

Improved PHEV Emission Measurements in a Chassis Dynamometer Test Cell

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ABSTRACT

A Constant Volume Sampler (CVS) over dilutes the exhaust gas sample when testing Plug-In Hybrid Electric Vehicles (PHEV). This is because the CVS continues to fill the sample bag when the engine is shutdown. With a PHEV, it is possible to complete an FTP test with the engine running less than 20% of the time, resulting in a CVS bag dilution ratio in the range of 100 to 300. The CVS dilution ratio should be in the range of 5-25 for accurate results. At higher dilution ratios, the gas concentrations of CO, NO_x and THC approach the ambient background level in the test cell. At a dilution of 100, the CO₂ concentration in the sample bag is about 0.13%, which is only 3 times the air background concentration. The measurement errors caused by over dilution create errors of 10% to 30% in the calculated mass of CO₂, CO, and NO_x. Estimated errors for THC are in the range of 200%

Many of the limitations of a CVS can be eliminated by using a partial flow sampling system, such as a bag minidilutor (BMD), which maintains a constant dilution ratio of 5:1 at all exhaust flow rates. A BMD dilutes the exhaust gas with pure air, so no background correction for ambient air contamination is necessary. Testing a PHEV still poses measurement issues with a BMD, because the internal combustion engine may not run long enough during a test for the BMD to acquire a volume of exhaust gas sample sufficient for the gas analyzers to read accurately.

Modifications have been made to the CVS and BMD hardware and software to improve the measurement accuracy for PHEV testing. Vehicle emission data obtained with the modified test equipment is compared to data obtained previously with standard CVS and BMD sampling systems.

INTRODUCTION

Light duty Hybrid Electric Vehicles (HEV) have been tested for emissions and certification since they were introduced commercially to the U.S. in 1999. The HEVs have achieved battery charge balance over the standard test cycles [1] run for emission and fuel economy. When the cycle is charge balanced, there is no net contribution of energy from the battery, so the hybrid vehicle can be tested the same way as a conventional vehicle. The size of the battery is small in these HEVs, so they have an electric-only operating range limited to a few kilometers. Therefore, the internal combustion engine (ICE) must start and run over the majority of an FTP or highway fuel economy (HFE) test. The FTP urban dynamometer driving schedule (UDDS) test covers a distance of 7.45 miles, and the HFE test covers 10.3 miles. This means the exhaust emissions from the HEV are similar in mass and volume to that seen with conventional vehicles. HEV Emission measurements made with a conventional CVS achieve measurement accuracies that are close to those seen when testing conventional ICE vehicles.

A plug-in hybrid electric vehicle (PHEV) typically has a battery with three to four times the power of an equivalent HEV [1]. The larger battery enables the PHEV to operate as an electric vehicle (EV) over a significant distance. For example, it is possible for a PHEV to complete an FTP test of 7.5 miles of urban driving while the ICE does not run at all. This results in a CVS sample bag that is only filled with ambient air. It is common to observe the engine operating only for 10-20% of the FTP test. Because the CVS continues to fill the sample bag when the engine is shut down, this results in a CVS sample bag dilution ratio in the range of 100 to 300. The optimum dilution ratio for a CVS is in the range of 5-7. The dilution ratio should be less than 25 for accurate results. At higher dilution ratios, the gas concentrations of CO, NO_x, and THC approach the ambient background level in the test cell. At a dilution of 100, the CO₂ concentration in

the sample bag is about 0.13%, which is only three times the air background concentration. The measurement errors caused by over dilution create errors of 10% to 50% in the calculated mass of CO₂, CO, and NO_x. Estimated errors for THC are more than 200%.

A simulated PHEV FTP test was performed using a chassis test cell with an enhanced CVS and BMD sampling system [Fig. 1]. The CVS emissions data was obtained with a CVS-7200SLE enhanced constant volume sampling system, with a low-loss remote mixing tee and a MEXA-7200SLE bag analysis system. The partial-flow sampling system consists of a BMD-1000 bag minidiluter paired with an EXFM-1000 ultrasonic exhaust flow meter. The sampling systems are operated in parallel so that emission results are obtained simultaneously, which allows a direct comparison of CVS and BMD results for a single vehicle test. A 3.8L V6 vehicle was operated over an FTP test cycle, where the engine was running for only 15 seconds of the test. This simulated the PHEV engine duty cycle observed with PHEVs [2]. The resulting data demonstrates the CVS errors due to high DF are nearly 50% of the expected emissions. The simultaneous BMD sample data also demonstrates the limitations of a BMD in this application, where the BMD failed to acquire enough exhaust sample to perform a valid gas analysis.

