The use of CAN-Bus messages of an agricultural tractor for monitoring its operation

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Abstract

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The development of electronic components in engine regulation leads to the possibility of obtaining a large amount of parameters of control processes. Nowadays, these data can be read in an easy way due to the properties of used networks. The data obtained from the data bus must be processed carefully; otherwise, there is a risk of erroneous results. The article presents the results of measurements performed on four tractors. We focused on comparing the fuel consumption of engines and the accuracy of flow measurement readings from the CAN-Bus of these tractors. Even the same engines may show considerable differences in fuel consumption, taken from the CAN-Bus. The maximum deviation of the measured values ranged up to around 40%. However, the value of about 41% was measured in the range of fuel consumption of around 10 kg/h, the error of that tractor at the consumption of about 40 kg/h fell to 1.5 kg/h. A significant difference occurred in the tractor with a 235 kW engine. The consumption in the range of 50 kg/h showed an error of 8.4 kg/h. An improvement of the results can be achieved using derived regression functions. Based on our experience with the measurement of other types of tractors, we know that a similar situation with the accuracy of CAN-Bus data is also an issue in other categories of vehicles.

Keywords: fuel consumption; tractor testing; data-bus

Increasing demands on the operational performance of vehicle engines lead to a massive implementation of electronic systems for their regulation and control. Increasing requirements of emission reduction, including performance and fuel savings need solving precise regulation, which is provided only with the support of electronics. This trend can be seen also in agricultural machines and tractors in particular. Besides the engine, also other functional units such as transmission, hydraulic system and others are equipped with electronic control units. In order to effectively control the various systems, it is necessary to ensure communication between the control units. Electronic control units receive the information necessary for effective management from the internal sensors, with which the engine, gearbox and other parts of the vehicle are equipped. Data from the sensors are processed by the appropriate control unit and can be transmitted via the internal digital network CAN-Bus (controller area network) of the vehicle so that optimum control can be achieved. CAN-Bus is currently the most widely used bus for internal communication network of sensors and control units

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of vehicles. This is a serial data bus developed by Bosch. Transfer parameters are specified in standards (ISO 11898-1 2003; ISO 11783-1 2007; ISO 11783-7 2009; ISO 11783-10 2009; ISO 11783-6 2010; ISO 11783-4 2011; ISO 11783-5 2011). In vehicles equipped with so many sensors there is a possibility to use the transmitted data for monitoring different parameters e.g. engine load. The importance of the CAN-Bus protocol and its use in agricultural systems was proved and used in many research works (Auernhammer, Speckmann 2006; Suvinen, Saarilahti 2006). The advantage is that the vehicles do not have to be covered with external sensors, which are often difficult to mount in the suitable places. Installation of vehicle sensors is expensive and time consuming. Reading the relevant data from the CAN-Bus, by contrast, is relatively simple and cheap. A certain problem that we encountered is the accuracy of some data obtained in this way. This is especially true for the fuel consumption of the engine. The data of instantaneous fuel consumption are not directly measured but are determined indirectly by calculation. This method can bring, in most cases, a more significant error than direct measurement. Therefore, to obtain sufficiently accurate values, it is appropriate and in some cases even necessary to carry out calibration of the data thus obtained from the measuring instruments. Experimental work was carried out in the Laboratory of Vehicles at the Mendel University in Brno (Brno, Czech Republic). We carried out many tests of different types of tractors in operation conditions. Methodology of the tests involved collection of data read from the CAN-Bus. Before the start of field tests, the tractors were taken into a laboratory to determine essential parameters of the engine. Simultaneously with the measurement using the exact parameters of the engine in the laboratory, we conducted a verification of the accuracy of the data read from the network. The article presents the results of measurements of fuel consumption derived from the CAN-Bus of four tractors selected from different power classes.

MATERIAL AND METHOD

Experimental work focused on determining the accuracy of direct and indirect measuring techniques was realized in a test cell of the Laboratory of Vehicles at the Mendel University in Brno (Brno, Czech Republic). The aim of the measurements was to verify the possibility of using the messages from the CAN-Bus of a tractor to measure the instantaneous fuel consumption of a tractor engine during its operation. For this purpose it was necessary to compare the values from the internal sensors in the tractor with the ones from external sensors. Data obtained in the laboratory were tested in the next phase of the field tests. To evaluate the method, the following agriculture tractors were used: John Deere 5080RN (John Deere tractors, Mannheim, Germany), Claas Axion 850 Cebis (CLAAS Tractor SAS, Le Mans, France), John Deere 8320R (John Deere tractors, Moline, USA) and John

Table 1. Selected parameters of engines (source: manufacturer)

