Constant Volume Sampler System for Exhaust Emissions Measurement — SAE J1094a

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Scope—This SAE Recommended Practice describes uniform laboratory techniques for employing the constant volume sampler (CVS) system in measuring various constituents in the exhaust gas of gasoline engines installed on passenger cars and light trucks. The techniques described relate particularly to CVS systems employing positive displacement pumps. In some areas of CVS practice, alternate procedures are given as a guide toward development of uniform laboratory techniques.

The report includes the following sections:

1. Introduction: Development of CVS System—Constant volume sampler (CVS) systems have been used since the late 1950s. The engine exhaust to be sampled is diluted with ambient air so that the total combined flow rate of exhaust and dilution air mix is nearly constant for all engine operating conditions. The CVS system is sometimes called a variable dilution sampler. Recently constant volume sampler systems have been abbreviated PDP-CVS or CFV-CVS. The PDP-CVS system is the older system that uses a positive displacement pump to maintain a constant total flow. The CFV-CVS system uses a critical flow venturi to maintain a nearly constant total flow. Some of the newer CFV systems no longer use a heat exchanger to bring the mix of engine exhaust and dilution air to a constant temperature, but instead monitor the mix temperature continuously in order to calculate the total flow accurately. These CFV systems are not constant volume samplers, but since they are used to measure emissions, the units are discussed here.

Hydrocarbons in the dilution air were recognized from the first as a problem in the CVS procedure. Studies were initiated on the feasibility of removing the unwanted hydrocarbons. As a result, the installation of charcoal filters in the dilution air system was chosen as the most practical solution. Charcoal does not remove any of the hydrocarbon materials, but it does stabilize their concentration level during a given test and thereby permit the collection of an accurate background sample.

2. Definitions—The following definitions apply to the term indicated as the term is used in this recommended practice.

2.1 Analytical Train—A general term to define the entire system required to sample and analyze a particular constituent in exhaust gas. Typically, this train will include items such as tubing, condenser, particulate filter, sample pump, analytical instrument, and flow meter.

2.2 Calibration Curve—Normally, the dependent variable y, the concentration of the calibration gas, is plotted as a function of the independent variable x, the instrument voltage. For nonlinear analyzers, a polynomial of degree no greater than the fourth power is used. Sufficient data points should be used to adequately define the analyzer response. The calibration curve should agree to within 1% of the measured data point.

2.3 Calibration Frequency—Analyzers should be checked at least monthly to determine if significant change has occurred in the calibration. In addition, the calibration should be verified when a problem is suspected and when large gain shifts are observed.

2.4 Calibrating Gas—A gas mixture of accurately known concentration which is used periodically to calibrate the analytical instruments. Usually, calibration requires a number of mixtures of different concentrations. Calibrating gases are usually divided into groups such as NBS standard reference gases, golden standards, primary standards, and working gases. The naming of the working gases should be traceable to the NBS standard reference gases.

2.5 Chassis Dynamometer—A laboratory power absorption unit capable of simulating to a limited degree the road operation of a vehicle. The dynamometer should possess the capability to simulate the inertia and road load power developed by a vehicle.

2.6 Chemiluminescent (CL) Analyzer—An instrument which measures nitric oxide by measuring the intensity of chemiluminescent radiation from the reaction of nitric oxide with ozone. The addition of a converter will permit the measurement of the oxides of nitrogen.

2.7 Chock—A block or wedge that prevents movement of the wheels of a vehicle.

2.8 Coastdown—The procedure used to determine the total horsepower absorbed by a dynamometer at 50 mph (80 km/h). The time required for the rolls to coast down from 55–45 mph (88–72 km/h) is observed.

2.9 Constant Volume Sampler (CVS)—A device for collecting samples of diluted exhaust gas. The exhaust gas is diluted with air in a manner that keeps the total flow rate of exhaust gas and dilution air constant throughout the test. The device permits measuring mass emissions on a continuous basis and also, through use of a second pump, allows a proportional mass sample to be collected.

2.10 Converter—A thermal or catalytic reaction device which usually precedes the chemiluminescent analyzer and converts oxides of nitrogen to nitric oxide. The converter may also convert ammonia and other nitrogen containing compounds to nitric oxide.

2.11 Counter—A mechanical and/or electrical device that totalizes the number of revolutions of the CVS for each test phase.

2.12 Curve Fitting—See calibration curve, Lagrangian fit, polynomial fit.

2.13 Detector—That component in an analytical instrument which is sensitive to a particular gas.

2.14 Dilution Air—Ambient air which is passed through filters to stabilize the background hydrocarbon concentration and which is used to dilute the vehicle exhaust.

2.15 Dilution Factor—Based on stoichiometric equation for fuel with composition $CH_{1.85}$, the dilution factor is defined as:

$$\frac{13.4}{CO_2 + (HC + CO) \times 10^{-4}}$$

where CO_2 is equal to the concentration in dilute exhaust sample in mole percent, HC in ppm carbon equivalent, and CO in ppm corrected for water vapor and CO_2 extraction.

2.16 Dilution Ratio—The ratio of CVS volume to exhaust volume, usually found by dividing the undiluted exhaust CO_2 concentration by the dilute CO_2 concentration.

2.17 Driver Aid—An instrument used to guide the vehicle driver in operating the vehicle in accordance with the specified acceleration, deceleration, and cruise operating modes of a specific driving procedure.

2.18 Exhaust Emissions—Substances emitted to the atmosphere from any opening downstream from the exhaust port of a motor vehicle engine.

2.19 Fifth Wheel—A calibrated wheel, axle and tachometer generator assembly that can be used to determine the true speed of the vehicle (by towing the wheel assembly), or true speed of the dynamometer rolls (by permitting the rolls to drive the fifth wheel assembly).

2.20 Filter Cell—That portion of the NDIR instrument which is filled with a particular gas in order to reduce interference signals.

2.21 Flame Ionization Detector (FID)—A hydrogen-air flame detector that produces a signal proportional to the mass flow rate of hydrocarbons entering the flame per unit time.

2.22 Hang-Up—The absorption-desorption of sample (mainly higher molecular weight hydrocarbons) from the surfaces of the sample system that can cause instrument response delay and lower concentration at the analyzer, followed by higher readings in subsequent tests.

2.23 Heat Exchanger—An air-to-air or air-to-water heat exchanger, which is used to control the temperature of the dilution air-exhaust gas mixture.

2.24 Horsepower

2.24.1 ABSORBED HORSEPOWER—Total horsepower absorbed by the absorption unit of the dynamometer and by the frictional components of the dyna-

The ϕ symbol is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. If the symbol is next to the report title, it indicates a complete revision of the report.

mometer.

2.24.2 ABSORBED HORSEPOWER AT 50 MPH (80.5 KM/H) ROAD LOAD—The dynamometer setting values for various inertia weight vehicles published in the Federal Register.

2.24.3 FRICTIONAL HORSEPOWER—Horsepower absorbed by the frictional components of the dynamometer.

2.24.4 INDICATED HORSEPOWER—Horsepower values indicated by the horsepower meter of the dynamometer.

2.24.5 INDICATED HORSEPOWER AT 50 MPH (80.5 KM/H) ROAD LOAD—The dynamometer setting values, determined by calibration, that correspond to the dynamometer setting values published in the Federal Register.

2.25 **Inertia Weights**–A series of rotating disks used on a chassis dynamometer to simulate to the nearest 125, 250, or 500 lb (57, 113, or 227 kg) increments of the test weight of a vehicle during accelerations and decelerations. The inertia weights have no effect during steady states.

2.26 **Lagrangian Fit**—A computer technique used to interpolate polynomial curves generated from a set of data points (calibration points). N data points are required to generate a curve to $N - 1$ deg. A feature of this technique is that the interpolated curve goes through each data point exactly.

2.27 **Laminar Flow Element (LFE)**—A flow rate measuring device that has a linear relationship between flow rate and pressure drop.

2.28 **Light-Duty Vehicle**—A motor vehicle designed for transportation of persons or property on a street or highway and weighing 6000 lb (2722 kg) gvw or less.

2.29 **Loaded Vehicle Weight**—The curb weight of a light-duty vehicle plus 300 lb (136 kg).

2.30 **Mixing Device**—A device that is used in the main flow stream of a CVS to promote mixing of the exhaust gas with the dilution air.

2.31 **Mode**—A particular operating condition (for example, acceleration, cruise, deceleration, or idle) of a test cycle.

2.32 **Nondispersive Infrared (NDIR) Analyzer**—An instrument to determine carbon monoxide, carbon dioxide, nitric oxide, and hydrocarbons in exhaust gas. Now primarily being used for carbon monoxide and carbon dioxide determinations.

2.33 **Normalizing Gas (Span Gas)**—A single calibrating gas blend routinely used in calibration of each analytical instrument.

2.34 **Optical Filter**—That portion of the NDIR instrument which eliminates wavelength regions where interference signals are obtained.

2.35 **Oxides of Nitrogen**—The sum total of the nitric oxide and nitrogen dioxide in a sample expressed as nitrogen dioxide.

2.36 **Ozonator**—An electrical device that generates ozone from oxygen or air.

2.37 **Parts per Million Carbon**—The mole fraction of hydrocarbon measured on a methane equivalence basis.

2.38 **Polynomial Fit**—A technique of generating a calibration curve from a set of points.

2.40 **Positive Displacement Pump**—A CVS blower, gas pump, or constant displacement pump that delivers a metered amount of air per revolution measured at inlet conditions.

2.41 **Probe**—A sample line inserted into the exhaust stream of a vehicle or engine in such a manner as to obtain a homogeneous or well-mixed exhaust sample.

2.42 **Reference Cell**—That portion of the NDIR instrument that is usually filled with air (sometimes nitrogen) and provides the reference signal to the detector.

