Feature Article

Application

Emissions and Fuel Economy Measurement System Using Intermittent Sampling CVS for PHEV

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Recently, Plug-in Hybrid Electric Vehicles (PHEVs) attract attention while the reduction of the consumption of the fossil fuel is demanded. On the other hand, high Dilution Factors (DFs) and low concentrations of gaseous components in the Constant Volume Sampling (CVS) are imposed by the intermittent operation of the engine in the PHEV. Such a dilution condition causes a numerical error of DF by the assumption of negligible ambient components and an analysis error of gaseous components. New emission measurement method which provides intermittent sampling synchronized with engine operation mode has been investigated in this study. The results showed the ability of proposed system to improve emissions and fuel economy measurement accuracy by increasing gaseous concentrations in the CVS system.

Introduction

Recently, concerns about energy issues and global warming have stimulated the reduction of the consumption of fossil fuel for all types of vehicles. The Plug-in Hybrid Electric Vehicle (PHEV) is one of the next-generation vehicles attracting attention from such a point of view. PHEV can be driven by both an internal combustion engine and electric motors with a battery storage which can be charged from an off-board source of electricity. One of the main characteristics of the PHEV is the powertrain management system which manipulates the engine and the electric motors in order to drastically improve the fuel economy. It achieves this by using the off-board source of electricity, along with enabling the engine shutdown during traffic stops, running the engine at its more efficient operating points during driving and charging the battery with recovered kinetic energy during deceleration. Legislation requires that the same fuel economy measurement method which is applied to conventional vehicles is also used in order to determine the fossil fuel economy of the PHEV. Basically, the vehicle's official fuel economy is determined by measurement of the amount of Carbon Dioxide (CO_2), Carbon Monoxide (CO) and Total Hydrocarbon (THC) emitted from the vehicle during defined driving patterns (test cycles). Constant Volume Sampling (CVS) is used for this purpose. CVS is also utilized for PHEV fuel economy measurement[1], however, its measurement accuracy may not be so high relative to the measurement of conventional vehicles because of the particular driving behavior of the PHEV. The intermittent sampling method, which was devised to improve the precision of fuel measurement of PHEVs by CVS, is introduced in this report.

Overview of CVS Method

Fuel economy measurement by CVS

CVS is widely used for emissions and fuel economy measurement of vehicles and engines exhaust gas. Figure 1 shows configuration of a conventional CVS system. CVS has an exhaust gas inlet which is directly connected to the vehicle tailpipe and a dilution air inlet. The Critical Flow Venturi (CFV) which is located downstream keeps the total flow constant using a high capacity blower. All of the vehicle exhaust flow is diluted with air and the total diluted exhaust flow is controlled to a constant rate. Parts of the dilution air and diluted exhaust are sampled into separate batch containers (bags) at a constant flow rate. The mass of each gaseous component is then determined from the gaseous concentrations in the bags and accumulated volume of diluted exhaust. Equation 1 shows a formula for the determination of CO_2 mass. Where, m_{CO2} is the mass of CO_2, V_{mix} is the total volume of diluted exhaust during the test cycle, ρ_{CO2} is the density of CO_2, $c_{s,CO2}$ is the

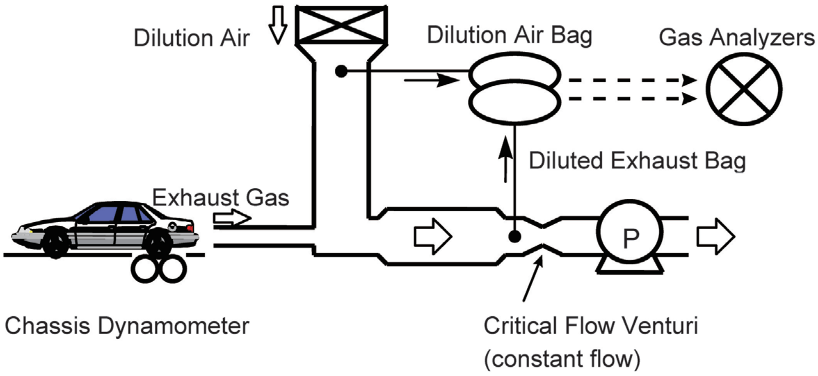


Figure 1 Configuration of the conventional CVS system

gaseous concentration in the diluted exhaust bag, $c_{a,CO2}$ is the gaseous concentration in the dilution air bag and DF is the dilution factor of CVS.

