The paper presents the problems of fuel consumption in internal combustion engines are analyzed on the economic and ecological levels which require developing modern fuel consumption monitors. The main property that such monitors must exhibit is the resistance to arduous operating conditions of combustion engines and no interference with the engine fuel supply and engine control systems. Additionally, such monitors should be met the requirements to ensure accurate assessment of the costs associated with the operation of the vehicle. Such requirements can be met provided that the determination of fuel consumption with sufficient accuracy. This applies to both total consumption expressed in l/km and instantaneous consumption expressed in g/s.

Keywords: fuel consumption measurement method, measuring devices

1. INTRODUCTION

The measurement of fuel consumption is one of the main aspects enabling optimum operation of vehicles. Excessive fuel consumption has an adverse effect on the transport economics and natural environment [1]. Fuel consumption may constitute diagnostic information allowing an assessment of the condition of the engine and its subcomponents, the example of which may be the friction resistance in engine kinematic pairs. Accurate fuel consumption measurement may be helpful in the identification of the friction loss (resulting from the wear of the cooperating surfaces) in the piston crankshaft assembly [7].

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Fuel consumption is determined based on road trials performed under preset driving conditions at variable or constant speeds. Fuel consumption depends on the parameters of the vehicle, its engine, operating conditions and the driver [5, 6].

The paper presents some problems of the applied methods of on-road fuel consumption in modern vehicles. The solution to these problems is an indicator of the extent of application of fuel consumption as a diagnostic signal providing information on the engine technical condition.

2. VOLUMETRIC METHODS

The problem of fuel consumption in modern vehicles plays an important role. There are a variety of methods of fuel consumption and the possibility of their application depends on:

– required accuracy of measurement,
– extent of modification of the fueling system,
– cost of the measurement system.

Methods of on-road fuel consumption measurement allow a direct measurement of fuel consumption in all conditions of its operation. This is done with equipment and procedures implemented on the operated test vehicle.

In volumetric methods, fuel consumption is determined based on the consumed volume and mass of fuel. This is then referred to the covered distance or performed work.

The accuracy of volumetric methods is high, but its application under actual conditions of operation is difficult [4]. It requires additional supervising personnel and fuel fill-ups. The vehicle must also be fitted with an additional fuel tank allowing the determination of the fuel mass.

One of the volumetric methods (‘full tank’ method) is applied by city bus operators and on stationary engines. It is also used by carmakers, during road tests (inter alia rolling resistance tests).

A fundamental device for the measurement of fuel consumption is the fuel level sensor [3]. The sensor reads the fuel level inside the fuel tank, Fig. 1. The sensor is composed of a wire resistor or a potentiometer. The voltage characteristics of the sensor allows for the shape of the fuel tank. The signal from the sensor should be proportional to the changes of the fuel volume inside the tank.

In order to more accurately measure the consumption of fuel by the engine, a special measurement module (converter) can be applied. This device is connected to the original fuel sensing system through the wiring between the fuel tank and the original sensor. Fig. 2. The device measures the voltage (depending on the type of fuel sensor). Due to low accuracy of the original factory made fuel sensors and the free surface effect the measurement must be averaged.
The main disadvantage of such measurement systems is the occurrence of a ‘blind zone’. The accuracy of the measurement is limited when the tank is fully or almost empty. The measurement with a fuel sensor still provides reliable results though, if the fuel consumption is averaged. The measurement accuracy of this system is 5–10%.
Another example of volumetric fuel consumption measurements is the ‘fuel table’ method inside the tank. Examples of such solutions are systems of measurement probes.

The SKT (System for Transport Control) is composed of a measurement probe, fitted in the upper part of the fuel tank and a data recorder. The system continuously monitors the fuel level inside the fuel tank. The measurement is more accurate than in standard float systems. The recorder registers the data from the vehicle and its own sensors.

The probe is composed of two capacitors located inside a casing that is at the same time the capacitor separator. The measurement is based on the changes of fuel level against the capacitance of the capacitor. This is a standalone device and it does not interfere with other equipment fitted in the vehicle.

The measurement accuracy of the SKT system in terms of fuel consumption reaches 1% of the fuel tank capacity for a single fill-up. The measurement of the fuel level is made continuously, even when the engine is off.

The potential unreliability of fuel consumption measurement by capacity probes is particularly conspicuous when measuring the level of diesel fuel. Low electrical conductance of diesel fuel and its high sensitivity to temperature changes leads to frequent measurement errors, which results in a reduction of its effectiveness.