2.43 **Remote Filter Box**—Particular CVS design that has the dilution air filters and mixing chamber housed in a separate cabinet which can be located close to the tailpipe of the test vehicle.

2.44 **Sample Cell**—That portion of the NDIR instrument which contains the flowing sample gas.

2.45 **Stratification**—Variation in concentration of a sample stream when samples are taken at different points on a cross section of the mixed CVS stream just ahead of the CVS positive displacement pump.

2.46 **Tailpipe Pressure**—The static pressure measured at the tailpipe when a CVS is connected to a test vehicle.

3. Test Facilities and Equipment

3.1 **Sampler**—CVS systems can exist in a variety of physical configurations, but all of them permit measuring emissions of vehicles.

3.1.1 Basic Equipment–The principal component of a CVS is either the positive displacement pump (PDP) of the older models or the critical flow venturi (CFV) of more recent designs. The positive displacement pump consists of a pair of symmetrical rotating, two-lobe impellers driven in opposite directions and encased by a housing. A critical flow venturi CVS has a CVS compressor unit that is used in conjunction with the critical flow venturi. Fig. 1 shows a sketch of a CFV-CVS.

3.1.1.1 A dilution air filter system consisting of a particulate (dust) filter, a charcoal filter, and a second particulate filter which removes airborne particles, stabilizes hydrocarbons, and traps charcoal particles.

3.1.1.2 A flexible coupling to the tailpipe of the test car brings in undiluted exhaust gas to the mixing chamber.

3.1.1.3 A mixing chamber combines the automotive exhaust from the test car and the dilution air into a homogeneous (nonstratified) mixture.

3.1.1.4 A heat exchanger is used to control the temperature of the exhaust gas dilution air mixture. The heat exchanger should be capable of controlling the temperature of the dilute exhaust gas $\pm 10°F$ ($5.6°C$) during testing. In some models of CVS, a temperature controller regulates both the flow of cooling water or hot water (from a hot water heater) through the heat exchanger to control mixture temperature. In other models of CVS, the dilution air is preheated so that the temperature controller regulates the flow of cooling water through the heat exchanger in order to control the mixture temperature.

3.1.1.5 A secondary heater system maintains the heat exchanger at a temperature to prevent water condensation.

3.1.1.6 A sampling system transfers the exhaust-air mixture from the positive displacement pump inlet to the bag at a constant flow rate. The minimum sample flow rate should be 10 ft³/h (0.28 m³/h). Each sampling system consists of fiberglass filter, a diaphragm type pump, a flow control valve, and a flow meter or other gas measuring device. All of the surfaces in contact with the sample air or air-gas mixture are stainless steel or other nonreactive material.

3.1.1.7 A similar sampling system collects dilution air from a point just downstream of the air filter and transfers it to a separate bag.

3.1.1.8 An evacuation and purge pump to remove the excess sample from the bags and purge the bags with clean air.

3.1.1.9 A set of bags (sample and background) and appropriate controls is needed for each of the test phases.

3.1.2 SUPPLEMENTARY EQUIPMENT—In addition to the above basic equipment, the following items can be added for operating convenience:

3.1.2.1 A muffler located after the CVS pump to reduce the noise.

3.1.2.2 A four-speed motor, transmission, or other suitable means for driving the positive displacement pump will permit a choice of different dilution ratios.

3.1.2.3 An optional remote control operating station containing the counter, the operations logic module, and the various control function switches and indicator lights that permit convenient operator control at a distance from the CVS console.

3.1.2.4 Optional modal analysis at the analytical bench during the filling of the bag is made possible through the use of a separate sampling probe(s). One probe is used if continuous modal analysis is conducted using undiluted exhaust.[1] The second probe in this case is used to monitor diluted CO_2 which is used as a tracer gas to determine engine flow. Tail pipe sample should either be returned to the CVS bulk stream if the amount withdrawn is a significant fraction of total exhaust flow (greater than 1%), or the loss in tail pipe sample should be corrected mathematically.

3.2 **Analysis Instrumentation—Bag Analysis**

3.2.1 SCHEMATIC—Fig. 1 is a sketch of the sampling and analysis train that is a typical flow schematic for the bag analysis of engine exhaust using the CVS.

3.2.2 COMPONENT DESCRIPTION—The following components are suggested for the CVS bag sampling and analytical systems for the analysis of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), carbon dioxide (CO_2), and oxygen (O_2):

3.2.2.1 NDIR analyzers for measurement of CO and CO_2 with cells of appropriate length for concentration ranges being measured. Typical ranges are shown in Table 1.

3.2.2.2 Chemiluminescent (CL) NO analyzer or equivalent NDIR NO analyzer are both equipped with a bypass and NO_2 to NO converter for the measurement of NO_X with concentration range selection as shown in Table 1.

3.2.2.3 FID for measurement of HC. The instrument employed should be capable of measuring HC for ranges shown in Table 1.

3.2.2.4 Oxygen analyzer for measurement of O_2 with range of measurement as shown in Table 1.

3.2.2.5 Values V_{12} used to direct the sample or purge air to the analyzers.

3.2.2.6 Valves V_1, V_4, V_8 (optional). V_9, and V_{10} used to direct the sample, zero gas, or span gas streams to the analyzers.

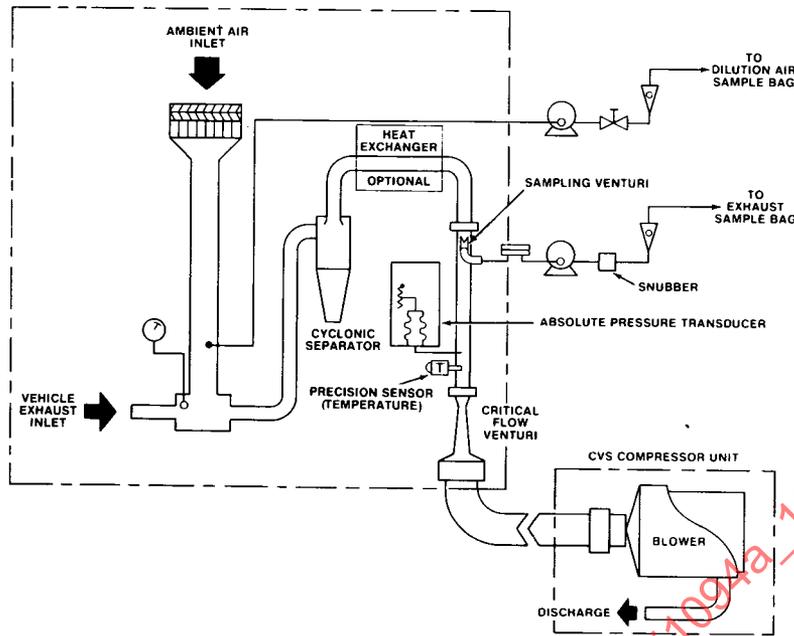[1] Two probes are required if continuous modal analysis is conducted using undiluted exhaust.

FIG. 1—CFV - CVS SAMPLER UNIT

3.2.2.7 Filters F_1 and F_2 for removing particulate materials from the sample prior to analysis. A glass fiber filter of at least 7 cm diameter is suitable.

3.2.2.8 Pumps P_1 and P_2 to move the sample through the system. Pumps should have stainless steel or aluminum chambers with diaphragms and valves made from or covered with an inert material, such as Teflon. Free air capacity should be approximately 40 ft^3/h (1.1 m^3/h). Pumps P_3 for bypass flow of chemiluminescent analyzer and vacuum pump P_4 (optional depending upon the design of the chemiluminescent analyzer) for evacuation of the chemiluminescent reactor chamber.

3.2.2.9 Needle valves N_1, N_4, N_7, and N_{11} to regulate sample gas flow to the analyzers.

3.2.2.10 Needle valves N_2, N_5, N_8, and N_{12} to regulate span gas flow to the analyzers.

3.2.2.11 Optional valve V_9 used to direct CO_2 span gas through the water bubbler for checking the performance of drier and absorber system or to check the H_2O and CO_2 interference rejection characteristics of the CO analyzer. Needle valve N_{20} is used to regulate CO_2 flow.

3.2.2.12 Needle valves N_3, N_6, N_9, N_{13}, and N_{15} to regulate zero gas flow to the analyzers.

3.2.2.13 Flow meters FL_1, FL_2, FL_3, and FL_4 to indicate span gas, zero gas, and sample flow to the analyzers.

3.2.2.14 Water trap T_1, if necessary, to partially remove water and a valve N_{14} to allow the trap to be drained.

3.2.2.15 Optional[2] sample conditioning columns CR_1 and CR_2 containing ascarite to remove CO_2 from the CO analysis stream, and WR_1 and WR_2 containing indicating $CaSO_4$ or indicating silica gel to remove the remainder of the water. Equivalent drying techniques such as diffusion driers may be used.

3.2.2.16 Optional valves V_6 and V_7 to permit switching from exhausted absorbing columns to fresh columns.

3.2.2.17 Optional water bubbler W_1 to allow saturation of CO_2 span gas to check the efficiency of the absorbing columns in the CO system.