$$m_{CO2} = V_{mix} \times \rho_{CO2} \times \left[c_{s,CO2} - c_{a,CO2} \times \left(1 - \frac{1}{DF} \right) \right] \quad \cdots\cdots (1)$$

The dilution factor corresponds to the volume ratio of diluted exhaust and raw exhaust gases. In the case of CVS measurement, dilution factors are not measured by the flows but estimated from CO_2, CO and THC concentrations in the diluted exhaust bags. In the case of gasoline vehicles, DF is determined by Equation 2.

$$DF = \frac{13.4}{c_{s,CO2} + c_{s,CO} + c_{s,THC}} \quad \cdots\cdots (2)$$

where, $c_{s,CO2}$, $c_{s,CO}$ and $c_{s,THC}$ are concentrations of CO_2, CO and THC in the diluted exhaust bag. “13.4” is the theoretical CO_2 concentration assuming the use of gasoline reference fuel, that the engine is operated under stoichiometric conditions and that the fuel is completely oxidized without residuals. The CO_2 concentration of the dilution air which is also sampled into the diluted exhaust bag is ignored in Equation 2. The influence of the error in Equation 2 to the CO_2 mass determination is negligible because the CO_2 concentration difference between diluted exhaust and dilution air is sufficient in the case of conventional vehicles.

The units of fuel economy are different by the country. However, fuel economy is commonly determined from the total masses of CO_2, CO and THC and is known as the carbon balance method. For example, fuel economy in g/km is determined by Equations 3 and 4 in Japan[2].

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

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

where, FC is fuel economy, e_{CO2}, e_{CO} and e_{THC} are mass emissions per 1 km, d is the travel distance during the test cycle and ρ_f is the density of gasoline.

Technical Challenges of PHEV Measurement

Figure 2 shows rough image of battery State of Charge (SOC) and raw exhaust flow when a PHEV is operating with fully charged batteries. The test cycle is the Urban Dynamometer Driving Schedule (UDDS) defined by US Environmental Protection Agency (EPA). The SOC of the PHEV decreases after the vehicle starts and is finally stabilized at an almost constant level as shown in Figure 2. The PHEV is powered mainly by the electric motor and the engine stops for a long time while the SOC is decreasing. The CVS samples only dilution air into the bags because the exhaust volume is quite small in this condition. Therefore, any exhaust gas is over-diluted in the bag. The problem is that such a high dilution increases the measurement error of the gaseous concentrations and the influence of DF error[4, 5]. Furthermore, a small amount of air may flow through the cylinders in the engine, drawn by the slightly negative tailpipe pressure at the inlet to the CVS when both intake and exhaust valves on the engine are open during engine shutdown. This air flow cools the exhaust catalyst below its designed operating temperature.

