Feature Article

Application

Improving the accuracy of Fuel Consumption Measurement in CVS system

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Since reducing the consumption of fossil fuel is imperative, fuel efficiency in automobiles has become an important commercial value. Along with the improvement of fuel efficiency, the CVS method that is a de facto standard for fuel consumption measurement method has been continuously improved, nevertheless, small error factors which were needless to care until recent years, have higher demand for reduction. In addition to the reduction measures have already been implemented in the conventional product, the methods to improve the accuracy of fuel consumption measurement adopted to MEXA-ONE and CVS-ONE will be introduced.

Introduction

During the latter half of the 1990s, causes of measurement errors in regulated substances such as carbon monoxide (CO), total hydrocarbons (THC) and nitrogen oxides (NO_X) became a subject of discussion as the "low-emission vehicle" regulation was adopted in the state of California in the U.S., leading to improved measurement accuracy. These days, regulation values are being set up for emissions of carbon dioxide (CO_2) in order to reduce greenhouse gases. This CO_2 emissions regulation actually has the same meaning as regulation of fuel efficiency. Furthermore, fuel efficiency performance has grown dramatically in product value due to the rapidly rising fuel prices. To address better fuel efficiency performance, automobile manufacturers have developed various fuel efficiency improvement techniques including engine combustion efficiency improvement, vehicle weight reduction, driving energy loss reduction and hybrid vehicle development and introduced them into the market.

As enormous amount of investment is required in improvement of automobile fuel efficiency, high accuracy and high reproducibility are also demanded for fuel efficiency measurement. This article describes the causes of error that affect fuel efficiency measurement accuracy and introduce the methods to reduce these error causes as well as MEXA/CVS-ONE, a new measurement system equipped with the technology.

Fuel Efficiency Measurement using Carbon Balance Method

The nominal fuel efficiency (catalog fuel efficiency) measurement method in automobiles is specified by the laws and regulations of each country. Fuel efficiency measurement for small vehicles is calculated based on the masses of CO_2, CO and THC emitted while a completed vehicle is driven in a specified pattern (Figure 1). In this measurement method, gas concentrations are measured using a constant volume sampling system (CVS) in a similar fashion to emission mass measurement on engine exhaust gas. Figure 2 shows the schematic diagram of the measurement system configuration using CVS. The entire volume of exhaust gas from the vehicle is introduced into the system. There is a separate inlet for dilution air, and the exhaust gas flow rate after dilution is controlled at a stable level by the critical flow venturi (CFV) and the

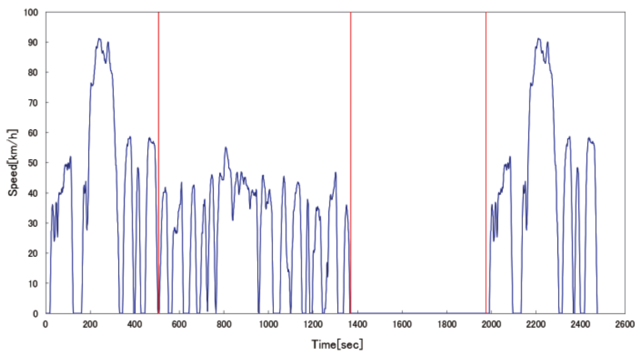

Figure 1 Driving cycle pattern (FTP75[1])

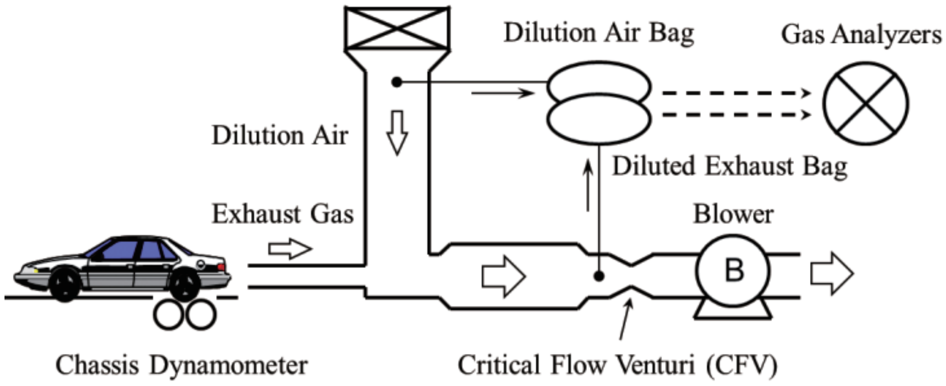

Figure 2 Configuration of CVS system

blower in the downstream stage. During the test, a part of the diluted exhaust gas and a part of the dilution air are collected into separate bags. The concentrations in each bag (average concentration during test period) are measured using an analyzer (MEXA) after test completion.