Tractor	John Deere 5080RN	Claas Axion 850 Cebis	John Deere 8320R	John Deere 8320RT
Model	CD4045L096429	6068HRT83DPS	RG 6090L078771	RG 6090L07567
Maximal power (ECE-R24)	64 (kW)	169 (kW)	255 (kW)	255 (kW)
Maximal power with boost (ECE-R24)	–	193 (kW)	261 (kW)	261 (kW)
Engine speed at P_{max}	2,100 (1/min)	2,000 (1/min)	2,100 (1/min)	2,100 (1/min)
Maximal torque	334 (Nm)	1,020 (Nm)	1,419 (Nm)	1,419 (Nm)
Engine speed at M_{tmax}	1,600 (1/min)	1,500 (1/min)	1,500 (1/min)	1,500 (1/min)
Number of cylinders	4	6	6	6
Displacement	4,525 (cm^3)	6,788 (cm^3)	9,000 (cm^3)	9,000 (cm^3)
Cooling	water cooled	water cooled	water cooled	water cooled
Air support	turbocharger	turbocharger	turbocharger	turbocharger
Injection system	common rail	common rail	common rail	common rail

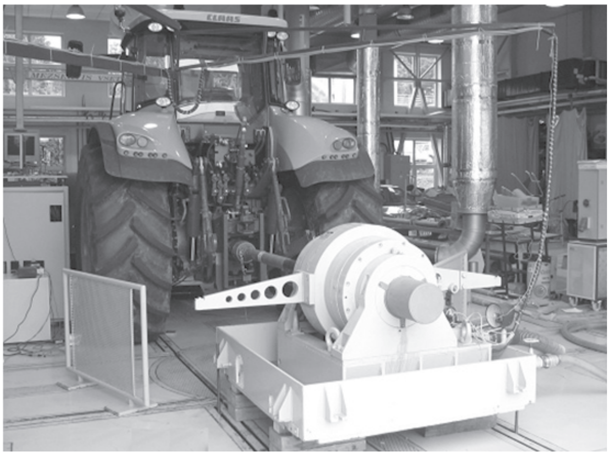

Fig. 1. Agricultural tractor Claas Axion 850 Cebis during testing via power take-off

Deere 8320RT (John Deere tractors, Moline, USA). Basic technical data of the measured tractors are listed in Table 1. There are three wheeled tractors and a John Deere 8320RT tractor equipped with tracked chassis. Both of the John Deere 8320 tractors are powered by the same engine. All tractors were new. The maximum number of 207 h of operation were on the monitor of John Deere 8320RT tractor.

For an objective assessment of accuracy of fuel metering in different modes of engine work, measurements were carried out at varying load, engine speed and fuel supply. Engine parameters were measured during loading by an eddy current dynamometer via power take-off (PTO) (Fig. 1). Fuel consumption was measured together with engine torque, PTO speed, intake air temperature, compressed air temperature at the output of the intercooler, the intake air pressure, the engine oil temperature, engine coolant temperature and exhaust gas temperature. Within the same time base, the data transmitted via CAN were collected and processed. The CAN-Bus of all tractors was fully compliant with SAE J1939. The communication speed was 250 kbps and analysis of the messages was relevant to selected channels. During the tests also atmospheric conditions were measured: temperature, pressure and relative humidity in the laboratory. In all tests the general requirements of the (ISO 789-1 1990) standard were met. The measured data were recorded in the time base of 55 ms and stored in the memory of the measuring computing system. The following instrumentation was used when carrying out the tests (list according to physical quantity).

Table 2. Technical specification of used dynamometer V500

Parameter	Value
Type of dynamometer (–)	V500
Speed (1/min)	150 1,500 3,000
Power (kW)	4,500 500
Torque (Nm)	254 3,184 1,592
Cooling (–)	water cooled
Load capacity (–)	permanent

Engine torque

Engine torque was measured at a bench equipped with the eddy current dynamometer V500 (MEZSERVIS Ltd., Vsetín, Czech Republic) (Fig. 1), which was connected to the rear output shaft of the tractor (PTO). Technical features of the dynamometer are given in Table 2. The regulation of the dynamometer and data acquisition is provided by the vehicle management computer system and a higher data server system.

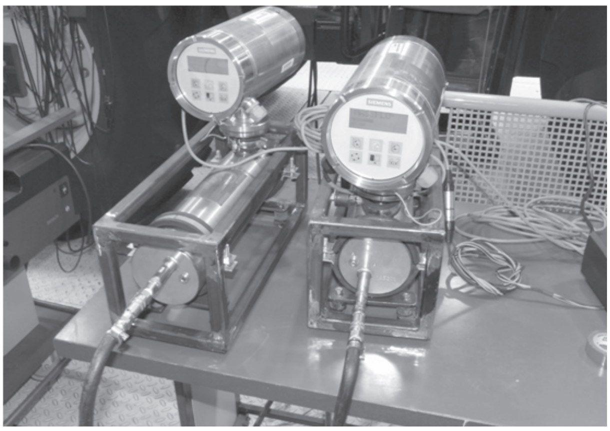

Fig. 2. Coriolis mass flow meters Sitrans FC MassFlo Mass 6000 used for fuel consumption metering

