a single work task. Since some of the results are calculated from a single continuous measurement, it is difficult to give any deviation figures for the results. Generally, the order of the magnitude of the results is similar to the figures found in literature (Ortiz-Cañavate, J. & Hernanz, 1999; Mikkola & Ahokas, 2009). The refueling information is also found in the manual bookkeeping, and a rough calculation done by the basis of this information also verifies that the results are of correct magnitude.

Table 1. Average fuel consumption figures (l ha^{-1}) from the measured data

Type of work	Farm 1. 2010	Farm 1. 2011	Farm 2. 2011
Harrowing	8.1	10.0	7.1
Sowing	5.3	7.0	7.5
Combine harvesting	10.6	8.9	9.4
Ploughing	-	-	16.3
Manure spreading*	-	-	3.6
Cutting grass	4.1	4,7	-
Baling	5	-	-
Loader wagon operation	-	14.5	-

*Liquid slurry, 12 m dribble bar

There are some differences in the results between the years and the farms, which can be explained with different conditions, working methods and machinery. In sowing there is a remarkable difference between the figures from years 2010 and 2011 in farm 1. This is probably caused by using different tractor for pulling the seed drill. In year 2011, the seed drill was pulled with a New Holland TM155 model 2002. In 2010, a brand new Valtra T162e was used. The difference in fuel consumption is probably caused by the modern transmission and engine management used in the newer tractor. In addition, Valtra T162e has an ‘EcoPower’ engine with an option to lower the engine nominal speed to 1,800 1 min^{-1}. According to the manufacturer, this reduces the fuel consumption ca. 10% (Valtra 2012).

Another notable matter is a great difference between the fuel consumption in baling and loader wagon operation. The fuel consumption for loader wagon includes naturally the transport to the storage while the bales are left on the field to be transported later. However, the results indicate that the energy consumption of these tasks could be worth more detailed analysis.

Working efficiency

Some examples of working efficiency analysis are shown in table 2. The working efficiency can be calculated with method used in present work only for tasks which comprehend a single processing time for the whole examined field area. For example harrowing the working efficiency cannot be calculated, since the number of passes is usually more than one and different passes cannot be separated from the results. Calculating the working efficiency with this method is also not sensible for tasks, which require the driver to follow a certain path, like when harvesting silage.

Table 2. Working efficiency for some tasks based on the measurements

Work task	Working efficiency, %
Sowing	76
Combine harvesting	76
Cutting grass	87

Uncertainty analysis

The aim of this study was to produce average figures for the energy analysis, and therefore a very high accuracy was not a main target. An error level of ca. 10% was determined to provide a satisfactory accuracy for this purpose. The accuracy of this measurement is affected by several factors:

- Resolution of the voltage data loggers
- Resolution of the fuel level sensors
- Accuracy of the fuel volume measurement during the calibration
- Possible hysteresis of the fuel level sensor
- Volume of the fuel tank
- Inclination of the machine during the measurement (slopes, ploughing)
- Error caused by averaging the values in the start and end of measurement.

The factors listed above affect the absolute accuracy of the results. The relative accuracy can be improved by increasing the length of the measurement. This increases the total amount of consumed fuel, decreasing the relative error. The increase in the fuel consumption rate also improves the relative accuracy for the same reason. The relative error can be calculated with the equation (3):

$$x_R = \frac{x_A}{Aq} 100 \qquad (3)$$

x_R – relative error, %;
x_A – absolute error, l;
A – processed area during the measurement, ha;
q – work specific fuel consumption, l ha^{-1}.

Fig. 2 describes the effect of measured acreage and fuel consumption rate to the relative error. In this example the absolute error has been set to the level of 10 liters.

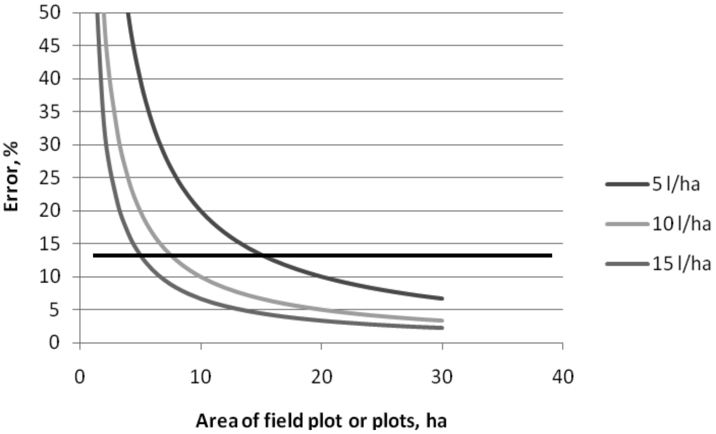

Fig. 2. The effect of the measured area and the fuel consumption rate to the relative error in the results. The absolute error is set to 10 liters.