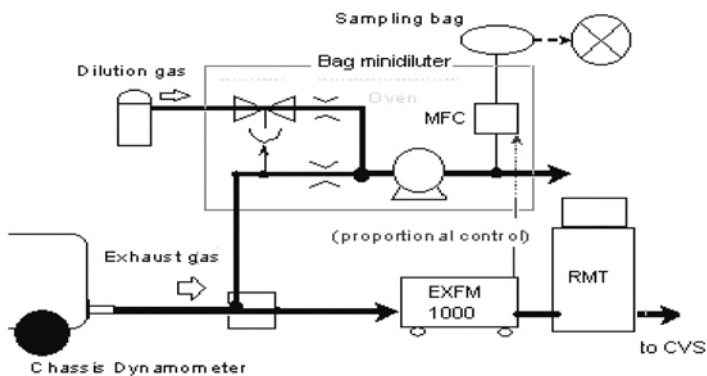


Figure 1. The bag mini-diluter sample is taken at the vehicle tailpipe, with the remaining exhaust going to the exhaust flow meter and then the remote mixing tee and CVS.

Many of the limitations of a CVS can be eliminated by using a partial flow sampling system, such as the bag minidiluter (BMD), which maintains a constant dilution factor of 6 at all exhaust flow rates [5,6,7]. A BMD dilutes the exhaust gas with pure air, so no background correction for ambient air contamination is necessary. Testing a PHEV still poses measurement issues with a BMD, because the internal combustion engine may not run long enough during a test for the BMD to acquire a volume of exhaust gas sample sufficient for the gas analyzers to read accurately. If the ICE runs for only 10% of the FTP test time, the BMD will

generally acquire only 10% of the expected sample bag volume. A typical emission gas analysis requires 16 liters of sample for an accurate measurement. The ICE must operate for 50% or more of the FTP test in order for the BMD to acquire a 16 liter diluted exhaust sample.

We propose some modifications to test procedures in order to accommodate PHEV tests with a BMD. For example, during a series of Charge Depletion (CD) UDDS tests where the ICE runs 15% of the time, each UDDS test may result in about 3 liters of sample. If six of these UDDS tests were combined in a single BMD sample bag, the total bag volume of 18 liters would be sufficient for an accurate gas analysis. We also present preliminary results of an optimized BMD sampling procedure, where the sample bag volume is increased to a sufficient level with an additional post-test sample dilution procedure.

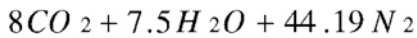
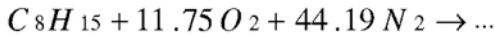
LIMITATIONS OF PHEV MEASUREMENT

CVS LIMITATIONS

A Constant Volume Sampling System (CVS) is considered the reference for accurate emission measurements. The CVS captures 100% of the vehicle exhaust, and the exhaust dilution is controlled with highly accurate Critical Flow Venturis (CFV), so the sample mass emissions can be reliably calculated. With a typical gasoline ICE, the total flow of the CVS is selected so that the exhaust dilution ratio is greater than 5 at the maximum expected engine speed and load. With a conventional vehicle, the engine operates during 100% of the test cycle, resulting in an average exhaust dilution ratio in the range of 10-20 for a dynamic test such as the FTP. While an overall dilution ratio of 10-20 is higher than the target ratio of 5-7, measurement accuracy is typically within 1% for CO₂ and fuel economy. The engine operating schedule for a PHEV can be difficult to predict [1,8,9,10]. The engine can operate almost at random with a duty cycle from 0% to 100% during an emissions test. The CVS must be configured so the tunnel draws enough dilution air to guarantee an exhaust dilution ratio of 5 when the ICE runs at maximum speed and load. If the engine runs less than 50% of the test time, sample over-dilution occurs, and measurement accuracy is compromised. With the engine stopped, the exhaust dilution factor is high, greater than 600. If the CVS were configured so the tunnel draws enough dilution air to provide an overall dilution factor of 6 when the engine runs 50% of the time, then the effective dilution factor would be less than 6 during engine operation, and the exhaust gas will condense water and compromise measurement accuracy. There is no CVS configuration that can maintain moderate exhaust dilution ratios over the wide dynamic engine operating range from 0% to 100% exhaust flow.

There are several assumptions that apply to operation of a CVS [4,11]. One is that the internal combustion engine is operating under stoichiometric conditions. The CVS dilution factor is calculated by measuring the total recovered carbon in the sample bag, and it assumes the engine exhaust generated a CO₂ concentration of 13.4%.

The calculated Dilution Factor:



$$[CO_2]_{p,ideal} = \frac{8}{8 + 7.5 + 44.19} = 13.4[\%]$$

$$DF = \frac{13.4}{[CO_2]_{sam,bag} + [CO]_{sam,bag} + [THC]_{sam,bag}}$$

This DF calculation neglects the effect of ambient CO₂. This results in significant errors at high DF [Fig 2]. For example, when the actual DF is equal to 50, the CO₂ concentration in the sample bag is 0.31%, and the calculated DF is equal to 43.6. This represents an error in the DF of -12.8%. When the actual DF is equal to 200, the CO₂ concentration in the sample bag is 0.11%, and the calculated DF is equal to 125.5. This represents an error in the DF of -37.3%. It is seen in Figure 2 that when the DF is less than 25, there is a good match between the actual dilution factor and the calculated DF.