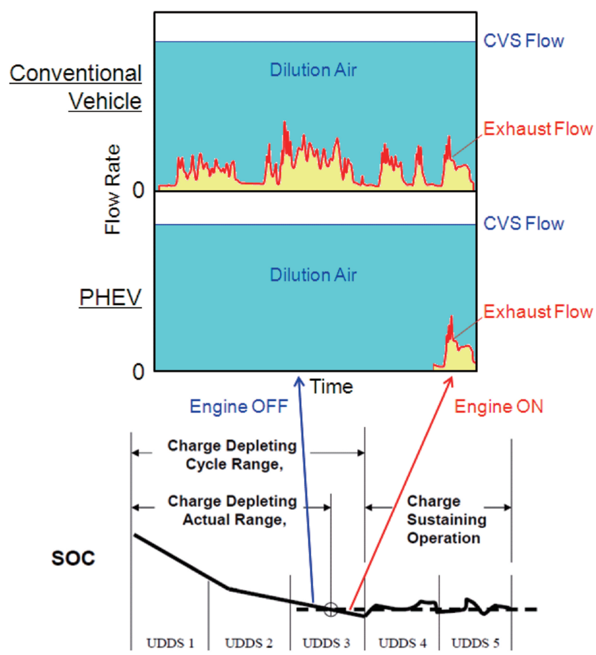


Figure 2 Comparison of exhaust flow between conventional and plug-in hybrid electric vehicles[3]

Intermittent sampling CVS

The authors applied an intermittent sampling method, synchronized to the engine operation, to the CVS in order to improve PHEV measurement accuracy. The engine operation is monitored by an ignition pulse detector and the sampling of the vehicle exhaust into the CVS and bags is activated only when the engine is running. The configuration of intermittent sampling CVS system is described below.

Configuration of the system

Figure 3 shows the intermittent sampling CVS system configuration. Mass flow controllers (MFCs) were applied in this system instead of critical flow venturis which are in common use as sample flow controllers in a conventional CVS system. The total sampling time during which diluted exhaust is pumped into the bags varies in each test because the time period when the engine is running during the test cycle depends on the engine load and battery SOC. Using the MFCs, sample flows can be flexibly set based on the total sampling time in order to obtain sufficient bag volume for the stable gaseous concentration analysis. In addition, gas flow through the MFCs is kept flowing and discarded to the bypass in the same condition as bag sampling during engine shutdown. A fast response tailpipe shut-off valve is located on the transfer tube between tailpipe outlet and sample inlet of the CVS system so that tailpipe can be disconnected from the CVS system during engine shutdown. The shut-off valve eliminates flow through the after treatment system by the small amount of air drawn by the slightly negative CVS tailpipe pressure to prevent cooling of catalysts from affecting emissions.

A ignition pulse detector was installed on the test vehicles in order to detect the engine operation modes. The detector signal was used as a trigger for the bag sampling, accumulation of the diluted exhaust flow and the switching of the shut-off valve. It is necessary to account for the delay time in the system between the sampling points, where diluted exhaust is transferred to sample bags, from the mixing point in which exhaust gas is diluted by ambient air when the bag sampling is switched. Figure 4 shows the time chart of intermittent sampling system. A 5 second delay was set at the engine shutdown for the sampling system so that the entire volume of exhaust gas can be sampled into the bag.