To find out the needed length of the measurement to reach the desired accuracy, the absolute error sources must be examined. Since the several uncertainty factors were not known, the analysis were made by simple method described by Holman (2001), where the error was defined as the maximum error in any parameter used to calculate the results. Table 3 represents the known error sources for the machines used in the study. Since the fuel tank, fuel level sensor and used data loggers are different between the machines this evaluation has to be done separately for each machine. For some newer machines, for example, the fuel sensor reading changed discrete in steps but for the older ones the behavior was analogical. Therefore the resolution of the fuel sensor for these newer machines can be calculated and it is relatively large. When the calculation of sensor resolution was not possible, it was replaced with a tank volume coefficient factor which was estimated as 5% of the fuel tank volume. This coefficient includes the estimated error of fuel sensor hysteresis and calibration.

Table 3. Error sources for the measurements. The dominating absolute error for each machine is written in bold

Machine	Logger resolution	Fuel sensor resolution	Fuel tank volume	Volume coefficient factor (5%)	Total fuel amount required for 90% accuracy	Area required for 90% accuracy, fuel rate 10 l ha^{-1}
Valtra T162e	5.6 l (40 mV)	**23 l**	240 l	-	230 l	23 ha
Valtra N141	4.1 l (40 mV)	**14 l**	200 l	-	140 l	14 ha
Valmet 6400	5.1 l (100 mV)	-	130 l	**6.5 l**	65 l	6.5 ha
Valmet 6600	4.2 l (100 mV)	-	130 l	**6.5 l**	65 l	6.5 ha
New Holland TM155	8.6 l (100 mV)	**10 l**	235 l	-	100 l	10 ha
Case MX120	0.07 l (1 mV)	-	220 l	**11 l**	110 l	11 ha
Case MX150	0.10 l (1 mV)	-	330 l	**16.5 l**	165 l	16.5 ha
Deutz Fahr Agrotron 130	0.09 l (1 mV)	-	310 l	**15.5 l**	155 l	15.5 ha
Sampo Rosenlew 2065	2.4 l (40 mV)	-	255 l	**12.8 l**	128 l	12.8 ha
Claas Lexion 410	0.32 l (1 mV)	-	400 l	**20 l**	200 l	20 ha

In table 3, the total amount of consumed fuel for reaching the desired 90% accuracy is calculated. This is based on the absolute error of each machine (bolded figure in table 3). Absolute error presents the maximum of the known errors in this measurement, and it is considered to dominate over the smaller error sources. Table 3 represents also the area required for reaching the 90% accuracy level with work specific fuel consumption of 10 l ha^{-1}.

The inclination of the machine was assumed to be compensated by the averaging of the first and last 10 readings when calculating the fuel consumption. The averaging itself caused also some error, since a 2.5 minutes period from the start and the end of the measurements was then neglected. This error was ignored in table 3, since it was always dominated by some other error factor.

Other unknown factors were the accuracy of the fuel measurement in calibration and the hysteresis of the sensor. The calibration curves were created with a farm fuel tank meter, which has accuracy of ±1% according to the manufacturer. This error source was considered to be included in the volume coefficient factor. The possible hysteresis of the fuel level sensor was not examined. For the hysteresis analyses the calibration curve should have been done for two directions. This was not done for practical reasons (large number of machines and large fuel tanks).

The results of the error analysis show, that the size of the measured area has to be relatively large to obtain reliable results. This is however affected by type of the machine, fuel consumption rate and the volume of the fuel tank. The critical limit is the tank volume; if the total amount of fuel needed to reach the desired accuracy is bigger than the size of the tank, the accuracy cannot be reached, since the absolute error begins to multiply after each refueling and the relative error will not be improved any further. On the other hand, the smaller tank size improves the absolute accuracy and therefore the size of the required area decreases. According the error analysis, the most crucial factor is the fuel level sensor. If the resolution of the sensor is too small, the needed accuracy may not be reached. This situation is close with the first tractor in table 3.

Conclusions

Measuring the fuel consumption of agricultural machinery with fuel level sensor and GPS position information is a useful method with certain conditions. The continuous measuring periods have to be long enough to achieve reliable results. The fuel tank volume sets the final limit for the accuracy: the absolute error must be smaller than the desired relative accuracy multiplied by the fuel tank volume, or otherwise the desired accuracy cannot be reached. Under these conditions the accuracy is improved when the measured area or fuel consumption rate increases. The crucial factor in the measuring system is the accuracy of the fuel level sensor.

This kind of measuring method can be used to provide energy consumption figures for energy analysis. It can also be used to find the critical working methods or processes. The accuracy depends on the type of the machine, length of the measuring period and the fuel consumption rate. The method is best suited for large farms with relatively large field plots. On the other hand, small farms have usually smaller machines with smaller fuel tanks, resulting better absolute accuracy.

Separating the road transport from field works increase the workload of data analysis. If the transport distances are long, this method may not be suitable for fuel consumption measurement, especially if the field plots are small.

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