Apart from capacity fuel measurement probes, fuel consumption can also be measured by hydrostatic or ultrasound probes. The application of types of fuel probes other than the float type allows greater accuracy of measurement. The downside of this solution is the high cost of the probe and the need to modify the engine fuel system.
The pressure probe (hydrostatic) is designed to measure fuel consumption inside fuel tanks of motor vehicles, heavy machinery and locomotives (Fig. 5). The measurement is based on the relation of the fluid column and the generated hydrostatic pressure.

The probe is composed of two parts: the sensing part, placed in the steel tube and the electronic part placed in an aluminum casing. The measuring element is the piezoresistant sensor separated from the medium by a membrane. The pressure sensing is realized on the membrane level of the immersed probe. Depending on the type of fuel tank (pressurized or under ambient pressure) the pressure measurement is compared to the ambient pressure or the pressure inside the fuel tank.

In fuel consumption measurement, the probe ensures high measurement accuracy and resistance to ultrasound distortions and fuel contamination.

Ultrasound probe serves the purpose of fuel level measurement in tanks of vehicles and machinery powered by diesel fuel. To measure the fuel level, the probe utilizes the properties of ultrasounds by emitting a sound wave to the tank and receiving its echo. The fuel level is determined by the analysis of time needed for the echo to return.

Ultrasound probes are very prone to damage of the microphone and ultrasound speakers caused by fuel contaminants and temperatures.

The analysis of the data from the probe is similar to the analysis coming from the fuel level sensor. The only difference is the accuracy and stability of the measurement, which in the case of the probe reaches approx. 0.1 percent. The accuracy of the results however is several percent.

Fuel level probes are not suitable for all fuel tanks. The main issue is the height of the tank (insufficient length of the probe). There are also vehicles fitted with more than one fuel tank. In such a case more measurement probes need to be fitted.
3. FUEL FLOW METERS

Fuel flow meters measure the fuel consumption in real time during vehicle operation. This method of measurement is more complex than the volumetric method as it requires special equipment and calibration of the flow metres [2].

Fuel flow meters can be classified in terms of the measurement method of the consumed fuel, indications and analysis of the measured values.

Fuels metering systems for diesel engines based on fuel flow meters manufactured in a variety of configurations depending on the types of engines and their operating conditions. Aside from the general division of fuel metering systems according to engine power, fuel consumption, and type of fuel system, an important element is the system specific features such as lack of fuel return line. Depending on these features, the installation of a fuel metering system may differ from the general schematics shown in Fig. 6. An unchanged element, however, is the fitting of the fuel metering system in the suction line, upstream of the fuel feed pump. In some fuel systems installation of an additional heat exchanger is necessary (engines fitted with pump nozzles).

![Fig. 6. Schematics of the fitting of the fuel metering system in a diesel engine](image)

Fuel metering systems used in spark ignition engines differ from those applied in diesel engines (Fig. 7). Diesel engines do not have a fuel return line.

![Fig. 7. Schematics of the fitting of the fuel metering system in a spark ignition engine](image)
Problems in the application of on-road fuel consumption measurement methods

Depending on the design, we can distinguish two main types of fuel metering systems responsible for the measurement of the fuel flow. These are systems based on a pump with a rotating piston and systems based on separate piston systems.

The principle of operation of differential flow meters is calculation of the fuel consumption as a difference between the flow of fuel in the fuel lines and the flow in the fuel return line.

There are also fuel meters fitted with a separate fuel tank. In this tank fuel is accumulated, chilled and subsequently fed to the suction line of the fuel system. In this way the manufacturers eliminate the second fuel flow meter and reduce the costs of the system at the same time increasing the metering accuracy. The average accuracy of such systems is approx. 1%.

An example of such a fuel meter is MasterFlow, applicable in vehicles, locomotives, tractor-trailers or construction machinery. The system is based on a pump fitted with a rotating piston pumping a certain amount fuel in a unit of time.

Measurements based on mass flow minimize the inaccuracies related to the volumetric metering of fluid. The Coriolis flow meters, measure the mass of the flowing fluid or gas.

The principle of operation of the Coriolis flow meters is based on the measurement of a deformation of a pipe filled with flowing fuel generated by the Coriolis force. The value of this force and the subsequent deformation is proportional to the velocity and density of fuel; hence the deformation of the fuel pipe is proportional to the flowing mass of fuel.