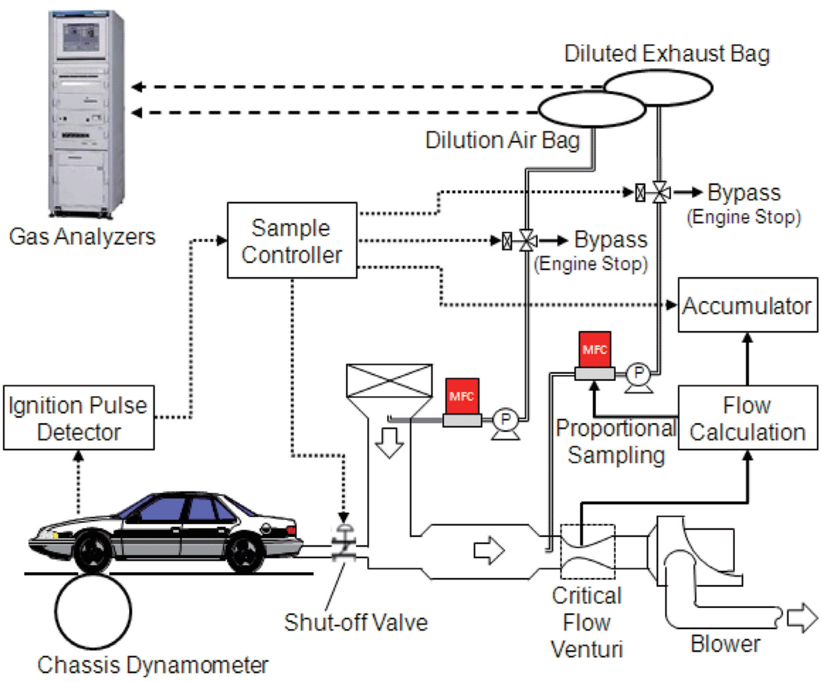


Figure 3 Configuration of the intermittent sampling system

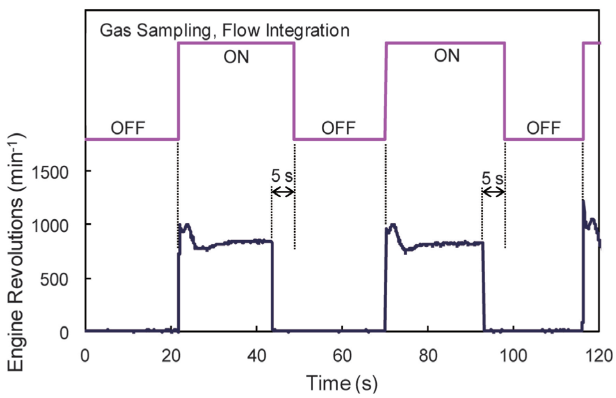


Figure 4 Timing chart for bag sampling

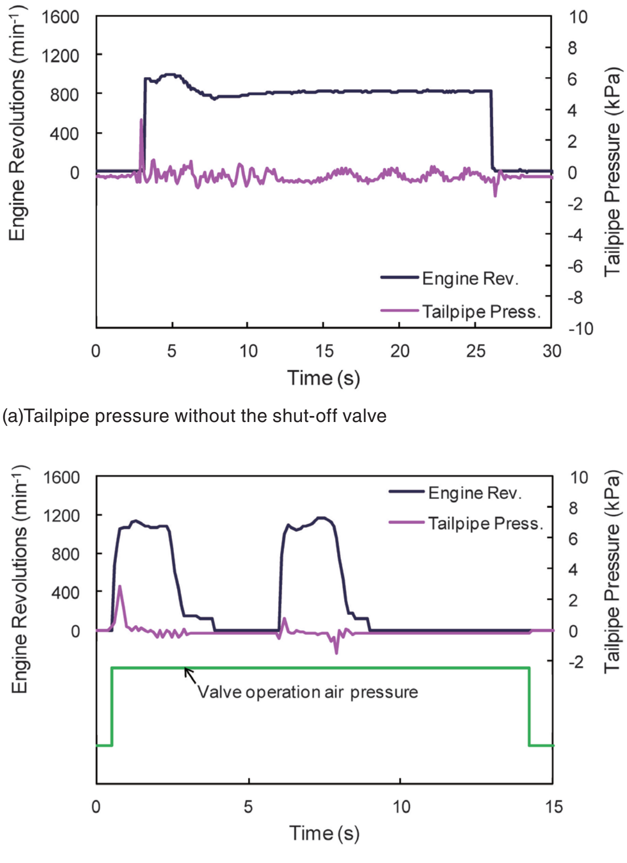
Validation of the shut-off valve

The specification of the shut-off valve is listed in Table 1. The shut-off valve should have a fast response time so that there is no restriction to the raw exhaust flow in the tailpipe when the engine is started. Tailpipe pressure was measured when the shut-off valve was opened with the detection by the ignition pulse detector of