Fig. 3. Front panel of the software used for CAN listening

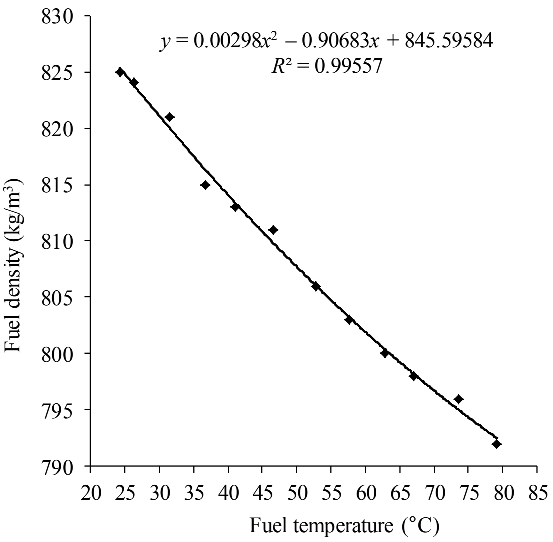

Fig. 4. Fuel density dependence on temperature

Engine speed

Dynamometer speed is measured by an incremental sensor LUN 1326.02-8 (Mesit, Uherské Hradiště, Czech Republic), which forms a part of the dynamometer. The signal from the sensor is adjusted by a forming circuit and transmitted into the measuring system.

Fuel consumption

Measurement of fuel consumption was carried out using the Coriolis mass flow meter Sitrans FC MassFlo Mass 6000 (Siemens, Nordborg, Denmark). In order to minimize possible effect on the fuel supply system, two independent flow meters were used. Fig. 2 shows the connection method. Sitrans FC MassFlo Mass 6000 is an accurate flow meter with a range of 0–300 kg/h and its accuracy is 0.1% of the reading.

CAN-Bus data

In addition to measuring individual values by external mounted sensors, all the tests were performed by obtaining readings from the sensors via a digital communication link – CAN-Bus. The tractors network corresponding to ISO standards allows reading of the engine speed, engine load, instantaneous torque, engine oil temperature, engine coolant temperature, fuel temperature and other values. Necessary software application for CAN listening was developed at the Institute of Automobile Transport and Principles of Technology, Mendel University in Brno (Brno, Czech Republic) and written in LabVIEW (National Instruments, Austin, USA). Fig. 3 shows a mask used for the measurement software.

Measurement of other values

A steady mode of the engine parameters was determined by measuring the exhaust temperature and the temperature of lubricating oil in the engine. The intake air temperature from the cleaner, exhaust temperature, air temperature in the laboratory, barometric pressure and relative humidity were also measured. Temperatures were measured using a K-thermocouple (HTH8, Polička, Czech Republic), barometric pressure using a piezoresistive sensor (BD Sensors, Buchlovice, Czech Republic). Readings from all the sensors were continuously stored in the memory of the computing system. The PTO speed for all tests was set at 1,000 rpm. Since the fuel consumption taken from CAN-Bus is presented in volumetric units, the instantaneous temperature of fuel is necessary to be monitored for the determination of the density of fuel and its recalculation to mass flow. Specific gravity of fuel, depending on its temperature, was established in a laboratory measurement of the density of the fuel using Mohr's scales. The readings were fitted by a second-degree polynomial. A regression equation was determined for each measurement. The curve of calculated density in dependence on the fuel temperature is shown in Fig. 4.

RESULTS AND DISCUSSION

The paper presents evaluated data obtained from laboratory measurements of tractors Claas Axion 850 Cebis, John Deere 8320R, John Deere 8320RT and John Deere 5080RN. To assess the possibility of using data of CAN-logging indicated by l/h, it was necessary to compare the network data with the data obtained by exact measuring instrumentation. The Coriolis mass flow meters were used for accurate determination of fuel consumption. These are sensors indicating the mass flow in kg/h, which were inserted into the engine fuel delivery system in differential connection. Since all measurements were made at a steady-state mode and the temperature of the fuel

Table 3. Analysis of variance of regression of mass and volume fuel metering for consumptions higher than 25 l/h (Claas Axion 850 Cebis)

	Degree of freedom	Sum of squares	Mean square	*F* statistic	*F* > *P*
Regression	1	3683.152	3683.152	17695.17	5.6E-107
Error	93	19.35744	0.208145		
Total	94	3702.509			

did not change, it is possible to calculate the rate of fuel consumption using the Coriolis mass flow meters and CAN-logged values according to Eq. (1).

$$\rho = \frac{M_{phCor}}{M_{phCAN}} \quad (kg/l) \quad (1)$$

The resulting value should be invariant at a constant temperature. Fig. 5 shows the chart of the ratio depending on the mass consumption of the Claas Axion 850 Cebis tractor. The chart shows that for fuel consumption of more than 20 kg/h the indicated ratio can be regarded as constant. But the fuel consumption of less than 20 kg/h can be assumed as nonlinear.