The emission mass of exhaust gas components can be calculated based on the volume of diluted exhaust gas measured by CVS and bag concentration analyzed by MEXA. The calculation method is shown in Equation 1.

$$M = \rho \times V_{mix} \times \left\{ C_{smp} - C_{amb} \times \left(1 - \frac{1}{DF} \right) \right\} \quad \cdots\cdots (1)$$

Where,

- M : Emission mass [g]
- ρ : Density of subject component [g/L]
- V_{mix} : Diluted exhaust gas volume during operation period [m^3]
- C_{smp} : Component concentration in diluted exhaust gas bag [ppm]
- C_{amb} : Component concentration in diluted air bag [ppm]
- DF : Dilution ratio

While the operation formula for DF varies by the fuel used, an example is shown in Equation 2.

$$DF = \frac{13.4}{C_{smp\_CO2} + C_{smp\_CO} + C_{smp\_THC}} \quad \cdots\cdots\cdots\cdots\cdots (2)$$

Where,

- C_{smp_CO2} : CO_2 concentration in diluted exhaust gas bag [vol%]
- C_{smp_CO} : CO concentration in diluted exhaust gas bag [ppm]
- C_{smp_THC} : THC concentration in diluted exhaust gas bag [ppm]

"13.4" in equation indicates the theoretical CO_2 concentration (%) when it is supposed that the gasoline is always going through perfect combustion. DF is calculated as the simple ratio between this theoretical CO_2 concentration and CO_2, CO and THC in diluted exhaust gas bag. In this case, CO_2, CO and THC originating in dilution air are not taken into consideration. This operation formula is derived based on the fact that the amount of carbon does not change before and after engine combustion, and it is called the carbon balance method. Fuel efficiency is calculated based on the emission masses of CO_2, CO and THC and the distance traveled during test period.[2]

$$e_{CO2} = \frac{M_{CO2}}{d},\ e_{CO} = \frac{M_{CO}}{d},\ e_{THC} = \frac{M_{THC}}{d} \quad \cdots\cdots\cdots (3)$$

$$FC = \frac{866 \times \rho_f}{0.429 \times e_{CO} + 0.866 \times e_{THC} + 0.273 \times e_{CO2}} \quad \cdots (4)$$

Where,

- e_{CO2} : Emission mass of CO_2 per km [g/km]
- e_{CO} : Emission mass of CO per km [g/km]
- e_{THC} : Emission mass of THC per km [g/km]
- d : Traveling distance during test [km]
- FC : Fuel efficiency [km/L]
- ρ_f : Fuel (gasoline) density [g/cm^3]

Causes of Error in Carbon Balance Method

Accuracy of fuel efficiency measurement by carbon balance method is affected by not only the measurement accuracy included in operation formula but also whether the test conditions are close to those presumed. Figure 3 shows an example of error causes for fuel efficiency measurement by carbon balance method. The error causes can be classified largely into 6 classes[3].

- Input fluctuation
- Conc. Change in a system
- Conc. Meas.
- Flow setting/control
- Dilution Air
- Mass calculation