Table 1 Specifications of shut-off valve

Valve Structure	Ball Valve
Actuator	Air Operated
Supply Air Pressure	0.3 – 1.0 MPa (gauge)
Bore	101.6 mm
Maximum Temperature	315.6°C
Resisting Pressure	ANSI class 150 Compliant
Material	SUS 316

engine startup to verify that the tailpipe outlet was minimally pressurized. Figure 5 shows plots of engine speed measured by ignition pulse detector and tailpipe pressure. Slightly negative tailpipe pressure was observed without the shut-off valve during engine shutdown as shown in (a). On the other hand, (b) verifies that tailpipe pressure was equal to ambient when the engine speed was 0 min^{-1} and the shut-off valve was closed. Static pressure was also maintained within ±1.2 kPa[6], which is regulated by the CFR. Moreover, the peak pressure transients are almost same in both cases with and without the shut-off valve. It was concluded that the shut-off valve response speed is sufficient.



(a)Tailpipe pressure without the shut-off valve

(b) Tailpipe pressure with the shut-off valve

Figure 5 Effect and response of the shut-off valve

Comparison of Gaseous Concentrations in the Sample Bags for PHEV

A conventional CVS system and the intermittent sampling system have been compared by measuring PHEV emissions and fuel economy. Figure 6 shows the system configuration for the comparison between conventional and intermittent sampling methods. An intermittent sampling line controlled by a MFC and a continuous sampling line controlled by a critical flow venturi were installed in the intermittent sampling CVS.

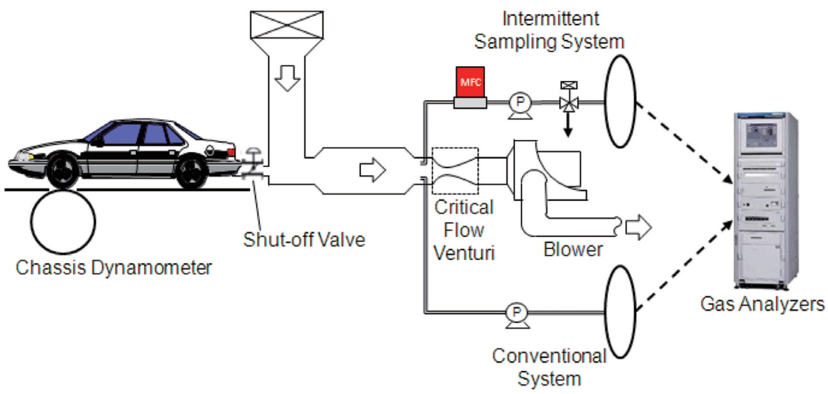


Figure 6 Setup of continuous and intermittent sampling systems

Test condition and engine operation

Test cycle

As shown in Figure 2, PHEVs switch main power source according to battery SOC. When in Charge Depleting (CD) mode, a PHEV with a fully charged battery will often be able to complete a test cycle with much less engine operating time than in Charge Sustaining (CS) mode. Therefore, for example, according to the California Air Resource Board (CARB) test procedure[2], a PHEV is tested under these two different vehicle operation modes by repeating UDDS test cycles. The PHEV has been tested to the CARB procedure in this study. The PHEV was preconditioned by one UDDS cycle and soaked for 18 hours before the emissions and fuel economy measurement. The PHEV battery was fully charged from an off-board source of electricity during the soak period. Four consecutive UDDS tests were performed. Figure 7 shows a speed trace of UDDS test cycle. The bag sampling was performed for each phase of UDDS by one bag set (total two bag sets) individually as shown in Figure 7.