3.3 Analysis Instrumentation—Modal Analysis (Undiluted Exhaust Gas)

3.3.1 GENERAL—Fig. 3 is a schematic drawing of the sampling and analysis train that is recommended for the modal analysis of spark ignition engine exhaust using the CVS. The system is very similar to that required for bag

[2]The criteria for CO interference by CO_2 and water is given in the Federal Register, Vol. 39, No. 101, May 23, 1974: "A CO instrument will be considered to be essentially free of CO_2 and water vapor interference if its response to a mixture of 3% CO_2 in N_2, which has been bubbled through water at room temperature (68–86°F), produces an equivalent CO response, as measured on the most sensitive CO range, which is less than 1% of full scale CO concentration on instrument ranges above 300 ppm CO or less than 3 ppm on instrument ranges below 300 ppm CO."
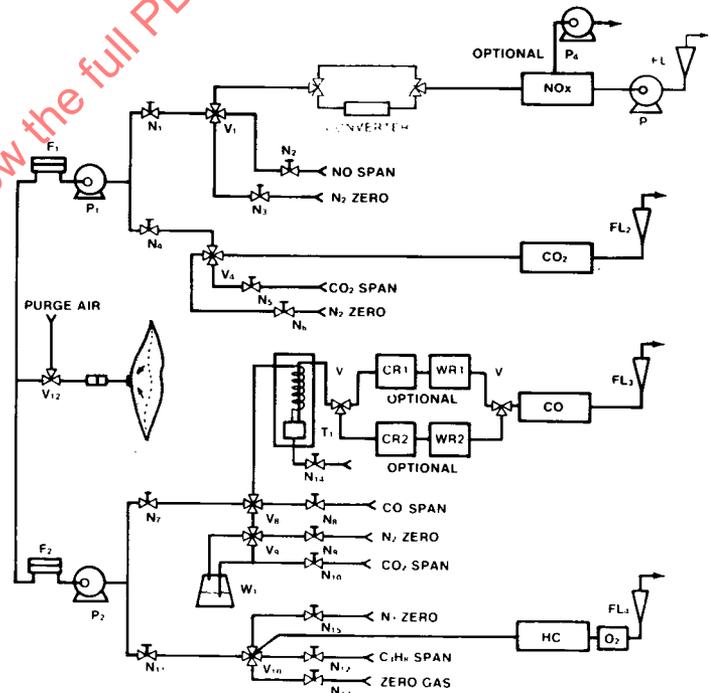

FIG. 2—BAG SAMPLING AND ANALYSIS TRAIN

analysis, with the exception that water traps are required on all instrument sampling streams and an additional CO_2 analyzer is required. In addition, instruments of only approximately $\frac{1}{10}$ the sensitivity of those used for bag analysis are needed. This system is based upon measuring continuously undiluted exhaust gas concentrations of HC, CO, NO_x, and CO_2 and the diluted exhaust CO_2 concentration.

The undiluted and diluted exhaust CO_2 concentrations are used to calculate a dilution factor which, in conjunction with the total diluted volume, can be used to calculate the vehicle exhaust volume. With the calculated exhaust volume and the undiluted exhaust concentrations, the modal mass emissions of each pollutant can be calculated as described in paragraph 5.2.2.

3.3.2 COMPONENT DESCRIPTION—The following components are recommended for the analytical systems for the modal analysis of CO, HC, NO$_x$, CO$_2$, and O$_2$.

3.3.2.1 NDIR analyzers for measurement of CO and CO$_2$ with cells of appropriate length for the concentration ranges being measured. Typical ranges are shown in Table 1.

3.3.2.2 The Co$_2$ analyzer for the measurement of CO$_2$ in the diluted exhaust stream can be modified to the extent that the reference cell is replaced with a second sampling cell through which dilution air is passed during sampling. This feature will automatically correct the measured CO$_2$ in the diluted exhaust for the amount of CO$_2$ in the dilution air.

3.3.2.3 Chemiluminescent (CL) NO analyzer equipped with a bypass and a NO$_2$ to NO converter for the measurement of NO$_x$ with the concentration range selection as shown in Table 1.

3.3.2.4 FID for measurement of HC. The instrument should be capable of measuring HC for the ranges shown in Table 1.

FIG. 3—MODAL SAMPLING AND ANALYSIS TRAIN

TABLE 1—TYPICAL LOW RANGES FOR ANALYSIS OF HC, CO, CO$_2$, NOx, AND O$_2$ IN SPARK IGNITION ENGINE EXHAUST

Component	Ranges	
	CVS Bag Sample	Undiluted Exhaust Gas
HC	0–30 ppmC	0–500 ppmC
CO	0–100 ppm	0–0.3%
NOx		
1975	0–250 ppm	0–2500 ppm
1976	0–10 ppm	0–250 ppm
CO$_2$	0–2.0%	0–15%
Dilute CO$_2$	—	0–5%
O$_2$	0–21%	0–10%

3.3.2.5 Oxygen analyzer for measurement of O$_2$ with range of measurement shown in Table 1.

3.3.2.6 Valves V_1 and V_{13} used to direct the sample of purge air to the analyzers or to purge air to the blowout traps.

3.2.2.7 Valves V_2, V_4, V_9, V_{10}, V_{14}, and V_{16} used to direct the sample, zero gas, or span gas streams to the analyzers. Valve V_4 is used to direct the span gas to the O$_2$ sensor.

3.3.2.8 Filters F_1, F_2, F_3, and F_4 for removing the particulate from the sample prior to analysis. A glass fiber type of at least 7 cm in diameter is suitable.

3.3.2.9 Pumps P_1, P_2, P_3, and P_4 to move the sample through the system. Pump P_5 for bypass flow of the chemiluminescent analyzer and vacuum pump P_6 (optional dependent on design of chemiluminescent analyzer) for evacuation of the chemiluminescent reactor chamber. Pumps should have stainless steel or aluminum chambers with diaphragms and valves made from or covered with an inert material, such as Teflon. Free air capacity should be approximately 40 ft^3/h (1.1 m^3/h).

3.3.2.10 Needle valves N_2, N_3, N_{10}, N_{12}, N_{17}, and N_{18} to regulate sample gas flow to the analyzers.

3.3.2.11 Needle valves N_4, N_6, N_{14}, N_{19}, and N_{22} and to regulate span gas flow to the analyzers.

3.3.2.12 Optional valve V_{21} used to direct CO$_2$ span gas through the water bubbler for checking the performance of the absorbers in the CO analyzer stream. Needle valve N_{23} (optional) is used to regulate CO$_2$ flow.

3.3.2.13 Needle valves N_5, N_7, N_{13}, N_{15}, N_{20}, and N_{21} to regulate zero gas flow to the analyzers.

3.3.2.14 Flow meters FM_1, FM_2, FM_3, FM_4, FM_5, and FM_6 to indicate span gas, zero gas, and sample flow to the analyzers.

3.2.2.15 Water traps T_1, T_2, and T_3 to partially remove water and valves N_{24}, N_{25}, and N_{26} to allow the traps to be drained.

3.2.2.16 Optional sample conditioning columns CR_1 and CR_2 containing ascarite to remove CO$_2$ from the CO analysis stream, and WR_1 and WR_2 containing indicating CaSO$_4$ or indicating silica gel to remove the remainder of the water. Ascarite produces water when it removes CO$_2$ from the stream. Equivalent drying techniques such as diffusion driers may be used. The volume of the conditioning columns must be sufficient to be effective for the duration of the test. Some operational ranges for continuous analysis may not require water and CO$_2$ removal. Some new CO instruments do not have water or CO$_2$ response.

3.3.2.17 Optional valves V_{19} and V_{20} to permit switching from the exhausted absorbing columns to fresh columns.
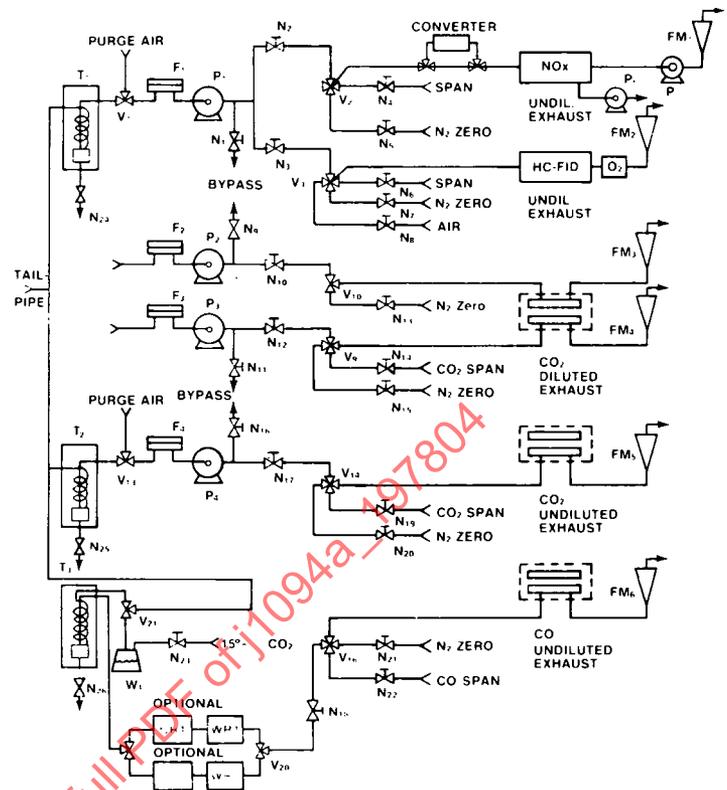
3.3.2.18 Optional water bubbler W_1 to allow saturation of CO$_2$ span gas to check the efficiency of the absorbing columns in the CO system.

3.3.2.19 Needle valves N_1, N_9, N_{11}, and N_{16} to regulate the bypass sample flow.

3.4 Instrument Operating Procedures—Follow the instrument manufacturer's start-up and operating procedure for the particular type instrument being used. In addition, the following minimum calibration and instrument checks should be included:

3.4.1 INITIAL—The following instrument checks should be accomplished prior to making emission measurements with the instruments:

3.4.1.1 *Optimize FID Response*

(a) Set burner fuel and air settings as prescribed by the manufacturer. Present burner fuel composition now recommended is 60% He, 40% H$_2$. However, best composition for burner fuel is now being investigated. Ignite the burner and set sample flow. Wait until the analyzer stabilizes before proceeding. Optimize the FID as suggested in SAE Procedure J254.