To determine the deviations of the actual fuel consumption taken from CAN-Bus fuel mass consumption was calculated for all measurements of volume consumption according to Eq. (2).

$$M_{phCANh} = M_{phCAN} \times (0.00298t^2 + 0.9068t + 845.6) \times 10^{-3} \quad (kg/h) \quad (2)$$

The difference between the two methods of measurement was determined precisely by computing the difference between real fuel consumption and the fuel rate obtained from the CAN of tractor Eq. (3).

$$\Delta M_{ph} = M_{phCor} - M_{phCANh} \quad (kg/h) \quad (3)$$

The calculated differences are plotted on the graph in Fig. 6. The graph shows the fact that the data from the CAN-Bus differ from the values precisely measured by Coriolis mass flow meters by –0.3 to 4.1 kg/h, which is –1.2% to 41% of the measured value. Given the above-mentioned high level of accuracy of used flow meters the inaccuracies were caused by the algorithm of the electronic control unit. Consumption is not measured, but is determined indirectly by calculation from the other readings. It is clear from the above that consumption obtained from the CAN-Bus may be very false and should not be used for precise analysis without appropriate correction.

Table 4. Calculation of the coefficient of regression function and its significance used for fuel metering of consumptions higher than 25 l/h (Claas Axion 850 Cebis)

	Coefficient	Standard deviation	*t* stat	*P* value
Intercept	0			
Mph_CAN	0.835711	0.001227	681.3597	8.8E-174

From the results shown in Fig. 5, it is suitable to split the curve into two parts and each should be evaluated separately. For consumption greater than 20 kg/h, which is about 25 l/h, the dependence of the measured flow of consumption from the CAN-Bus is plotted in Fig. 7. Readings were smoothed by least-squares regression, the parameters of which are listed in Tables 3 and 4. The tables contain the results of an *F*-test of the regression function and *t*-test of the regression coefficient. *F*-test results show a high significance of the calculated regression function. Similarly, the significance of the regression coefficient of the *t*-test is very high (Table 4). The value of the index of determination I^2 = 0.99477 also shows considerable dependence. Also, the residual plots in Fig. 8 show a small deviation of the measured values of fuel consumption in relation to the calculated values of fuel consumption when using the regression function. From these results it is clear that the value of fuel consumption under constant ambient conditions can be calculated by regression function and used to determine the actual fuel mass flow. Similarly, the results of fuel consumption lower than 25 l/h are shown in Fig. 9. The results of regression analysis are given in Tables 5 and 6. The dataset presents a high statistical degree of correlation, which follows from the calculated coefficient of determination (I^2 = 0.9612). Also, the *F*-test and *t*-test show high significance of test values.

The above analysis shows that fuel consumption logged from the CAN-Bus has a considerable error, which increases with decreasing fuel consumption (Fig. 6). Therefore it cannot be used in this way for large evaluation of engine operation without appropriate correction. Using the regression function derived in the graph in Fig. 9 and listed in Table 6, there

Table 5. Analysis of variance of regression of mass and volume fuel metering for consumptions lower than 25 l/h (Claas Axion 850 Cebis)

	Degree of freedom	Sum of squares	Mean square	*F* statistic	*F* > *P*
Regression	1	857.1125	857.112	1138.568	4.246E-34
Error	46	34.6287	0.7527		
Total	47	891.7412			

will be a possibility to significantly reduce errors in fuel consumption values even lower than 25 l/h (tractor Claas Axion 850 Cebis), which is demonstrated by the residues shown in the chart in Fig. 10.

Other measurements were done with the John Deere 8320R and John Deere 8320RT. Both the tractors were powered by the same engine. All the data from the measurements of these tractors were used for the construction of full speed maps of engines to evaluate the fuel consumption. Comparing the results of the engine parameters of both tractors, we found only minimal differences in their parameters, so we evaluated both engines in a single file. For the evaluation also the ratio of the flow rate of flow meter and consumption transmitted via CAN-Bus was calculated. The calculated ratio is plotted on the graph in Fig. 11. As the graph shows, also here there were deviations from the constant curve, especially for consumption lower than 15 kg/h and for more than 45 kg/h. For the determination of the actual error, the differences were calculated for mass consumption of both methods. The result is plotted on the graph in Fig. 12. The graph shows that the variation in fuel consumption between direct and indirect method is in the range from 0.39 to 8.4 kg/h.