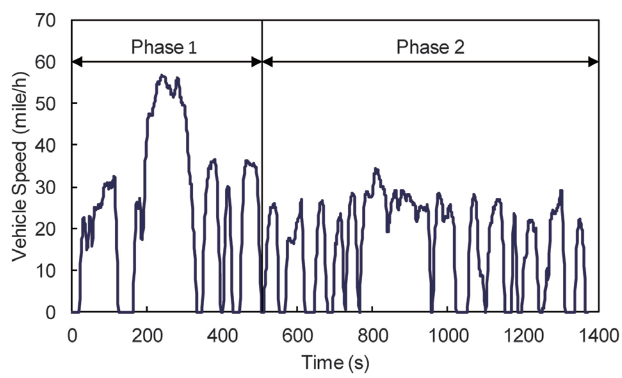


Figure 7 Vehicle speed setting of UDDS

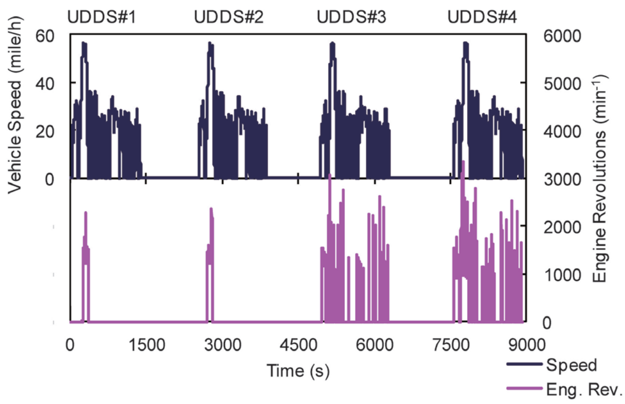


Figure 8 Engine speed during test cycles

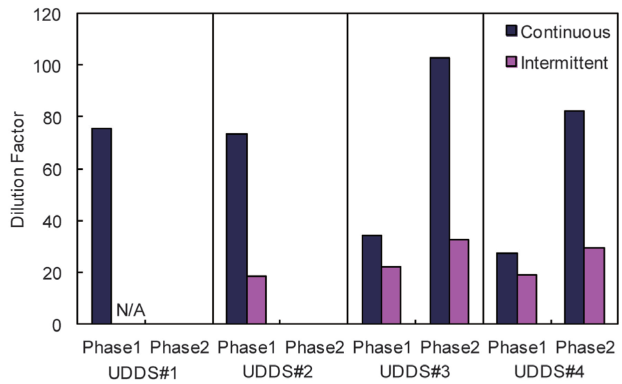


Figure 9 Dilution factors for PHEV per test cycle

Engine operation during test cycles

The speed of the PHEV and its engine speed during the four UDDS test cycles are shown in Figure 8. Engine speed was measured by the ignition pulse detector. Figure 8 shows the first test cycle (UDDS#1), the second test cycle (UDDS#2), the third test cycle (UDDS#3) and the fourth test cycle (UDDS#4) from left to right. Short term engine operations during high speed driving were observed in UDDS#1 and UDDS#2. On the other hand, engine operation time increased in UDDS#3 and UDDS#4. It was confirmed that the PHEV behaved in CD mode for UDDS#1 and UDDS #2 and in CS mode for UDDS#3 and UDDS #4.

Comparison between conventional and intermittent sampling CVSs

Dilution factors

Figure 9 shows a comparison between the conventional and the intermittent sampling methods of DFs which were measured for each phase over four consecutive UDDS tests. Enough gas volume for stable analysis of gaseous concentrations could not be obtained in a sample bag in the intermittent sampling method at the first phase of UDDS#1 because the sample flow setting was too small. However, it was verified to have enough volume to measure gaseous concentrations accurately by increasing sample flow into the bag shown in UDDS#2. The intermittent sampling method did not sample any diluted exhaust gas in the second phase of UDDS#1 and UDDS#2 because no engine operation was observed. CARB accepts omission of engine exhaust gas measurement when no engine operation is observed. Engine operation modes can be directly detected by the intermittent sampling method so that the sampling system automatically prevents unnecessary sampling during engine shutdown.