(b) Determine the optimum burner fuel flow for maximum response. A blend of 60% He and 40% H$_2$ is recommended for use as the burner fuel. The use of other fuels could produce a correlation problem. Introduce propane in N$_2$ at a concentration level of approximately 300 ppmC for undiluted gas analysis and propane in air for bag analysis. Vary the burner fuel flow to obtain the peak response. Normally, there is a plateau in the region of peak response. Select a flow in this region which results in the least variation in response with minor fuel flow variations.

(c) Determine optimum airflow. Set the burner fuel flow as determined in paragraph 3.4.1.1(b) and vary airflow to obtain maximum response. If the airflow is too high, excessive noise may result.

(d) If the airflow is significantly different from that used in paragraph 3.4.1.1(b), repeat step (b) with the new airflow.

3.4.1.2 *Determine Oxygen Response of FID Analyzer*—Variations in the oxygen content of the sample can affect the FID response. This effect must be determined and minimized.

(a) CVS bag analysis

(1) Set flows as determined in paragraph 3.4.1.1 and ignite the burner. Wait for stabilization. Normally, the burner is operated continuously to avoid the stabilization problem.

(2) Zero the analyzer on HC free air.

(3) Determine the oxygen response by introducing propane gas at a concentration of approximately 30 ppmC in the following diluents: 100% N$_2$,

95% N_2/5% O_2, 90% N_2/10% O_2, 85% N_2/15% O_2, and 100% air.

(4) Using the propane in the air gas as the baseline for no O_2 correction, plot a curve of the oxygen correction factor versus the percent O_2 in the sample:

$$O_2 \text{ correction factor} = 1.0 - \frac{(A - B)}{B}$$

where: A = HC response in N_2/O_2 blends
B = HC response in air

(5) Check the effect of O_2 using a propane concentration of 50 ppmC. If it is significantly different from the 30 ppmC correction data, establish a curve and apply the O_2 correction on a prorated basis as a function of HC concentration.

(6) If the O_2 correction factor is less than 0.96 over the normal O_2 range encountered in CVS sampling, see paragraph 3.5.2.

(7) It is recommended that a different detector be obtained if the oxygen correction factor is less than 0.90 for the O_2 range found in CVS samples.

(b) Modal Analysis—Undiluted Exhaust Gas

(1) Set flows as determined in paragraph 3.4.1.1 and ignite the burner. Wait for stabilization. Normally, the burner is operated continuously to avoid the stabilization problem.

(2) Zero the analyzer with N_2.

(3) Determine the oxygen response by introducing propane gas at a concentration of approximately 300 ppmC in the following diluents: 100% N_2, 95% N_2/10% O_2, 85% N_2/15% O_2, and 100% air.

(4) Using the propane in N_2 (0% O_2) as the baseline for no O_2 correction, plot a curve of the oxygen correction factor versus the percent O_2 in the sample, where:

$$O_2 \text{ corr factor} = \frac{\text{HC response with propane in } 100\% \ N_2}{\text{HC response with propane in } O_2 \text{ blends}}$$

(5) If the O_2 correction factor is greater than 1.05 over the range of 0–10% O_2, see paragraph 3.5.2.

(6) It is recommended that a different detector be obtained if the oxygen correction factor is greater than 1.10 for the O_2 range found in the undiluted exhaust gas samples.

3.4.1.3 Determine Linearity of FID Response

(a) Set up the FID as determined in paragraphs 3.4.1.1 and 3.4.1.2. Set the sample flow rate at a low value (approximately 5 ml/min) consistent with good signal to noise ratio.

(b) Using propane in air, or N_2, vary the concentration of HC over the expected HC range. If the response is linear, a sample linear calibration factor can be used. If the response is not linear, prepare a calibration curve.

3.4.1.4 *Optimize Performance of NDIR*—After adjusting the analyzers for optimum performance using the manufacturer's recommended procedures, a calibration curve must be generated for the ranges of the instrument that will be used. All emission measuring instruments are comparative devices. The generation of the calibration curves using standard gases (paragraph 3.5.1) should be as accurate as possible. Since many analyzers are connected to computers, a variety of curve-fitting techniques are being used. No specific technique will be recommended here. Polynomial and Lagrangian curve

FIG. 4—FLOW SCHEMATIC OF CONVERTER EFFICIENCY ANALYSIS SYSTEM

fitting techniques are widely used. It is recommended to examine carefully an accurate plot of the calibration curve to verify that a smooth curve was generated, rather than a curve that has only high correlation at the data points.

3.4.1.5 Optimize Performance of Chemiluminescence NO Analyzer—Using the manufacturer's recommended procedures, adjust the analyzer for optimum performance. In addition, determine the efficiency of the NO_2 to NO converter, at the converter temperature recommended by the manufacturer, using the flow system shown schematically in Fig. 4. A suggested procedure is given in Appendix A.

If the converter efficiency is below 90%, the converter temperature should be increased and the efficiency rechecked. Converter temperature should be set at a minimum required for near 100% conversion efficiency.

Care must be used to prevent condensation due to pressure buildup in the NOx sample train between the sample pump and the analyzer. This has been found to be a critical area of the NOx sample train, since condensation causes a lowering of the measured NOx concentration and, therefore, an incorrect NOx emission measurement.

3.4.2 MONTHLY—The following checks are to be made monthly or more frequently if there is any doubt regarding the accuracy of the analyses.

3.4.2.1 Calibrate the NDIR analyzers using the same gas flow rates as when sampling exhaust.

(a) Allow 2 h warmup of analyzers.

(b) Tune analyzer.

(c) Set zero and span using prepurified N_2 and the 100% range calibration gas.

(d) Recheck zero and repeat step 3.4.2.1(c), if necessary.

(e) Calibrate each analyzer with calibrating gases that are approximately 15, 30, 45, 60, 75, and 90% of each range used. The concentration of the standard gases should be known with at least ±2% accuracy. If the analyzer proves to be non-linear, use an eight point calibration with a set of calibration gases spread approximately uniformly over the analyzer range in question.

(f) Compare values with previous curves. Any significant change reflects some problem in the system. Locate and correct the problem and recalibrate.

3.4.2.2 Check FID analyzer O_2 response and HC response.

(a) Ignite the burner and then set the fuel, air, and sample flow rates as determined in paragraphs 3.4.1.1 and 3.4.1.2.

(b) Introduce HC free air zero gas (CVS bag analysis) or N_2 (Modal-undiluted exhaust gas analysis) and zero analyzer.

(c) Check O_2 effect on the response by introducing the calibration gases of propane in air, propane in N_2, and propane in 90% N_2/10% O_2.

(d) Compare the O_2 response values with the previous curves. Any significant change ($\pm 10\%$) indicates a change in the burner operating characteristics. Check the burner system and measure the flows. If the change in the response cannot be resolved, establish a new O_2 response curve as per paragraph 3.4.1.2.

(e) Check the calibration curve or response data as per paragraph 3.4.1.3.

3.4.2.3 Calibrate chemiluminescent analyzer using same flow rates as when sampling exhaust.

(a) Set the sample flow and oxygen flow to the recommended settings.

(b) Turn the ozone generator on and allow a 10 min warmup period.

(c) Using nitrogen, zero the meter on the most sensitive range or the range to be used by means of the dark current suppression adjustment.

(d) Set the span, using 100% range calibration gas on the range to be used.

(e) Calibrate the analyzer with gases blended in N_2 that are approximately 25, 50, 75, and 100% of the range being used.

(f) Check the values with the previous curves. Any significant change reflects some problem in the system. Locate and correct the problem and recalibrate.

(g) Caution. The correct standby position for the NOx converter is dependent on the converter type. See manufacturer's instructions.

(h) Caution. Some NO_2 to NO converters can be rendered useless for many hours if they are allowed to sample exhaust gas (even momentarily) from over rich vehicles where high levels of CO, low levels of O_2, and free H_2 are produced.

3.4.3 WEEKLY—Check the converter of the chemiluminescent analyzer using the procedure outlined in paragraph 3.4.1.5.

3.4.4 DAILY—Prior to daily testing carry out the following:

3.4.4.1 *NDIR Analyzers*—Normally, power is left on the NDIR analyzers continuously. Only the chopper motors are turned off. In some cases, more dependable performance has been achieved by leaving the chopper motors on.
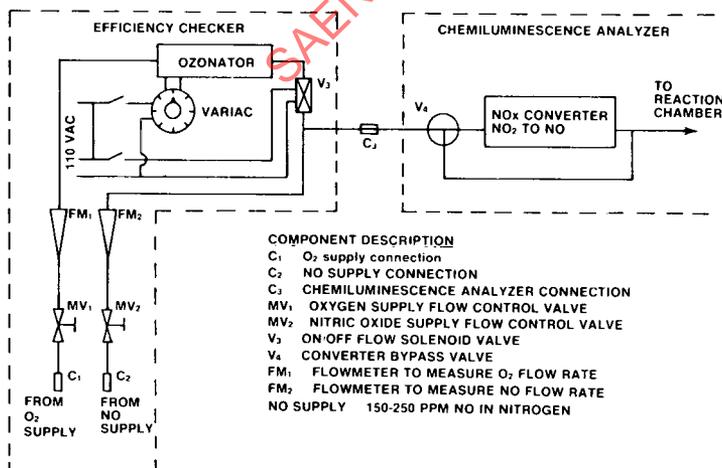
(a) Zero on prepurified N_2.

(b) Introduce span gas and set the gain to match the calibration curves. Use the same flow rate for calibration, span gas, and exhaust gas to avoid correction for the sample cell pressure change. Use span gas having a concentration of the constituent being measured that will result in 75–95% of full-scale deflection. If the gain has shifted significantly, check the tuning; if necessary, check the calibration.

(c) Check nitrogen zero and repeat steps 3.4.4.1(a) and 3.4.4.1(b), if necessary.