Also in this case, the fuel consumption of the tractor taken from the CAN-Bus can be established

Table 6. Calculation of the coefficient of regression function and its significance used for fuel metering of consumptions lower than 25 l/h (Claas Axion 850 Cebis)

	Coefficient	Standard deviation	*t* stat	*P* value
Intercept	3.953151	0.319442	12.37516	3.06E-16
Mph_CAN	0.683129	0.020245	33.74268	4.25E-34

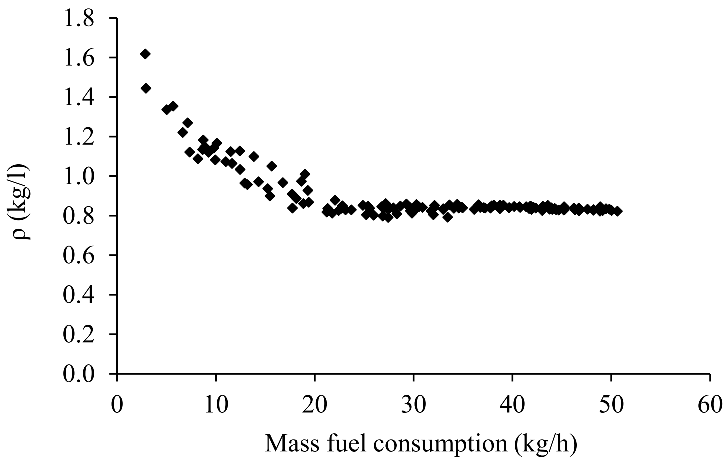

Fig. 5. Fuel consumption ratio dependence on the true value of fuel consumption

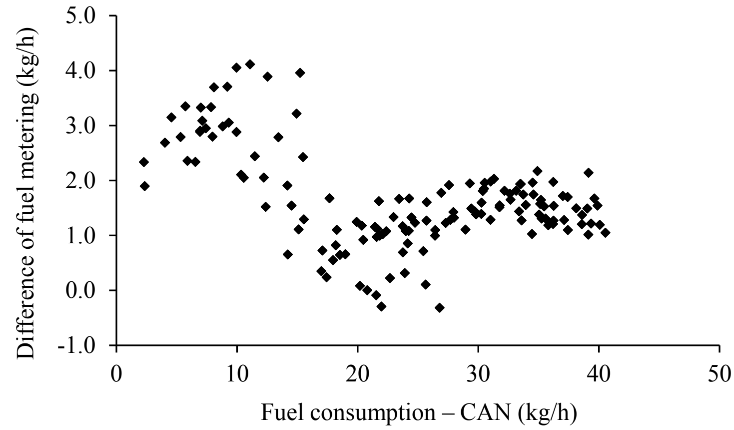

Fig. 6. Difference of values of direct and indirect fuel consumption metering (Claas Axion 850 Cebis)

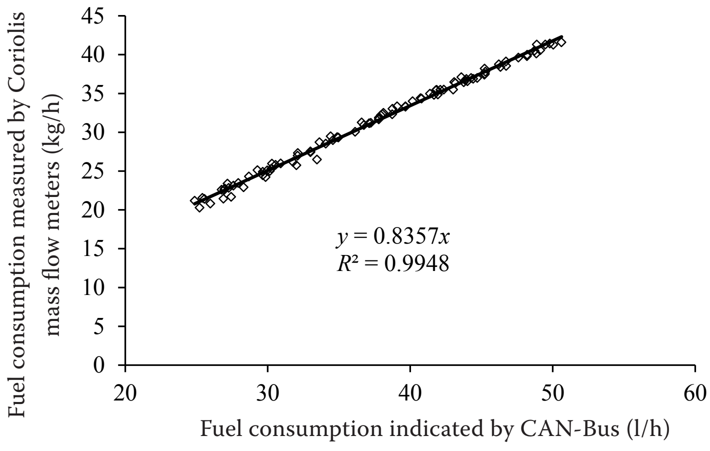

Fig. 7. Dependence of the mass and volume fuel metering for consumptions higher than 25 l/h (Claas Axion 850 Cebis)