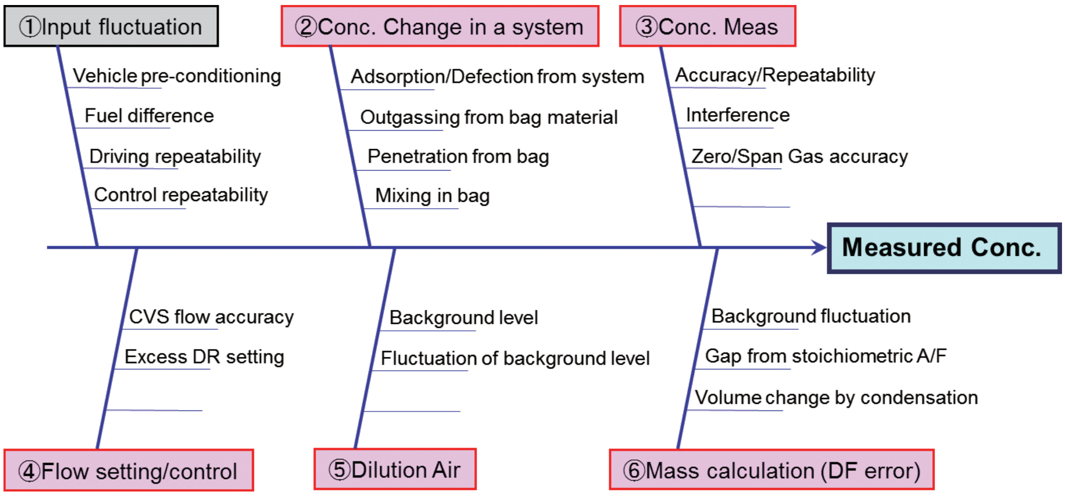

Figure 3 Cause and Effect diagram on CVS method

In this figure, the causes indicated by red frames have great influence on the accuracy of the exhaust gas measurement system. To reduce the errors caused by such cases, measures in the measurement system and devices are essential. Meanwhile, “input fluctuation” which is not in a red frame indicates fluctuations in concentration of CO_2 and so forth that are actually emitted due to the vehicle conditioning before testing, fuel conditions, operating conditions during test and so forth. Since this is not a cause in measuring instruments, it will not be delivered in this article. Furthermore, “Zero/Span Gas Accuracy” in “concentration measurement” causes indicates the standard gas accuracy used in calibration of analyzers. For CO_2 span gas, ±1.0% is specified for the grade 1 standard gas by JCSS and ±2.0% for grade 2 standard gas. As such gas concentrations and purities affect the fuel consumption measurement accuracy, they are also items that need to be considered sufficiently outside the measurement system.

Measures against Measurement Errors in ONE System

To improve the overall accuracy of measurement system, we need to accumulate small measures against individual causes of error including those with small degree of contribution. The section below introduces some of the measures to reduce measurement errors in MEXA and CVS, which belong to the ONE Series developed as the next-generation measurement systems with focus on improvement in fuel efficiency measurement accuracy.

Improvement in flow rate measurement accuracy

V_{mix} in Equation 1 is an integrated value for momentary diluted exhaust gas flow rate during test. This momentary flow rate is calculated by using Equation 5.

$$Q = C \times \frac{P}{\sqrt{T}} \quad \cdots\cdots (5)$$

Where,

Q : Momentary flow rate of diluted exhaust gas [m^3/min]

C : Venturi coefficient

P : Absolute pressure upstream venturi [kPa]

T : Temperature upstream venturi [K]

Venturi coefficient is a constant value unique for each venturi, and it is determined by flow rate calibration. The coefficient can be calculated more precisely by setting the environmental conditions stable during calibration and taking measurements accurately. Therefore, there is a tendency in recent years to add detailed calibration conditions to the test methods for exhaust gas regulation. Based on the equation, it is evident that the measurement accuracy for momentary flow rate also depends on accuracy of pressure and temperature measurements. It is especially necessary that the pressure is measured accurately as it is proportional to flow rate and its measurement accuracy directly affects the flowmeter measurement accuracy. Although accuracy of sensor single unit is important, regular calibration is also important. Cause of human error included in calibration is reduced by partially automating the calibration process.

In addition, correlation between benches is important in testing institutes and so forth which own multiple test benches and measurement systems, and it is ideal that the same measurement results are delivered when the same vehicle is measured using different measurement systems. Flow rate measurement units equipped with pressure sensors may often be installed in environments without air conditioning which does not provide stable environmental conditions, such as the machine room and underground pit instead of inside an air-conditioned bench. Pressure sensors are susceptible to the effects of temperature due to their principle and are equipped with circuits to compensate for this. However, these circuits are not sufficient for maintaining the accuracy necessary for the next-generation measurement systems. Thus by inserting the pressure sensor in a constant temperature box and adjusting the temperature in a temperature range higher than the room temperature, measurement errors caused by ambient temperature fluctuations can be reduced. This measure addresses a measurement system that is not affected by the environment of installation.

Reduction of concentration change in system

CO_2 is one of the major components contained in exhaust gas at a high concentration, and it is the most important component in fuel efficiency measurement by CVS carbon balance method. To measure it accurately, exhaust gas needs to be supplied through the sampling path to the gas analyzer without change. To prevent concentration change and so forth inside the sampling path, adsorption/desorption in parts that come in contact with gas in the sampling path, and prevention and reduction of gas permeation/denaturation are necessary.

While the effect of adsorption and desorption can be neglected for CO_2, caution is necessary for permeation. As the quantity of permeation increases when the gas stays longer in sampling path, the effect of this is the largest in sample bags, where the accumulation time is longest in CVS sampling path. There are various materials that can be used as the sample bag, and Tedlar® had been used conventionally. To reduce the deterioration of measurement accuracy and reproducibility by CO_2 permeation, KYNAR® was selected in ONE Series for its low CO_2 permeability. Figure 4 shows the results of verifying the permeability in new and old bags. As a method for verification, changes in CO_2 concentration in time was studied by filling the CO_2 gas (concentration 2.019 vol%) in the sample bag. Compared to Tedlar®, CO_2 permeability was smaller in KYNAR®. When the time since test completion to bag concentration measurement is 20 minutes, the effect of error can be expected to be reduced by approximately 0.1% by material change.