(d) Repeat steps 3.4.4.1(a) through 3.4.4.1(c) prior to each exhaust gas analysis.

(e) Span and zero should be rechecked after bag measurements.

3.4.4.2 *FID Analyzer*

(a) Ignite the burner and then set the fuel, air, and sample flow rates as determined in paragraphs 3.4.1.1 and 3.4.1.2.

(b) Introduce zero gas (HC-free air for CVS analyzers, N_2 for undiluted exhaust gas analyzers) and zero analyzer.

(c) Introduce HC span gas (propane in HC-free air for CVS analyzers, propane in N_2 for undiluted exhaust gas analyzers) of appropriate concentration to result in a response of at least 50% of full-scale on the range anticipated for use. If the calibration curve and span value disagree adjust the span potentiometer of the FID. Sample flow for zero and span must be the same as that used for analyzing exhaust sample.

(d) Repeat steps 3.4.4.2(a) through 3.4.4.3(c) prior to each exhaust gas analysis.

(e) Span and zero should be rechecked after bag measurements.

3.4.4.3 Chemiluminescent Analyzer—Normally power is left on continuously. Operate converter in standby mode as recommended by the manufacturer. Vacuum pumps are normally kept on continuously on those model analyzers using vacuum pumps. The ozonator should not be left on continuously for safety reasons. Vacuum pump and ozone problems can be minimized by replacing the pump oil with perfluorinated polyether fluid.

(a) Turn on the sample pumps.

(b) Set O_2 (in some models air is used) and sample flows using nitrogen.

(c) Turn on ozone generator and allow a 10 min warmup.

(d) With the converter in the NO mode, adjust the dark current suppression to zero the meter on the most sensitive range or the range to be used, using prepurified N_2.

(e) Introduce span gas and set gain to match the calibration curves. Use a span gas having an NO concentration that will result in 75–95% of full-scale deflection.

(f) Check dark current suppression and repeat steps 3.4.4.3(d) and 3.4.4.3(e) if necessary.

(g) Span and zero should be rechecked after bag measurements.

3.4.4.4 *Oxygen Analyzer*

(a) Introduce oxygen-free nitrogen and set zero.

(b) Introduce air and set O_2 span. This is usually done concurrently when setting the zero on the FID analyzer.

(c) Sample flow for zero and span must be the same as that used when analyzing exhaust gas samples.

3.5 Supplementary Discussion

3.5.1 Calibration Gases—There are several suppliers of calibration gases in the ranges used in this procedure. These can be obtained with an analysis accuracy of ±2% or better. Stated gas analysis accuracies should be explicitly defined in terms of traceability to NBS standard reference gases or applicable gravimetric standards. It is recommended that all working gases be renamed using NBS standard reference gases or in-house primary reference gases. If a reference gas cylinder value does not fall on a smooth calibration curve, then that cylinder must not be used.

The CO and CO_2 gas can be purchased as a mixture in nitrogen. NO calibrating gas should be diluted with oxygen-free nitrogen and must not be mixed either with CO or CO_2. Propane calibrating gases are purchased with HC-free air as the diluent for use in CVS bag analysis and with N_2 as the diluent for use in undiluted exhaust gas analysis.

Zero gas impurity concentration should not exceed 1 ppm for HC, 1 ppm for CO, 0.1 ppm for NO, 400 ppm (0.04%) for CO_2, and 3 ppm for H_2O.

3.5.2 REDUCING THE OXYGEN EFFECT ON RESPONSE—The oxygen correction for FID should be reduced to attain the limits described in paragraph 3.4.1.2. The oxygen effect on response for a particular FID burner design may depend upon (a) the type of burner fuel used, for example, H_2, 40% H_2/60% N_2, or 40% H_2/60% He; (b) on the sample flow rate into the burner; and (c) the air and fuel rate to the burner.

3.6 Tailpipe Connections—To obtain a good constant volume sample of exhaust gas it is imperative that no leakage, either into or out of the sampling

system, occur at the tailpipe connection between the vehicle and the CVS sampler. The CVS sampler must be provided with dual inlets to accommodate vehicles with dual exhaust systems. When a vehicle with a single exhaust is being tested, the second sampler inlet must be tightly capped to prevent leakage.

Piping between the sampler and the vehicle should be kept to a minimum length and be of adequate diameter. (See section 4 for more detail on this subject.) The actual connection between the vehicle tailpipe and the flexible tubing of the CVS can be made in one of two ways:

(a) A flanged fitting such as a Marmon coupling. One end of this coupling is welded to the flexible piping from the CVS and a mating section is welded to the exhaust pipe(s) of each vehicle to be tested.

(b) A silicone rubber boot clamped to the exhaust pipe and inlet plumbing to the CVS.

The first method, a flanged fitting, should be used whenever possible. However, when fittings cannot be welded to each vehicle to be tested, the silicone boot alternative has to be used. The main drawback of the silicone boot is that the hot exhaust gas causes rapid deterioration of the silicone. When vehicles with advanced control devices are tested, the very hot exhaust gases produced by these systems may cause the boot to crack internally after a single test.

3.7 Chassis Dynamometer

3.7.1 PROCEDURE FOR DYNAMOMETER ABSORBED HORSEPOWER CALIBRATION—The following procedure describes one method for determining the absorbed horsepower of a chassis dynamometer. The measured absorbed horsepower includes the dynamometer frictional horsepower as well as the power absorbed by the power absorption unit. The dynamometer is driven above the test speed range to 60 mph (96 km/h). The device used to drive the dynamometer (in most cases a vehicle) is then disengaged from the dynamometer and the roll(s) allowed to coast down. The kinetic energy of the system is dissipated by the dynamometer friction and absorption unit. This method neglects the variations in roll bearing friction due to the drive axle weight of the vehicle and also neglects the variations in friction due to different inertia weights. The difference in coastdown time of the free (rear) roll relative to the drive (front) roll may be neglected in the case of dynamometers with paired rolls.

3.7.1.1 *Equipment*

(a) Fifth wheel, tachometer generator, or other device to measure the speed of the front roll.

(b) Hydraulic jack or other equipment to lift vehicle's drive wheels from the rolls.

(c) Stop watch or other timing device to measure the time it takes the rolls speed to decrease from 55 to 45 mph (88.5 to 72.4 km/h).

(d) Pair of chocks, vehicle tie-downs, and other safety devices used to assure safe operation of a vehicle on the rolls.

3.7.1.2 *Preparation*

(a) Place the vehicle on the dynamometer rolls and set chocks against the front wheels. Tie-downs should be slack enough to allow the vehicle to be lifted from the rolls.

(b) Verify the calibration of the fifth wheel, tach generator, or other speed monitoring equipment.

(c) Position the lifting device at the rear of vehicle.

(d) Place the lift pads under the rear bumper, adjacent to the bumper brackets.

(e) Practice lift technique in disengaging the rear wheels to develop a familiarity with the lifting device's response.

(f) When satisfied, raise the lift pads until they are in contact with the bumpers so that there is sufficient tension to keep the lift pads in place until ready to use.

(g) Set dynamometer inertia to 4000 lb (1816 kg) or to the more common weight class to be tested.

3.7.1.3 *Test Procedure*

(a) Drive the dynamometer with the test vehicle to 50 mph (80.5 km/h).

(b) Adjust the dynamometer power absorption unit to an indicated 2.5 hp (1.9 kW).

(c) Accelerate the dynamometer test vehicle to 60 mph (96 km/h). At this point, disengage the drive wheels from the rolls by means of the lifting device.

(d) Record the time for the dynamometer to coast down from 55 to 45 mph (88.5 to 72.4 km/h).

(e) Repeat steps 3.7.1.3(c) and 3.7.1.3(d) two more times.

(f) Calculate an average from the three coastdown times.

(g) Repeat steps 3.7.1.3(a) through 3.7.1.3(f) for 5.0, 7.5, and 10.0 indicated hp (3.7, 5.6, and 7.4 kW) and calculate the average coastdown times for each.

3.7.1.4 *Calculations*—Calculate actual absorbed road horsepower from:

$$HP_{act} = \frac{1}{2} \frac{W_i}{32.2} \frac{(V_1^2 - V_2^2)}{550t} = \frac{0.06073 \, W_i}{}$$

where: W_i = equivalent inertia, lb
$\quad\quad V_1$ = initial velocity, ft/s (55 mph = 80.67 ft/s)
$\quad\quad V_2$ = final velocity, ft/s (45 mph = 66.00 ft/s)
$\quad\quad t$ = elapsed time for rolls to coast down from **55 to 45 mph (88 to 72 km/h)**

3.7.1.5 *Belt Drive Dynamometers*—The procedure outlined above has been applied extensively to belt drive dynamometers. The next step is to plot the **indicated road load horsepower at 50 mph (80 km/h) versus the actual road horsepower at 50 mph (80 km/h). Fig. 5.**

The Federal Register advises running coastdowns at the inertia weight most frequently used. Common practice is to run coastdowns at either all inertia weight settings of a dynamometer or at least all inertia weights that are used for testing.