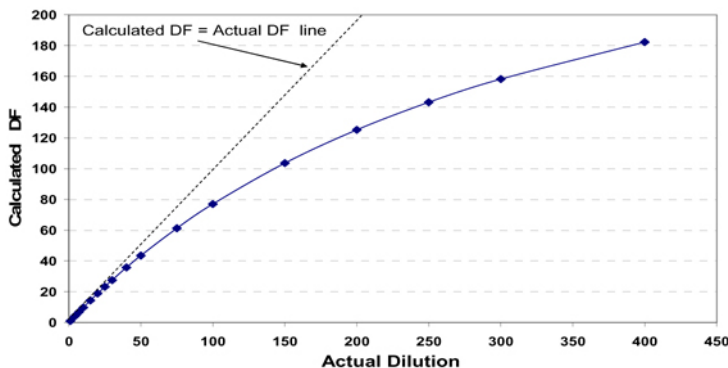


Figure 2. The calculated Dilution Factor compared to the actual CVS Dilution Factor. The errors at high dilution ratios are due to the 0.04% CO₂ concentration in the ambient dilution air.

NDIR ANALYZER ACCURACY LIMITATIONS

The CO₂ analyzer typically has a resolution limit of 0.001%, and measurement uncertainty of 0.005%. The ambient level of CO₂ is nominally 0.040%, where the analyzer uncertainty

represents 12-15% of the expected concentration. In the previous example where the DF is equal to 200, the CO₂ concentration would be 0.11%, and the analyzer uncertainty represents 5% of the expected concentration. The net CO₂ concentration is determined by subtracting the ambient bag CO₂ concentration from the sample bag concentration. In this example, both concentrations would have accuracy limited to 5% to 15% of the readings. This results in a net CO₂ concentration value that may be in error by 15%. This is not a defect in the CO₂ analyzer, but a result of operating the analyzer at 1% of its span concentration. Small absolute errors become large relative errors in this circumstance.

Note that a relative error of 15% in the CO₂ concentration applies directly to the DF calculation. This would result in an equivalent DF uncertainty of 15% based on the measured concentration of CO₂.

NDIR INTERFERENCE CURVE LIMITATIONS

The CO₂ analyzers have well known interferences due to water and oxygen [Fig. 3,4]. The changes in H₂O concentration in the sample bag are expected to cause less than a 1% variance in the CO₂ reading. However, the difference in oxygen concentration will change from around 5% when the DF is equal to five, to over 20% oxygen at DF greater than 50. This will cause the CO₂ analyzer to read 2% lower concentration than expected. This is a relatively minor error compared to those already described, but these errors are additive, and they all tend to be negative errors. That is, the CO₂ concentrations and mass will appear to be lower than the true concentrations.

<figures 3, 4 here>

BAG MINI DILUTER LIMITATIONS

Many of the limitations of a CVS can be eliminated by using a partial flow sampling system, such as a bag mini diluter (BMD), which maintains a constant dilution factor of 6 at all exhaust flows. Testing a PHEV still poses measurement issues with a BMD, because the internal combustion engine may not run long enough during a test for the BMD to acquire a volume of exhaust gas sample sufficient for the gas analyzers to read accurately. If the ICE runs for only 10% of the FTP test time, the BMD will generally acquire only 10% of the expected sample bag volume. Our gas analyzers require 16 liters of sample at standard temperature and pressure for an accurate measurement. The ICE must operate for 50% or more of the FTP test in order for the BMD to acquire a 16 liter diluted exhaust sample

SIMULATED PHEV EXPERIMENT

A simulated PHEV test was performed using a standard chassis test cell CVS and BMD sampling system operating simultaneously [Fig. 1]. A 3.8L V6 vehicle was tested over an FTP test cycle, where the engine was turned off for all but 15 seconds of the test. This simulated the PHEV engine duty cycle observed with a PHEV. The resulting CVS Bag report [Fig. 5] shows a Fuel Economy of 64 mpg, and a net CO₂ sample concentration of 0.0298% measured with a CO₂ analyzer where full scale is 3%. We expect these CVS results to exhibit poor accuracy. The calculated dilution factor is estimated to be about 50% low [Fig. 2], and the CO₂ analyzer measurement errors are expected to be around 30% of the sample concentration in this test. Both the DF and the CO₂ concentration errors directly affect the fuel economy result, so we expect the 64 mpg result will be in error by 30% to 50%. The MiniDiluter Bag report [Fig. 6] shows a fuel economy of 156 mpg, which is nearly 100 mpg greater than the CVS result. This difference is because the BMD failed to acquire enough exhaust sample to perform a valid gas analysis. There was only 1 liter of diluted exhaust in the sample bag, and the gas analyzers require at least 16 liters to perform a valid analysis. All of the emission calculations in the MiniDiluter report are invalid because of the small bag sample.