Improvement in analyzer accuracy

Fuel efficiency is bad when CO_2 emission is high and good when the emission is low. As the fuel efficiency for automobiles and engine is improved, less CO_2 is emitted. As the CVS method takes measurements by diluting the exhaust gas, the CO_2 concentration measured by gas analyzer becomes even lower. Therefore, we developed a new high-sensitivity CO_2 analyzer (Figure 5) in ONE Series to address measurement with high accuracy in low concentration range required by the CVS method.

As shown in Equation 1, emission mass is calculated by subtracting the dilution air bag concentration from the diluted exhaust gas bag concentration. Here, concentration of water content in the bag differs between the diluted exhaust gas bag which samples the exhaust gas containing moisture at a high concentration and dilution air bag which samples the air. One example is shown in Figure 6. In general, CO_2 analyzers adopting the non-dispersive infrared detection (NDIR) method have sensitivity to moisture (moisture interaction effect) in principle, and thus measurement errors can occur due to the difference in moisture concentration between the bags. We therefore reduced the measurement errors by establishing a CO_2 detector and interference correction moisture detector and correcting the moisture interaction effect continuously in

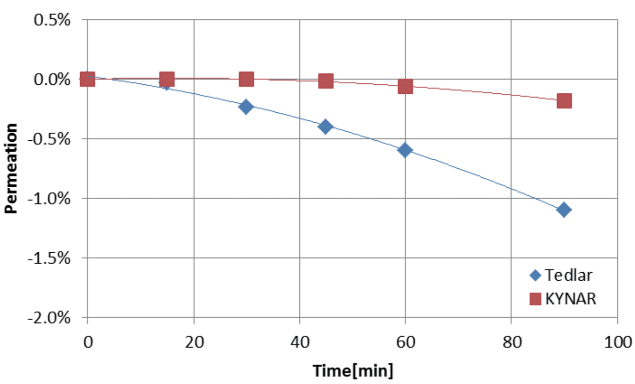

Figure 4 Comparison of CO_2 permeation performance

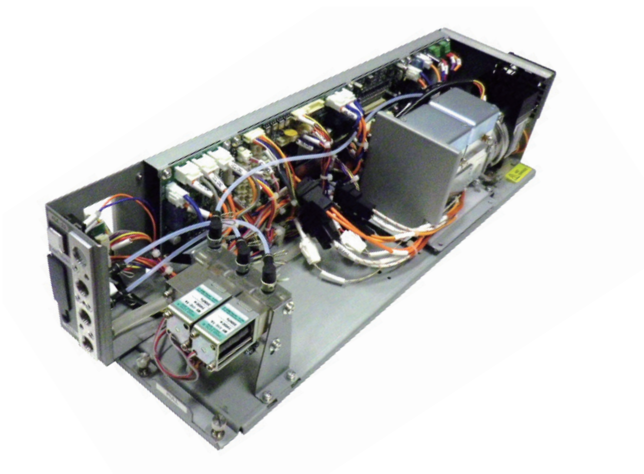

Figure 5 CO_2 Low Analyzer

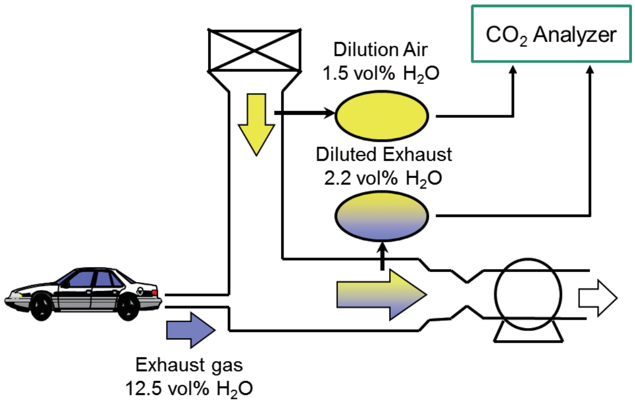

Figure 6 Image of Water Concentration in Bag

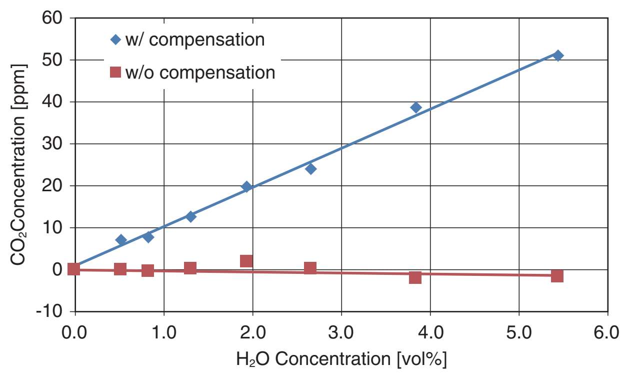

Figure 7 Effect of H_2O interference compensation

the newly developed NDIR-type CO_2 analyzer. A comparison of measurements with and without moisture interaction correction is shown in Figure 7. By adding interaction correction, accurate measurement is addressed without the effect of moisture concentration.

The rate of improvement in direct factors in fuel efficiency measurement becomes the rate of improvement in fuel efficiency measurement just as in flow rate measurement accuracy mentioned above. However, it is a little more complex to calculate the degree of the effect of this improvement in accuracy by moisture interaction correction, as the CO_2 concentration is included in both emission mass operation formula and DF operation formula while it does directly affect the CO_2 concentration measurement. We then verified the effect of moisture interaction correction on fuel efficiency measurement.
When it is supposed that the fuel (gasoline) goes through complete combustion and that the exhaust gas contains only CO_2, moisture and nitrogen so that existence of moisture interaction only can be compared, Equation 2 is expressed as follows:

$$DF = \frac{13.4}{C_{smp\_CO2}} \quad \cdots\cdots (6)$$

Substituting this in Equation 1,

$$M = \rho \times V_{mix} \times \left\{ C_{smp} - C_{amb} \times \left(1 - \frac{C_{smp}}{13.4} \right) \right\} \quad \cdots\cdots (7)$$

is obtained. The diluted exhaust gas CO_2 concentration when CO_2 emission mass is constant and CVS flow rate is varied is expressed as follows:

$$C_{smp} = \frac{\frac{M}{\rho \times V_{mix}} + C_{amb}}{1 + \frac{C_{amb}}{13.4}} \quad \cdots\cdots (8)$$

We calculated the effect of moisture interaction based on this CO_2 concentration and water content using the results in Figure 7. Figure 8 shows the effect of whether interaction is included or not on the fuel efficiency.

When moisture interaction correction is included, the fuel efficiency value does not change even when the dilution ratio is changed. However, the fuel efficiency value changes gradually as *DF* becomes larger if moisture interaction correction is not conducted. In general, *DF* is often measured in the range of 10 to 30, and accuracy is improved by 0.2 to 0.4% when moisture interaction correction is added in this range. It was also indicated that measurement is possible with high reproducibility as the effect of moisture is canceled by the difference in *DF*, even though *DF* becomes large when the same CVS flow rate is used as the fuel efficiency is improved since the CO_2 emission mass becomes smaller. In addition, it could also be valid for measurement subjects for which DF may become fairly large with very small emission levels such as hybrid vehicles. However, it must be noted that this effect will be very large if DF is extremely large, as the CO_2 contained in dilution air is not included in DF operation formula[4].

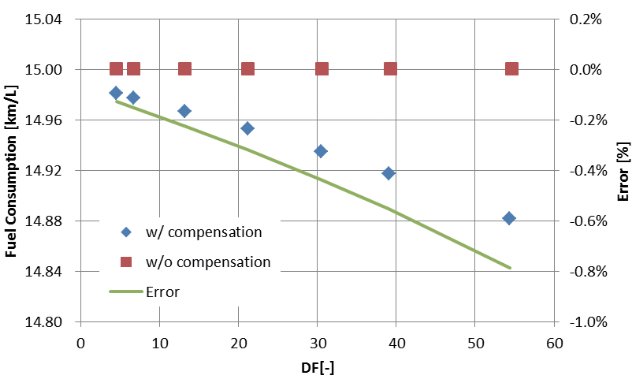

Figure 8 Comparison of Fuel Consumption

Conclusion

This article introduced the causes of errors that affect the fuel efficiency measurement accuracy by CVS carbon balance method and the techniques included in MEXA-ONE and CVS-ONE as measures against them. Fuel efficiency measurement at a higher accuracy than the conventional products can be expected by combining these techniques. In the future, it is expected that innovations to improve the fuel efficiency will further advance in concurrence with the growing awareness of the energy problem and environmental problems. To keep up with this, we would like to examine and evaluate the measurement techniques considered necessary in exhaust gas measurement and provide them as measurement applications by quickly grasping such changes in time, when we should consider partial change in conventional methods or even adoption of new methods in addition to working to improve the measurement accuracy of the conventional methods.

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