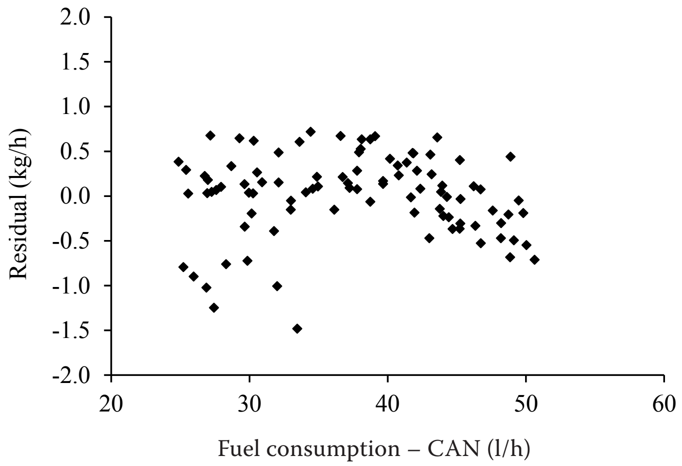

Fig. 8. Residuals of the fuel mass deviations from the regression line

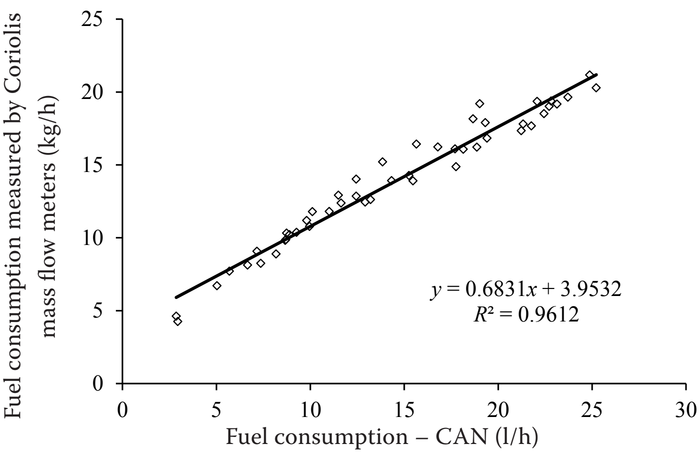

Fig. 9. Dependence of the mass and volume fuel consumption of tractor Claas Axion 850 Cebis for consumptions lower than 25 l/h

more exactly using regression functions derived in the graph in Fig. 13 and given in Tables 7 and 8. The test results indicated in the tables show a high significance in regression parameters. The calculated regression function can be thus used to determine the actual fuel consumption, with a significantly lower error (Fig. 14). Despite the fact that two engines were tested, which may be adjusted slightly differently by the manufacturer, the results are very positive.

The last measurement was focused on the engine of the John Deere 5080RN tractor. It is a tractor with the least power of all the above engines. The methodology of measurement was the same as mentioned above. The ratio of mass and volumetric fuel consumption is shown on the graph in Fig. 15. The measurement data bring interesting results. The whole range of calculated ratios does not significantly diverge from the constant curve, in other words the variability is very low. Also, the differenc-

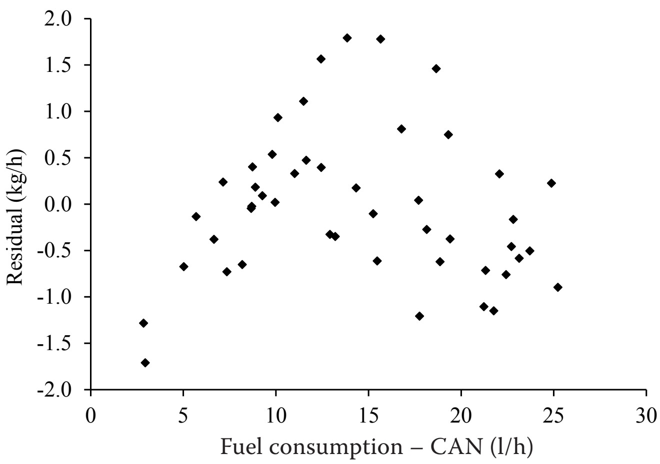

Fig. 10. Residual deviations of the mass fuel consumption from the regression line

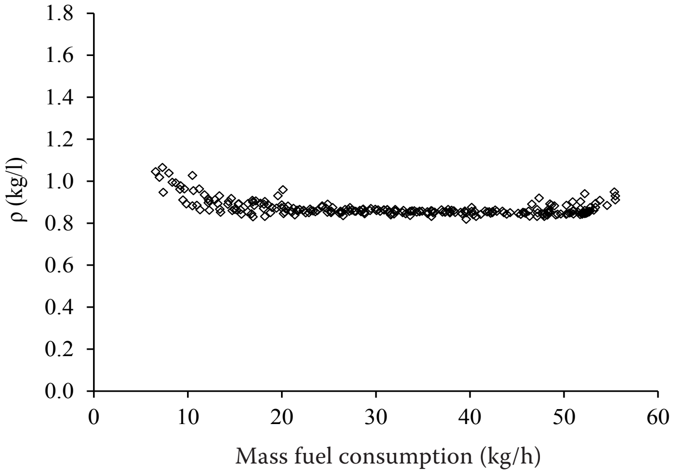

Fig. 11. Fuel consumption ratio dependence on the true value of fuel consumption (John Deere 8320R)

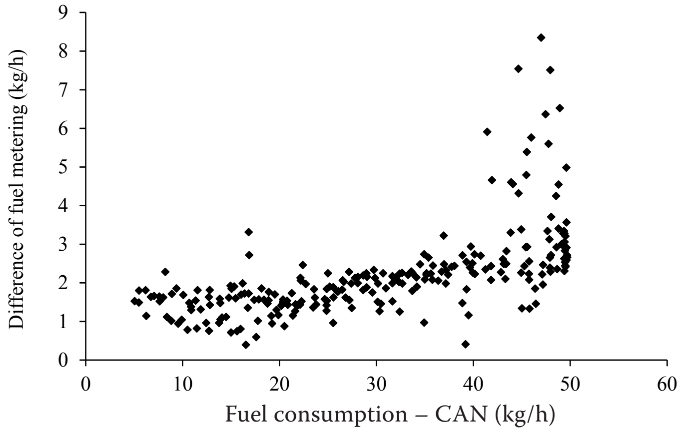

Fig. 12. Difference of the values of direct and indirect fuel consumption metering (John Deere 8320R)

es in mass fuel consumption measurements done by both methods are the smallest of all the engines (Fig. 16). The observed variation margin is calculated as deviations ranging from –0.4 to 1.2 kg/h. But even in this case, the error can be further reduced. The graph in Fig. 17 is plotted as the dependence of mass and volumetric fuel consumption. The chart also indicates the calculated regression equation function. The coefficient of determination I^2 = 0.9973 shows a high degree of correlation of calculated regression function. The result of *F*-test is given in Table 9. Parameters of the *F*-test show a very high significance of the calculated function. Also, *t*-test of the regression coefficient shown in Table 10 proved its very high significance. Residual deviations from the calculated regression function can be seen on the graph in Fig. 18. It shows a high degree of correlation of the measured data around