The main advantage of the Coriolis flow meters is their high accuracy reaching 0.1% of the mass, high repeatability and a wide range of measurable flow rates. The possibility of measuring the flow in both directions (return) is also noteworthy, which is not possible in many other flow meters i.e. measurement tubes, turbines and swirl flow meters.

4. CALCULATING THE FUEL CONSUMPTION BASED ON THE CAN BUS DATA

The calculation of the fuel consumption based on the CAN bus data depends on the type of vehicle and the solution applied by the vehicle manufacturer (in some vehicles the fuel consumption is calculated from the data processed by the fuel sensors in other it is the flow meters; Fig. 8).

The data obtained from the CAN bus are characterized by high accuracy of the measurement of the total fuel consumption, instantaneous fuel consumption, number of fill-ups and assessment of loss. A downside of this solution is that not every manufacturer allows permanent connection to the CAN bus in the warranty period and not every vehicle makes such data available.
The CAN module pulls the fuel level information from the fuel level sensor. The accuracy is tantamount to that of the fuel sensor and amounts to 3% to 10%. The CAN-based measurements, however, are calculated with the use of averaging algorithms implemented in the on-board computer. During longer trips, it is more accurate than the fuel sensor but is less accurate than the probe. The downsides are the blind zones and the impossibility to measure the fuel level when the engine is turned off.

5. FUEL CONSUMPTION MEASUREMENT METHOD BASED ON DURATION OF THE FUEL INJECTION

In engine fitted with a Common Rail fuel system, the fuel dose is determined by the opening time of the electromagnetic injector valve. This depends on the fuel pressure in the fuel rail, engine speed and the position and angular variation of the throttle [5].

A fundamental parameter in the monitoring of fuel consumption is the duration of the injection of individual injectors. The component that allows determining this duration is an induction sensor fitted in the positive wire powering the injector coil.

Fig. 9 presents an example tracing of current in the power wire of the injector along with the signal identification features.

The injection time of a single fuel dose to one cylinder is determined according to the following formula:

Another parameter that needs to be recorded in order to determine the fuel dose is the fuel pressure in the high-pressure accumulator. The on-board accumulator pressure sensor is a resistance sensor and sends signals to the EDC processor that subsequently calculates the injection time for individual injectors. This is realized based on the pressure in the accumulator, the engine speed and the throttle position.
Based on the obtained information related to the injection time (pre-injection, main injection) and the pressure in the accumulator one may determine the fuel dose injected to the cylinder by individual injectors. By summing up the individual doses in individual cylinders it is also possible to determine the consumption of fuel per covered distance or performed work.

An important feature of the fuel consumption monitoring method based on the duration of injection is that no modifications to the original vehicle systems are necessary. If the on-board fuel consumption recorder fails, it will not have impact on the operation of the engine and the entire vehicle, which is why this system can be installed in a vehicle without losing the manufacturer’s warranty.

The on-board fuel consumption recorder of this type does not have any mechanical parts, which is why this device is highly reliable, can be used in a wide range of temperatures and operating conditions. It is also characterized by the fact that it cannot be tampered with by the driver/operator, which would reduce its accuracy or limit its operativeness.

6. CONCLUSIONS

The problem of fuel consumption forces a development of modern fuel consumption monitors. The main property that such monitors must exhibit is the resistance to arduous operating conditions of combustion engines and no interference with the engine fuel supply and engine control systems.
METODY POMIARU ZUŻYCIA PALIWA
W WARUNKACH TRAKCYJNYCH

Streszczenie

W artykule przedstawiono problem zużycia paliwa w silnikach spalinowych, rozpatrywany na płaszczyźnie ekonomiczno-ekologicznej. Wskazano na konieczność opracowania nowoczesnego monitora zużycia paliwa i przedstawiono jego charakterystykę. Głównym celem stawianym monitorom zużycia paliwa jest odporność na trudne warunki eksploatacji silników spalinowych przy jednoczesnym braku ingerencji w układ zasilania lub sterowania silnika. Dodatkowo układy takie powinny spełniać wymagania gwarantujące precyzyjną ocenę kosztów związanych z eksploatacją pojazdu. Wymaganie to może być spełnione pod warunkiem określenia zużycia paliwa z dostateczną dokładnością. Dotyczy to zarówno zużycia całkowitego, wyrażanego w litrach na kilometr, jak i zużycia chwilowego, wyrażanego w gramach na sekundę.