<figures 5, 6 here>

ACTUAL DILUTION FACTOR FOR THE CVS

The actual DF for the CVS can be calculated based on the measured vehicle exhaust volume and total CVS flow. These values are obtained from the CVS and BMD Bag Reports (Fig 7) where the CVS volume is identified as V_{mix} (ft³), and the exhaust tailpipe volume is identified as M_{d Exh Vol}. The result is (2644.56 / 9.2) + 1 = 288.4. This DF is 85% higher than the DF of 154 generated by the standard CVS calculation. This is consistent with expected DF errors that were estimated earlier [Fig 2].

HAD03624							
3.8L V6 runs ~15 seconds during FTP_505							
CVS	THC	CO	Nox	CO2	FE(mpg)	CO2	3%
grams/ph	0.7678	3.5949	0.0521	48.9302	64.3083	RANGE	0.0809
grams/mi	1.8223	8.5319	0.1236	116.1283		SAMPLE	0.0514
						AMBIENT	0.0298
						NET	
BMD	THC	CO	Nox	CO2	FE(mpg)		
grams/ph	0	1.502	0.0024	21.1085	156.3749	CO2	0.6687%
grams/mi	0	3.5847	0.0057	50.0979			
BMD-CVS	-1.8223	-4.9672	-0.1179	-66.0304	92.0666		
DF = (V _{mix} / M _{d Exh Vol}) + 1 = 2644.06 / 9.2 + 1 = 288.4						DF	154.7566
						VMIX	2644.06
						Md ex vol	9.2
						WCF	1.02

Fig 7. The Dilution Factor calculated from the tailpipe exhaust volume and total CVS volume is 288.4. The Dilution Factor calculated by the CVS was 154.8.

COMPARE KNOWN CO₂ MASS

An estimate of the actual mass of CO₂ produced by the vehicle can be based on the integrated tailpipe exhaust volume [Fig. 8]. Assuming the engine produces 13.4% CO₂, and given an exhaust volume of 9.2 cubic feet, we calculate that 86.4 grams of CO₂ was produced by the engine. Compare this to the 48.9 grams of CO₂ recovered by the CVS [Fig. 5], which is about 60% of the actual CO₂ mass injected into the CVS. The calculated fuel economy is inversely related to CO₂ mass, so 86.4 grams of CO₂ gives a calculated fuel economy of 36.3 mpg. Compare this result to the 64.3 mpg CVS value, and we see that the apparent CVS fuel economy is nearly 2 times the correct value in this test.

$$48.9 \text{ g CO}_2 \rightarrow 64.3 \text{ mpg}$$

("raw" CVS mpg)

$$86.4 \text{ g CO}_2 \rightarrow 36.3 \text{ mpg}$$

(from measured exhaust volume)

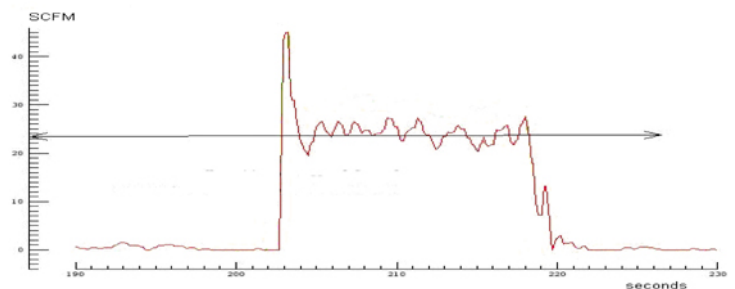


Fig 8. The tailpipe exhaust flow during the simulated PHEV test. The engine was started at 203 seconds, and stopped at 219 seconds. The exhaust flow is approximately steady at 25 scfm for 16 seconds. The integrated exhaust flow was 9.2 cubic feet.

COMPARE THE CORRECTED RESULTS

The CVS carbon dioxide mass calculation is based on the following equation:

$$\text{CVS mass} = V_{\text{mix}} \cdot \rho \cdot (C_{\text{sample}} - C_{\text{ambient}}) \cdot (1 - 1/\text{DF})$$

where V_{mix} is the total tunnel sampled volume, rho is the density, C_{sample} is the concentration of CO₂ in the sample bag, C_{ambient} is the concentration of CO₂ in the ambient bag, and DF is the CVS dilution factor.

Use of the corrected Dilution Factor, namely 288.4, when applied to the CVS CO₂ mass calculations is not a sufficient