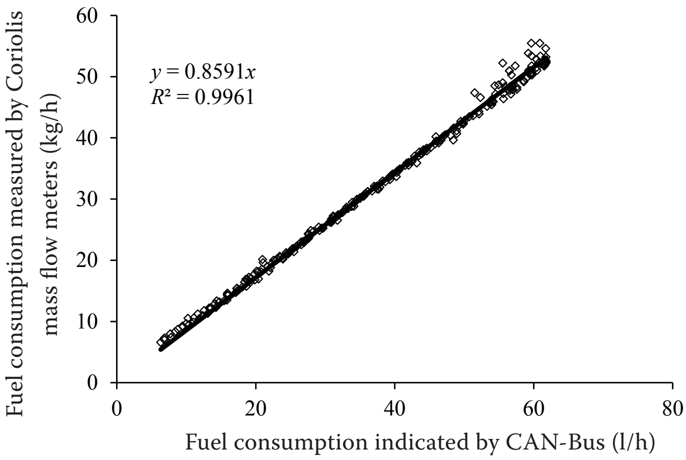

Fig. 13. Dependence of the mass and volume fuel metering (John Deere 8320R)

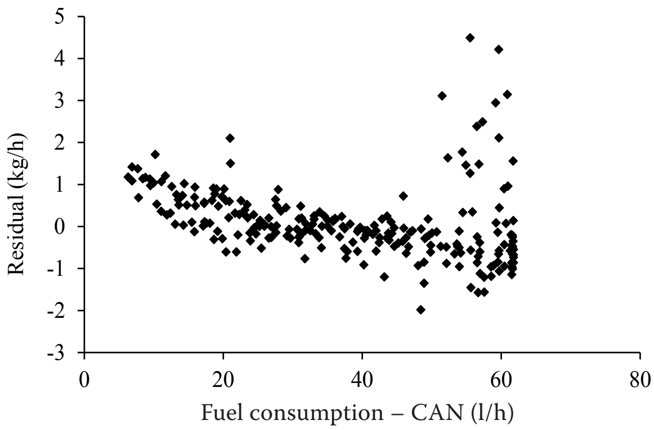

Fig. 14. Residual deviations of mass fuel consumption from the regression line

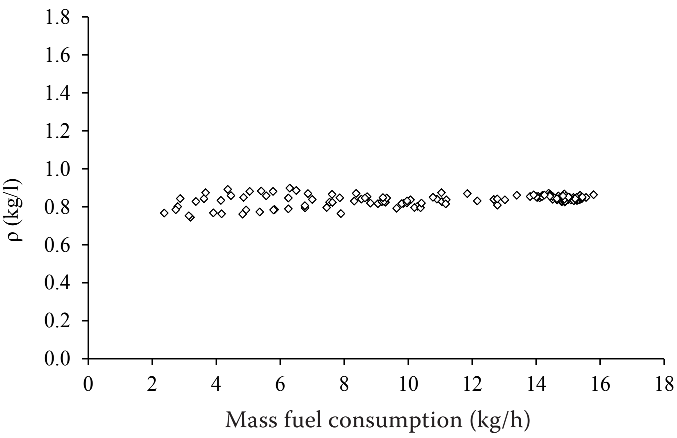

Fig. 15. Dependence of the fuel consumption ratio on mass fuel consumption of the tractor John Deere 5080RN

the regression line. The deviations lie in the range of about ±0.4 kg/h.

The results of measurements may be very different if they are taken from the CAN-Bus without proper corrections. Usually, they are used for analysis, e.g. for global pollution, which gives inaccurate results in change of dimension. Murthy and Ramakrishna (2009) used data obtained from CAN-Bus to quantify the performance of a tractor engine (John Deere 5000 Series). However, the use of incorrect units, kg/h instead of l/h, significantly increased the value of specific fuel consumption.