3.7.1.6 *Direct-Drive Dynamometers*—The same procedure can be used for direct-drive dynamometers as for belt drive dynamometers and should be used for manual loading calibration of these units. However, automatic loading features of the new direct-drive dynamometers can improve the coastdown procedure. An outline of a direct-drive dynamometer procedure is given in Appendix C.
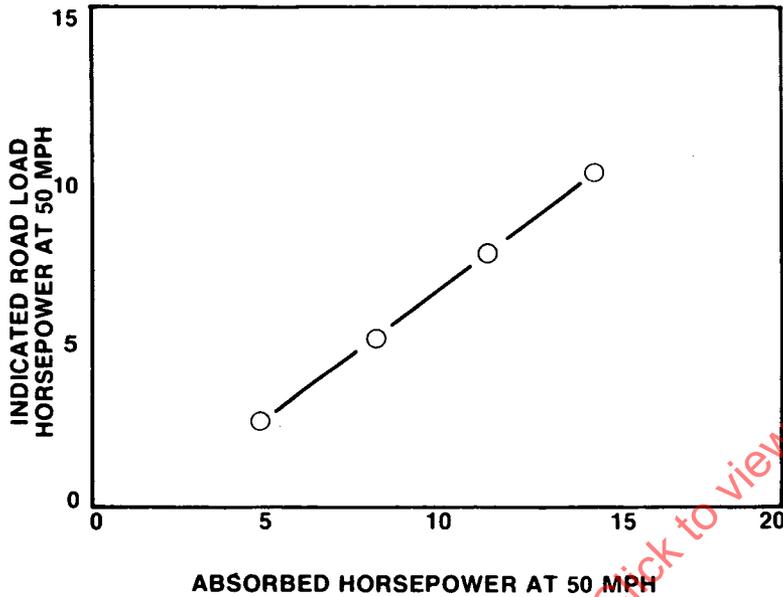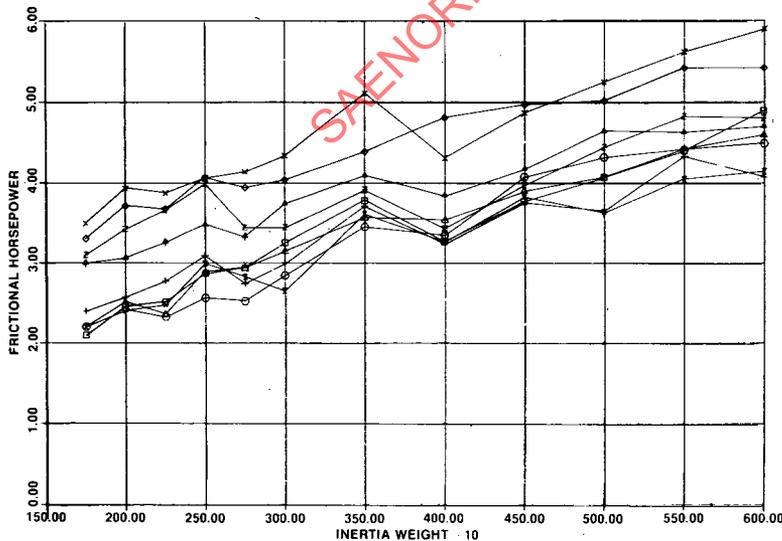

FIG. 5 – DYNAMOMETER CALIBRATION CURVE

The direct-drive dynamometer procedure sets up the dynamometer for operation at the desired operating points rather than finding a linear range for each inertia weight. This procedure is rapid and reproducible in both running coastdowns and in operation. It is recommended that a plot of frictional horsepower versus inertia weight be made for each set of coastdown data. These plots can aid in determination that the coastdown data is valid.

In Fig. 6, the frictional power is plotted as a function of inertia weight for nine automatic loading direct-drive dynamometers. The data show that the frictional powers are confined to an approximate 1 hp (745 W) band. On these plots, the "over 5500" values are plotted at 6000 for convenience.

An example of the effect of recalibration is shown in the frictional power versus inertia weight **plot in Fig. 7.** A dynamometer recalibration indicated a shift of over 0.5 hp (0.3 kW) friction. A recalibration showed that a speed calibration error had been made. After correction, a typical shift of less than 0.5 hp (0.3 kW) was observed.

3.7.2 DYNAMOMETER PROCEDURE

3.7.2.1 The vehicle shall be tested from a cold start. Engine startup and operation over the driving schedule make a complete test run. Exhaust emissions are diluted with air to a constant volume and a portion is sampled continuously during each of the three test phases. The composite samples, collected in three bags, are analyzed for HC, CO, NO_x, and CO_2. Three parallel samples of dilution air are similarly analyzed. CO_2 is measured because it is needed in determining the carbon balance fuel economy.

3.7.2.2 A fixed-speed cooling fan with a nominal capacity of 5300 ft^3/min (150 m^3/min) is positioned during dynamometer operation so as to direct cooling air to the vehicle in an appropriate manner with the engine compartment cover open. In the case of vehicles with front engine compartments, the fan is squarely positioned between 8 and 12 in (200 and 300 mm) in front of the cooling air inlets (grill). In the case of vehicles with rear engine compartments (or if special designs make the above impractical), cooling fan or fans should be placed such that engine/vehicle temperatures normally encountered during road operation are approximated. The vehicle should be nearly level when tested in order to prevent abnormal fuel distribution.

3.7.2.3 Flywheels, electrical, or other means of simulating inertia as shown in Table 2 should be used. **If the equivalent inertia specified is not available on the dynamometer being used, the next higher equivalent inertia available, not exceeding 250 lb (113 kg), should be used.**

3.7.2.4 *Power Absorption Unit Adjustment*

(a) The power absorption unit is adjusted to reproduce absorbed horsepower at 50 mph (80 km/h) road load. The relationship between absorbed power and indicated power for a particular dynamometer should be determined by the procedure previously outlined.
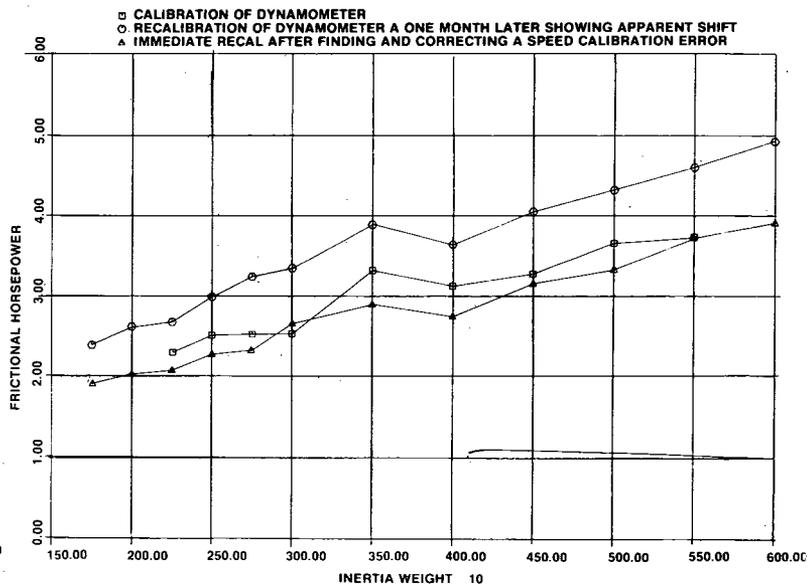

FIG. 6 – TYPICAL FRICTIONAL HORSEPOWERS

FIG. 7 – EFFECT OF RECALIBRATION

(b) The absorbed power listed in Table 2 is used or the vehicle manufacturer may determine the absorbed power by the following procedure and request its use:

(i) Measure the absolute manifold vacuum of a representative vehicle of the same equivalent inertia weight, when operated on a level road under balanced wind conditions at a true speed of 50 mph (80 km/h).

(ii) Note the dynamometer indicated power setting required to reproduce the manifold vacuum, when the same vehicle is operated on the dynamometer at a true speed of 50 mph (80 km/h). The tests on the road and on the dynamometer should be performed with the same vehicle ambient absolute pressure (usually barometric), that is, within ±5 mm of Hg.

(iii) The absorbed power values are listed in Table 2.

3.7.2.5 The vehicle speed must be measured by a tachometer generator installed on the rear (or idler) roll. A tachometer generator installed on the front (or drive) roll is used to measure coastdown speed. Even though most tests conducted integrating front and rear tachometer generator speeds over the test cycle have shown only small differences in total distance, the rear (or idler) roll must be used to measure vehicle speed because of tire distortions that occur on accelerations which change the rolling radius.

3.7.2.6 The Federal Register recommends that minimum throttle action should be used to maintain the proper speed-time relationship. When using a two-roll dynamometer, a truer speed-time trace may be obtained by minimizing the rocking of the vehicle in the rolls. The rocking of the vehicle changes the tire rolling radius on each roll. The rocking may be minimized by restraining the vehicle horizontally (or nearly so) by using a cable and winch. Care must be used to prevent tightening this cable too much as this could cause vehicle to be pulled off rolls.

3.7.2.7 Drive wheel tires must be inflated to a cold gage pressure of 40 psi (280 kPa). This recommended practice acknowledges that all is not fully understood regarding the rolls-tire interaction. Recent tests using vehicles having engines of 100–450 in.^{3} (1.6-7.4 $\times$ 10^{-3} m^3) displacement show that the average drive wheel tire pressure increased from gage pressure of 40 psi (280 kPa) to 47 ± 3 psi (320 ± 21 kPa) after running the 1975 Federal Test Procedure. When the 75FTP was immediately followed by a Highway Driving Cycle, the average gage pressure at the end of the test was 50 ± 3 psi (340 ± 20 kPa). These observed tire pressure increases are approximately twice those observed when vehicles are run on the road, confirming that the tire deflections on rolls probably generate more heat and thereby increase the tire pressure. Further study is needed in this area. The cold gage pressure recommended above is an initial step to minimize tire variations.

3.7.2.8 *Warmup of Dynamometer*—If the dynamometer has not been operated during the 2 h period immediately preceding the test, it should be warmed up for 15 min by operating it at 30 mph (48 km/h) using a nontest vehicle.

4. *Calibrating and Operating Procedure*

4.1 Calibration Procedure—The purpose of this procedure is to provide a reliable method for calibrating CVS systems.

A detailed discussion of the major requirements for conducting an accurate CVS calibration follows. The individual sections are arranged in proper sequential order and provide detailed instructions for conducting the necessary checks that must be performed for satisfactory results.

