

Evaluation and Modification of Constant Volume Sampler Based Procedure for Plug-in Hybrid Electric Vehicle Testing

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ABSTRACT

Plug-in hybrid electric vehicles (PHVs) consume both fossil fuel and grid electricity, which imposes emission testing challenges on the current constant volume sampler (CVS) test method. One reason is that in the charge depleting cycle, PHVs having all-electric range operate the engine for a small portion of the traction energy need, causing the CVS to overdilute the exhaust gas. The other reason is that the dilution factor (DF) in the EPA calculation has an error caused by ignoring the CO₂ concentration in ambient air. This paper evaluates these challenges by testing a Toyota PHV on the industry standard CVS system combined with additional continuous sampling methodology for continuous diluents, smooth approach orifice (SAO) measurement for ambient air flow, and fuel flow meter (FFM) measurement for fuel consumption. The current EPA DF can produce an error resulting in higher mass calculation. For the test car, the error for THC is in the range 0-20% on the urban dynamometer driving schedule (UDDS), and 0-75% on the highway fuel economy test (HWFET), though it is estimated that this error amounts to less than 4.7% error for non-methane organic gas (NMOG) compared to the current SULEV emission standard. For the test car, the error for CO, NO_x, and CO₂ is in the range of 0-8%, 0-3.6%, and 0-0.5%, respectively, which are negligible compared to the current SULEV emission standard. An alternative procedure is proposed for the charge depleting cycle using the continuous sampling

method to ignore the time period before the engine first starts, thereby eliminating overdilution. This technique can reduce the impact of potential gas analyzer and DF error to one third compared to the current CVS method. The FFM and CVS showed matching measurements during most portions of testing and only demonstrated discrepancy of fuel consumption measurement during the first engine start cycle. The detailed reason why the FFM measured 13 grams more CO₂ than the CVS on average is likely associated with exhaust left in the vehicle tailpipe and CVS sampling line, though more investigation is needed with future testing.

INTRODUCTION

Vehicle emission testing on the chassis dynamometer has been used since the 1960's when studies attributed a significant portion of air pollution to the automobile. At the same time, the constant volume sampler (CVS) was developed as the most robust method for determining the mass of gaseous emissions from vehicles [1]. CVS dilutes the entire tailpipe exhaust flow to a constant flow rate which is assured a critical flow venturi (CFV), and samples a proportional flow into a sample bag for measurement. In parallel, ambient air is also sampled to account for its influence on the concentration measurement in the sample bag. The compensation calculation must use a dilution factor (DF) parameter stipulated by Federal Register [2]. The procedure is outlined by the EPA in

the CFR (Code of Federal Regulations) [3]. Under the EPA's increasingly stringent emission standards, it has become challenging to accurately measure the very low level of emissions generated. Several enhancements to the CVS have improved emission measurement accuracy [4, 5].

Until 1999, all vehicles tested for emissions certification were powered solely by internal combustion engines. Since then, hybrid electric vehicles (HEVs) have been introduced to the commercial market and tested for emissions certification. HEVs have two or more prime movers, usually a petroleum fueled internal combustion engine and a secondary battery powered electric motor. HEVs have regenerative braking capability, idle-stop, and engine operating optimization to improve fuel economy, which, compared to conventional vehicles, generates less exhaust during certain emissions testing driving cycles [6]. However, the net energy output from the battery is close to zero compared to the energy output from internal combustion engine, generating the same net level of emissions in mass and volume compared to conventional vehicles, ultimately allowing HEVs to be tested the same way as conventional vehicles [7].

A plug-in hybrid electric vehicle (PHV) with all-electric range capability is able to operate exclusively with the electric powertrain until the battery is depleted because the battery is designed to be not only an energy buffer, but also the traction energy source. Consequently, a PHV can complete driving cycles without the engine running at all, or with the engine operating for only a small percentage of the cycle time. In such a scenario, the traditional CVS test method results in a sample bag filled primarily with ambient dilution air and a DF over 100; far beyond the

optimum DF range of less than 25 [7]. Over-dilution makes the emission concentration in sample bag close to that in the ambient air. Previous research on PHV emission testing questions the accuracy of current sampling technology at such a high dilution ratio [7-9]. This work proposes an improvement for the CVS system to overcome the unique PHV emission sampling challenges. Repeatable emission testing of a Toyota PHV was performed both at the Horiba test facility in Ann Arbor, Michigan, and at the Toyota Technical Center in Gardena, California.

EMISSION SAMPLING SYSTEM CONFIGURATION

Figure 1 shows the CVS-based emission sampling system configuration used for this testing. In addition to the standard CVS equipment, a smooth approach orifice (SAO) was used as a secondary DF measurement, a fuel flow meter (FFM) was used as a secondary fuel consumption measurement, and continuous sampling was used as a secondary sample gas concentration measurement.

VEHICLE EQUIPMENT

A Toyota PHV was used for the emission testing based on the proposed California Air Resource Board test procedure [10]. The vehicle has the ability to run in an all-electric mode during a standard UDDS drive cycle, and be recharged through a standard NEMA-15 120 volt outlet. The PHV was equipped with precise measurement equipment by TEST CELL B. A CVS continuous sampling system was enabled, and a Micro Motion® CMF010 coriolis flow and density meter was installed between the vehicle fuel pump and the injectors with the fuel flow and pressure control provided by the vehicle. The parameters measured are listed in Table 1.