CONCLUSION

The control processes of present tractors are very often realized with the application of more control-

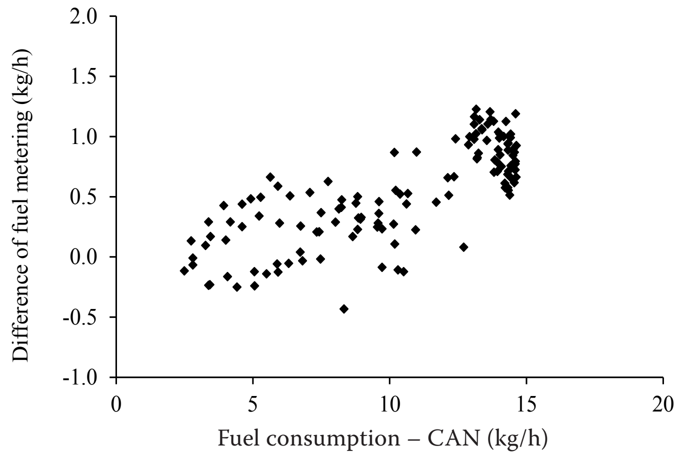

Fig. 16. Variations of results of direct and indirect consumption metering (John Deere 5080RN)

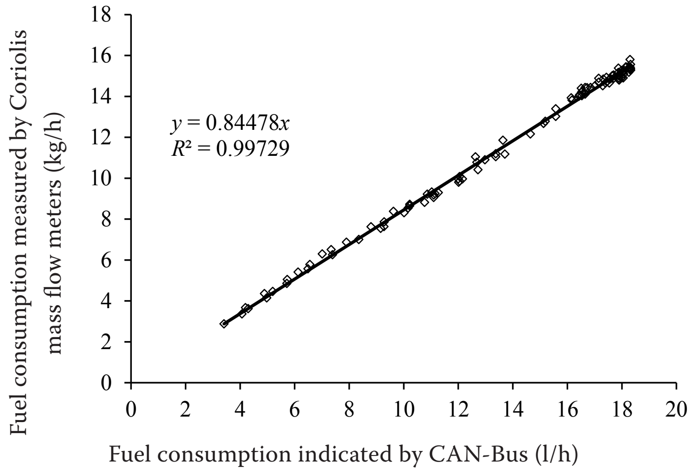

Fig. 17. Dependence of fuel consumption detected by the Coriolis flow meter on CAN fuel consumption of John Deere 5080RN tractor

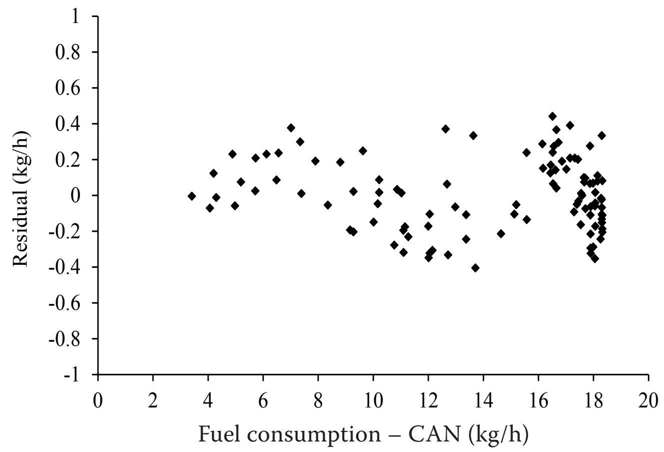

Fig. 18. Residual deviations from the calculated regression line (John Deere 5080R)

lers or electronic units. In the case of a distributed system it is required to transmit information between these units. A tractor uses a CAN-Bus for this purpose. Its parameters are sufficient for comprehensive regulation of various systems built in a tractor. The data transmitted by the network may be accurate only if the value is calculated in appropriate bit resolution. Only single-byte values provide rough results and further analysis with other measurements is necessary for applicability. Multiple-byte values may be used directly. The paper shows the ability to read parameters from the bus, their interpretation for testing and verification of their particular size in comparison with direct methods of measurement. As the point of interest, the accuracy of fuel consumption was taken because the injection system knows only the time of opening the injector, while the direct method is based on measuring mass flow of fuel.

Table 7. Analysis of variance of regression of mass and volume fuel consumption evaluation (John Deere 8320R)

	Degree of freedom	Sum of squares	Mean square	*F* statistic	*F* > *P*
Regression	1	310569.9	310569.9	391737.4	>>0.0010
Error	245	194.2363	0.792801		
Total	246	310764.1			

Table 8. Calculation of the coefficient of regression function and its significance used for fuel consumption dependence (John Deere 8320R)

	Coefficient	Standard deviation	*t* stat	*P* value
Intercept	0			
Mph_CAN	0.859081	0.001373	625.8893	>>0.001

Table 9. Analysis of variance of regression of mass and volume fuel consumption evaluation (John Deere 5080RN)

	Degree of freedom	Sum of squares	Mean square	*F* statistic	*F* > *P*
Regression	1	1534.929	1534.929	38946.26	8.8E-137
Error	106	4.177614	0.039411		
Total	107	1539.106			

Table 10. Calculation of the coefficient of regression function and its significance used for fuel consumption dependence (John Deere 5080RN)

	Coefficient	Standard deviation	*t* stat	*P* value
Intercept	0			
Mph_CAN	0.844781	0.001312	643.8112	3.1E-192

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