4.1.1 PREPARATION OF CVS SYSTEM FOR CALIBRATION

4.1.1.1 Installation of Sampling Taps and Lines—For measurement of the pressure differential across the CVS pump, install static pressure taps of the type shown in Fig. 8 at the top and bottom of the CVS pump drive head plate, centering on the inlet and outlet pump cavities. The same static pressure taps used for CVS calibration should be used for vehicle emission testing. The location should provide at least one diameter of straight pipe up and downstream from the tap to minimize flow disturbances. If a straight length of pipe is not available, a piezometer ring from which a single gage connection is led may be used.

4.1.1.2 If the straight section of pipe is vertical, the static tap can be installed anywhere around the periphery. If the pipe is horizontal, the tap should be located in the periphery of the upper half (above the pipe centerline). The pump inlet pressure tap should be located downstream from the gas sample probes.

The diameter and hole edge rounding of the pressure tap should conform with the recommendations shown in Table 3.

NOTE: It is realized that it will seldom be practical and, generally, it will be impossible actually to measure the radius of the hole-edge rounding. However, if any dulling or rounding is done, the values in Table 3 offer a guide for estimating the maximum desirable degree of edge rounding. [3]

All burrs and irregularities should be removed from the inner wall surface near the static tap.

[3]"*Static Pressure Cups and Fluid Meters—Theory and Application*," Fifth Chapter, Section A3, pp. 18–19. American Society of Mechanical Engineers, 345 East 47th Street, New York, New York 10017.
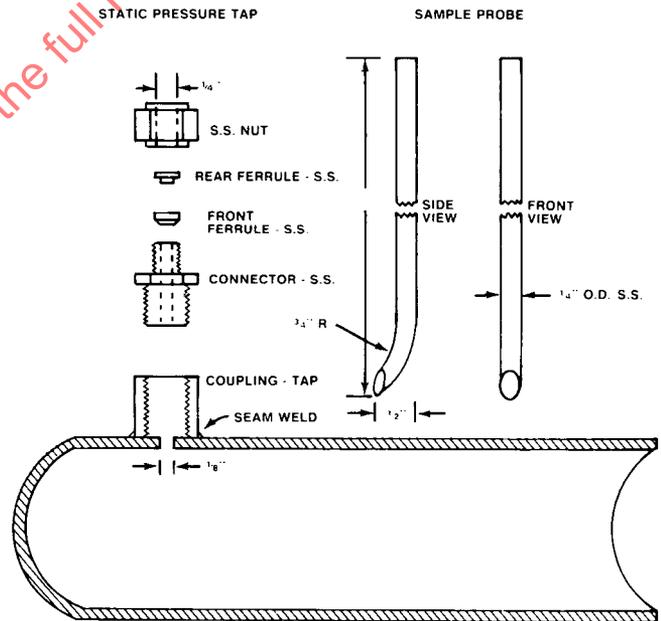

FIG. 8—STATIC PRESSURE TAP FITTINGS AND PROBE DESIGN

TABLE 2—EQUIVALENT INERTIA WEIGHT AND ABSORBED POWER

Loaded Vehicle Weight		Equivalent Inertia Weight		Absorbed Power at 50 mph (80 km/h) Without and With Air Conditioning Load Simulation			
				Without		With	
lb	kg	lb	kg	hp	kw	hp	kw
Up to 1125	Up to 511	1000	454	5.9	4.4	6.5	4.8
1126 to 1375	512 to 624	1250	568	6.5	4.8	7.2	5.4
1376 to 1625	625 to 738	1500	681	7.1	5.3	7.8	5.8
1626 to 1875	739 to 851	1750	795	7.7	5.7	8.5	6.3
1876 to 2125	852 to 975	2000	908	8.3	6.2	9.1	6.8
2126 to 2375	976 to 1085	2250	1022	8.8	6.6	9.7	7.2
2376 to 2625	1086 to 1195	2500	1135	9.4	7.0	10.3	7.7
2626 to 2875	1196 to 1306	2750	1250	9.9	7.4	10.9	8.1
2876 to 3250	1307 to 1475	3000	1362	10.3	7.7	11.3	8.4
3251 to 3750	1476 to 1700	3500	1590	11.2	8.4	12.3	9.2
3751 to 4250	1701 to 1930	4000	1816	12.0	8.9	13.2	9.8
4251 to 4750	1931 to 2150	4500	2045	12.7	9.5	14.0	10.4
4751 to 5250	2151 to 2380	5000	2270	13.4	10.0	14.7	11.0
5251 to 5750	2381 to 2610	5500	2500	13.9	10.4	15.3	11.4
5751 or more	2611 or more	5500	2500	14.4	10.7	15.8	11.8

TABLE 3—PRESSURE TAP HOLES

Nominal Inside Pipe Diameter		Pressure Hole Diameter		Hole-Edge Rounding Radius	
in	cm	in	mm	in	mm
Under 2	Under 5	1/4 ± 1/8	6.4 ± 3.2	About 1/64	About 0.4
2 to 3	5 to 7.5	3/8 ± 1/8	9.5 ± 3.2	Less 1/32	Less 0.8
4 to 8	10 to 20	1/2 − 1/8 + 1/4	12.7 − 3.2 + 6.4	Less 1/32	Less 0.8
10+	25+	3/4 ± 1/4	19.0 ± 6.4	Less 1/16	Less 1.6

4.1.1.3 The sample probes should be made of stainless steel and be of the design shown in Fig. 7. They should be faced upstream directly into the flow. All sample lines leading from the probes should be routed upward. This will allow any water which may condense to drain out of the lines and thereby prevent hydraulic blockage. (Similar precautions should be taken when installing static pressure lines.)

4.1.2 Flange Gaskets—When installing the plumbing on the inlet side of the pump, compression of the gasket may cause a decrease in its inside diameter. If this occurs, it will affect the restriction on the pump and may affect the accuracy of the static pressure reading if the gasket protrusion is upstream of the static tap. Therefore, when assembling the plumbing insure that the gasket ID as installed is not smaller than the pipe ID.

The placement of modal analysis probes relative to the bag sample probe can also disrupt sampling. It has been shown that the backflushing of a modal analysis cart through a probe can significantly affect the bag sampling probe sample during a CVS calibration verification with propane injection.

4.1.3 PRIMARY CVS CALIBRATION WITH LAMINAR FLOW ELEMENT

4.1.3.1 This procedure utilizes a laminar flow element and a variable restriction device to generate a pump performance curve (flow rate as a function of pressure differential). Fig. 9 is a schematic of the test layout and instruments required to perform this calibration. The volumetric flow is determined by a laminar flow element (LFE) placed upstream of the CVS pump (as shown in Fig. 9) to avoid introducing flow disturbances in the LFE. A straightener section of 10 times the exit diameter is added to the outlet of the LFE. This is followed by an adjustable restriction valve. Since the LFE and the pump are in series, it is necessary that all connections between these two items be free of leakage. It is advisable to plug all openings and pressure test the system to insure that the system is free of leaks.

Some LFE have straightener sections built into the device. This obviates the use of a straightener section. However, these LFEs are subject to calibration shifts if they are disassembled for cleaning. If these units are cleaned, they should be recalibrated.

When conducting calibration, the restriction device should be used to generate data points above and below the normal CVS system operating pressure. Data should be obtained beginning with the pump inlet depression corresponding to LFE as the only restriction. Pump inlet depression should be increased by increments of 2–5 in H_2O (500–1250 Pa) until 6–8 data points are determined. Usually, it is difficult to get points below the normal CVS system operating pressure unless the heat exchanger is removed from the system. Most calibrations are done with the heat exchanger in the system.

The following listing of the data to be recorded, unit conversions, and calculations will be followed by a sample calculation and a computer print-out.
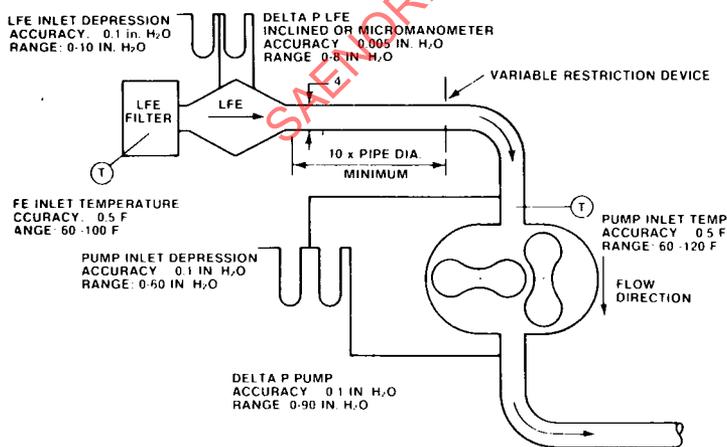

LFE INLET DEPRESSION ACCURACY. 0.1 in. H₂O RANGE: 0-10 IN. H₂O

DELTA P LFE INCLINED OR MICROMANOMETER ACCURACY 0.005 IN. H₂O RANGE 0-8 IN. H₂O

VARIABLE RESTRICTION DEVICE

LFE FILTER

LFE

10 x PIPE DIA. MINIMUM

FE INLET TEMPERATURE CCURACY. 0.5 F ANGE 60-100 F

PUMP INLET TEMP ACCURACY 0.5 F RANGE 60-120 F

PUMP INLET DEPRESSION ACCURACY 0.1 IN. H₂O RANGE: 0-60 IN. H₂O

FLOW DIRECTION

DELTA P PUMP ACCURACY 0.1 IN H₂O RANGE 0-90 IN. H₂O

FIG. 9—CVS CALIBRATION WITH LAMINAR FLOW ELEMENT - SCHEMATIC

4.1.3.2 *Data Recorded*
(a) LFE inlet depression, in H_2O (Pa).
(b) Delta P LFE, in H_2O (Pa).
(c) LFE inlet temperature, °F (°C).
(d) Pump inlet depression, in H_2O (Pa).
(e) Pump inlet temperature, °F (°C).
(f) Delta P pump, in H_2O (Pa).
(g) Barometric pressure, in Hg (Pa).
(h) Pump rpm.