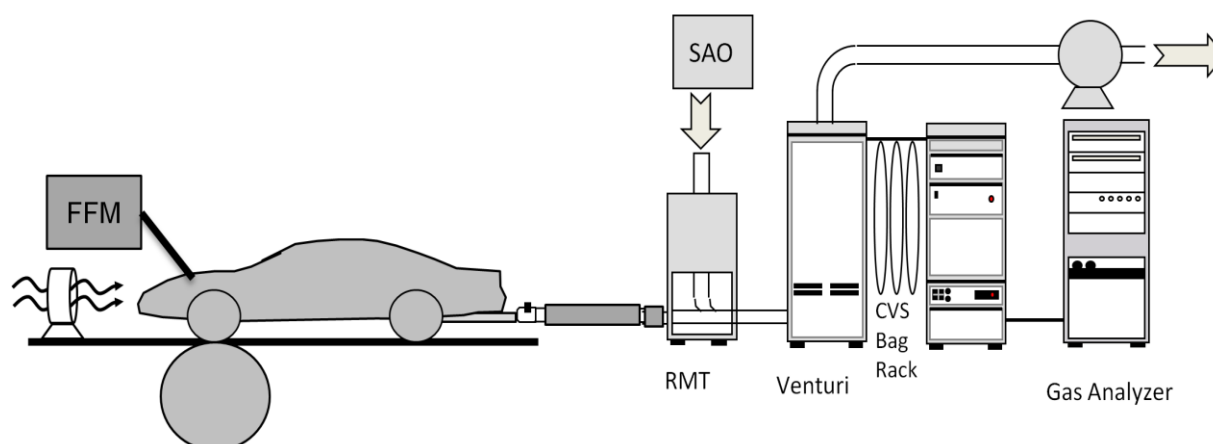


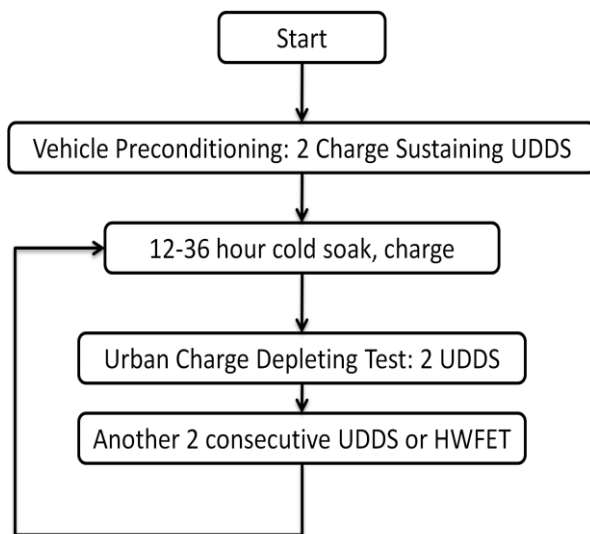
Figure 1: PHV emission testing configuration.

Table 1: List of data acquired during testing

Variable Name	Definition	Units	Frequency
SYSTEM_TIME	Time	Second	10HZ
DIL_HC	HC concentration in diluted gas	ppm	10HZ
DIL_CO	CO concentration in diluted gas	ppm	10HZ
DIL_CO ₂	CO ₂ concentration in diluted gas	ppm	10HZ
DIL_NO _x	NO _x concentration in diluted gas	ppm	10HZ
SCH_SPD	Vehicle speed	MPH	10HZ
CVS_VOL	CVS volume	cubic meter	10HZ
SAO_VOL	SAO volume	cubic meter	10HZ
AUX1_C-ENTRY	Catalyst temperature at inlet	degree C	10HZ
AUX2_C-CTR	Catalyst temperature at center	degree C	10HZ
AUX3_C-EXIT	Catalyst temperature at outlet	degree C	10HZ
AUX4_LLC	Engine temperature	degree C	10HZ
AUX5_B-REAR	Current from rear battery	Amp	10HZ
AUX6_B-FRONT	Current from front battery	Amp	10HZ
AUX7_FFM	Fuel flow	kg/h	10HZ

TEST CYCLE

Before each test was initiated, the vehicle battery was fully charged and vehicle was soaked for more than 12 hours at ambient test temperatures. According to the CARB test procedure and the all-electric range of this PHV, four consecutive UDDS tests were performed, covering charge depleting mode in UDDS1, transition between all-electric and charge sustaining in UDDS2, and charge sustaining mode in UDDS3 and UDDS4. A ten minute key-off soak was included in between each two UDDS cycles and one CVS sample bag was used for each UDDS cycle. In addition, at TEST CELL A, UDDS3 and UDDS4 were replaced by two consecutive Highway Fuel Economy Test (HWFET) cycles in some tests. Figure 2 shows the test sequence.

**Figure 2: Test Sequence.**

CVS ERROR ANALYSIS

Equation 1 shows the CVS formula used to calculate the mass of each gas in a certain test cycle. V_{mix} is the total volume flowing through the critical flow venturi (CFV); C_{sam} is the gas concentration in the emission sample bag; C_{amb} is the gas concentration in ambient sample bag; ρ is the gas density; and DF is the dilution factor theoretically defined to be the ratio between mixed volume and tailpipe exhaust volume shown in Equation 2.

Equation 1

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

Equation 2

$$DF \equiv \frac{V_{mix}}{V_{tp}}$$

DF ERROR

In the standard CVS, the exhaust flow rate cannot be measured and V_{tp} is not available directly. Alternatively, DF can also be obtained by mass and volume conservation in the mixing process as shown in Figure 3, in which C_{tp} is the average gas concentration in the vehicle exhaust during one sampling cycle and V_{amb} is the corresponding volume of dilution air.

**Figure 3: Illustration of the gas mixing process.**