Figure 9 shows DFs close to 80 were observed in UDDS#1 and UDDS#2 with the conventional sampling method. It is common to limit the DF to around 20 in the case of conventional vehicle measurement. However, in this case, the raw exhaust gas was over-diluted due to the minimal engine operation. DFs with the continuous sampling method in the second phase of UDDS#3 and UDDS#4 are also quite high. On the other hand, the DFs of the intermittent sampling method are within 20 to 30 at each phase. The DF variation of the intermittent sampling method by the variation of engine operation time is also small. It is also permitted and common to sample the entire UDDS test cycle into one bag. Sampling with a single bag imposes significant challenges with a conventional continuous sampling method in UDDS#1 and UDDS#2 because of over-dilution during the second phase. On the other hand, it is expected that the intermittent sampling method maintains the DF at the same proper range as shown in Figure 9.

Gaseous concentrations in sample bags

Figure 10 shows a comparison between the conventional and the intermittent sampling methods for gaseous concentrations in the diluted exhaust sample bags. Gaseous concentrations for all components in the sample bags of the intermittent sampling method are higher than concentrations of the conventional sampling method in all test cycles as expected from DF results shown in Figure 9. A relatively large difference is observed in the first phase of UDDS#2 in which the engine is operated for only a short time. In this case, the intermittent sampling method can have an advantage for improvement of emissions and fuel economy measurement accuracy for PHEV compared to conventional systems. The CO_2 concentrations (which is the primary component for determining fuel economy), in the diluted exhaust sample bags of the intermittent sampling method are 3.5 times higher than the concentrations of the conventional sampling method in the second phase of UDDS#3 and UDDS#4. It is an increasing requirement for the accurate measurement of CO_2 emissions and fuel economy, and the intermittent

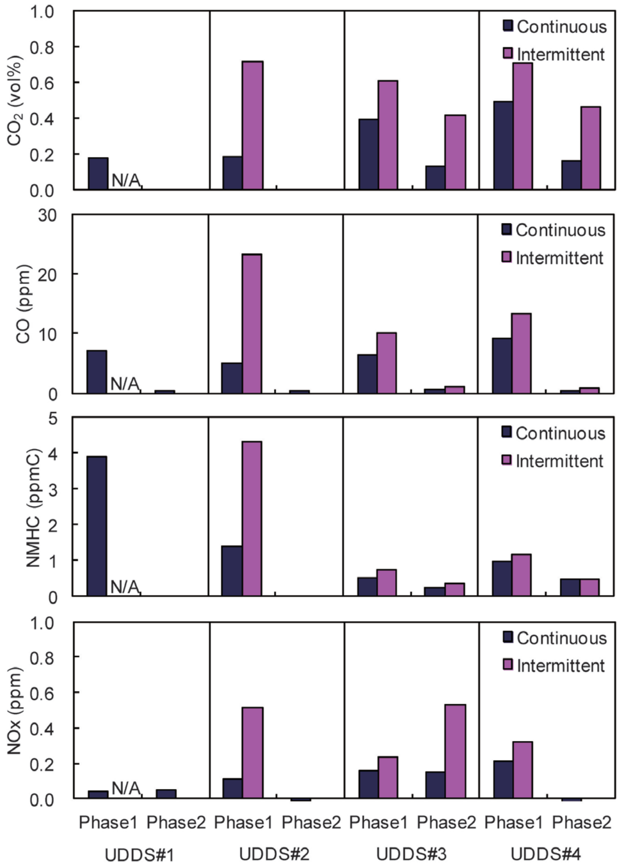


Figure 10 Gas concentrations for PHEV per test cycle

sampling method has a significant impact on maintaining the accuracy of measurement when applied to PHEVs.

Conclusions

The intermittent sampling method for the accurate measurement of emissions and fuel economy of PHEVs using CVS is introduced. The development and practical application of next generation vehicles and powertrains continues to advance rapidly to meet social, environmental and economic requirements. Such developments also drive the requirement to develop both modified and new measurement technologies from those currently applied to conventional vehicles, fuel economy and emissions measurement for PHEVs is just one example. We are willing and intend to propose the use of the CVS intermittent sampling technique as described in this paper as a future standard measurement method.

References

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