4.1.3.3 *Conversion of Units*
(a) Convert in H_2O to in Hg pressure:

LFE inlet depression (in Hg) = LFE inlet depression (in H_2O)
× 0.07335 in Hg/in H_2O
Pump inlet depression (in Hg) = Pump inlet depression (in Hg)
× 0.07355 in Hg/in H_2O

(b) Convert from degrees Fahrenheit to degrees Rankine:

LFE inlet temperature (R) = LFE inlet temperature (°F) + 460
Pump inlet temperature (R) = pump inlet temperature (°F) + 460

(c) Conversion to absolute pressure:

Absolute pressure (in Hg) at LFE inlet = barometric pressure (in Hg)
− LFE inlet depression (in Hg)
Absolute pressure (in Hg) at pump inlet = barometric pressure (in Hg)
− pump inlet depression (in Hg)

4.1.3.4 *Calculations*
(a) Determine air viscosity correction factor for LFE inlet air temperature from LFE correction curve obtained from LFE manufacturer.
(b) Determine pressure correction factor for LFE inlet pressure from LFE correction table obtained from LFE manufacturer.
(c) Determine uncorrected volume flow rate from curve supplied by LFE manufacturer and pressure drop. Then determine corrected volume flow rate by multiplying uncorrected volume flow rate × air viscosity correction factor × pressure correction factor.
(d) Using Ideal Gas Law, convert the volume flow rate at LFE standard conditions (530 R, 29.92 in Hg) to the volume flow rate at the pump inlet temperature and pressure:

$$\text{Pump ft}^3/\text{min} = \text{LFE ft}^3/\text{min} \times \frac{29.92}{\text{pump abs inlet pressure (in Hg)}} \times \frac{\text{pump inlet temperature (R)}}{530}$$

(e) Determine pump ft³/rev by dividing ft³/min by the pump rpm.
(f) Plot pump ft³/rev versus the square root of pump delta P. Determine the first degree equation of the line by the least squares method.

4.1.3.5 *Example of Calculations* for LFE CVS calibration, using typical data from a 400 ft³/min LFE
Data Recorded
(a) LFE inlet depression = 1.00 in H_2O.
(b) Delta P of LFE = 6.520 in H_2O.
(c) LFE inlet temperature = 75.5°F.
(d) Pump inlet depression = 37.8 in H_2O.
(e) Pump inlet temperature = 78.0°F.
(f) Delta P pump = 60.0 in H_2O.
(g) Barometric pressure = 29.34 in Hg.
(h) Pump rpm = 1421.
Conversion of Units:
(a) LFE inlet depression = 0.07355 in Hg.
(b) Pump inlet depression = 2.78 in Hg.
(c) LFE inlet temperature = 535.5 R.
(d) Pump inlet temperature = 538 R.
(e) LFE inlet, absolute pressure = 29.27 in Hg.
(f) Pump inlet, absolute pressure = 26.56 in Hg.
Calculations:
(a) Air viscosity correction factor at 75.5°F (from LFE manufacturer's curve) = 1.006.

(b) Pressure correction factor = $\frac{29.27}{29.92} = 0.9783$.

(c) Uncorrected flow rate (from LFE manufacturer's curve) = 342.8 ft³/min.
(d) Corrected volume flow rate = 342.8 × 1.006 × 0.9783 = 337.4.

(e) Pump ft³/min = $337.4 \times \frac{29.92}{26.56} \times \frac{538}{530} = 385.8$.

(f) Pump ft³/rev = $\frac{385.8}{1421} = 0.2715$.

4.1.4 Gas Stratification Check

4.1.4.1 With the CVS operating in its testing configuration, introduce a tracer gas, such as 100% propane, into the vehicle exhaust inlet of the CVS system as shown in Fig. 10. The tracer gas should be introduced at a rate that will give a bag sample which produces at least a $\frac{3}{4}$ full-scale deflection on the HC range normally used for reading bags. The use of a continuous HC analyzer on the dilute continuous sampling probe makes this rate determination simple. The continuous analyzer is needed for the profile determination of paragraph 4.1.4.2.

4.1.4.2 Starting with the sample probe inlet opening at one side of the dilute stream, run a cross-sectional profile of the pipe, sampling at 0.5 in. (13 mm) intervals (wall to wall). Record the concentration at each sampling point location. Conduct a second cross-sectional profile at 90 deg to the first profile. If concentrations from wall to wall vary more than 1%, there is incomplete mixing.

4.1.5 Independent CVS System Verification

4.1.5.1 *Introduction*—The system verification technique involves the introduction of a measured quantity of a tracer such as propane (or CO) at the tailpipe sampling location. If all components of the system are functioning properly, the quantity of tracer calculated from that collected in the sample bag should agree closely with the quantity which was injected. A measured amount of tracer gas partially diluted with air from a small auxiliary blower (Fig. 11) is then mixed with dilution air in the main stream of the CVS. To avoid possible leakage, the tracer gas should be introduced downstream of the auxiliary blower. The auxiliary blower is needed to aid mixing of the 0.02 ft^3 (0.56 L) of propane that is used in a test. When propane is used as the tracer gas, it may be necessary to remove the charcoal filter from the CVS. This will equalize the HC background in the two dilution air streams.

4.1.5.2 *Equipment*

(a) CVS system to be checked.

(b) A container of instrument grade tracer gas.

(c) Analytical balance with a capacity to weigh the charged gas container and flow regulator with a resolution of 0.01 g.

Instead of the weighing technique, flow measurement techniques can be used to determine the amount of tracer gas injected into the CVS. These include: wet test meter, rotometer, and critical flow orifice.

(d) A tracer gas flow regulator which is capable of adjustment to yield bag concentrations which are normally encountered during testing.

(e) An auxiliary blower of 10–30 ft^3/min (0.005–0.014 m^3/s) capacity.

(f) Analyzers to measure tracer gas.

4.1.5.3 *Procedure*

(a) Turn on CVS and allow stream pressure and temperature to stabilize.

(b) Weigh gas container with the flow regulator connected and record weight.

(c) Purge the gas sample bags with dilution air.

(d) Simultaneously, activate CVS mixture and dilution air bag sampling and the positive displacement pump revolution counter.

(e) After 30 s, begin injecting tracer gas into the CVS. Set tracer gas flow rate to yield sample stream concentrations approximating those encountered during vehicle testing.

(f) Record CVS data during tracer gas injection:

Average pump inlet temperature, °F (°C).

Average pump inlet pressure, in. H$_2$O (Pa).

Average pump differential pressure, in. H$_2$O (Pa).

(g) After 14 min 30 s total elapsed time, stop the tracer gas injection.

(h) After 15 min total elapsed time, stop the CVS mixture and dilution air bag samples and the pump revolution counter simultaneously. Record total CVS pump revolutions.

(i) Analyze gases in the CVS mixture and dilution air sample bags. Record concentrations.

(j) Weigh tracer gas container and record weight.

(k) Determine the injected weight of tracer gas by subtracting weight measured in step 4.1.5.3(j) from weight measured in step 4.1.5.3(b). Record difference.

4.1.5.4 *Calculations*

(a) Determine the mass of injected tracer gas indicated by the CVS using the following formula:

$$\text{Calculated mass} = V_{\text{mix}} \times \text{density} \times \text{conc}$$

where:

$$V_{\text{mix}} = K_1 \times V_0 \times N \times \frac{P_p}{T_p}$$

$$K_1 = \frac{528\ R}{29.92\ \text{in. Hg}}$$

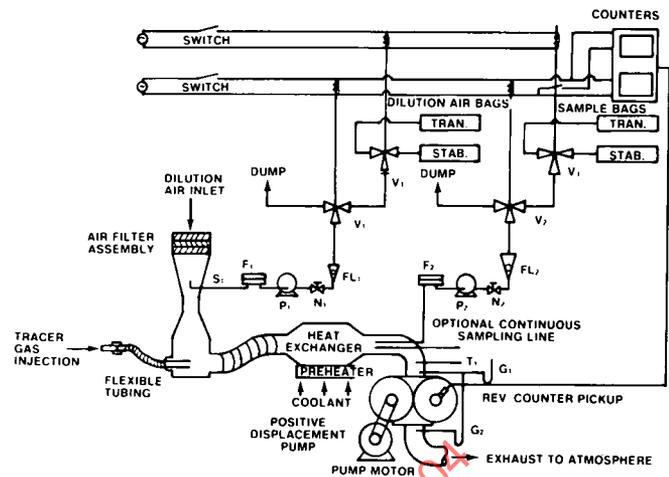V_0 = volume of gas pumped by the positive displacement pump,

FIG. 10—EXHAUST GAS SAMPLING SYSTEM

ft^3/rev at ambient conditions. This volume is dependent on the pressure differential across the positive displacement pump

N = number of revolutions of the positive displacement pump during the test while samples are being collected

P_p = absolute pressure of the dilute exhaust entering the positive displacement pump, that is, barometric pressure minus the pressure depression below atmospheric of the mixture entering the positive displacement pump

T_p = average temperature of dilute exhaust entering positive displacement pump during test while samples are being collected, R

Density = density of tracer gas, g/ft^3 at 68°F and 29.92 in. Hg pressure.

Example: Propane = 51.91 g/ft^3

CO = 32.97 g/ft^3

Conc = concentration of gas in sample bag minus concentration of gas in background bag

(b) Compare the measured tracer gas weight to the calculated tracer gas weight and determine the percent difference, based upon the measured weight.

(c) If the difference is greater than ±2% investigate possible sources of error and repeat the verification.
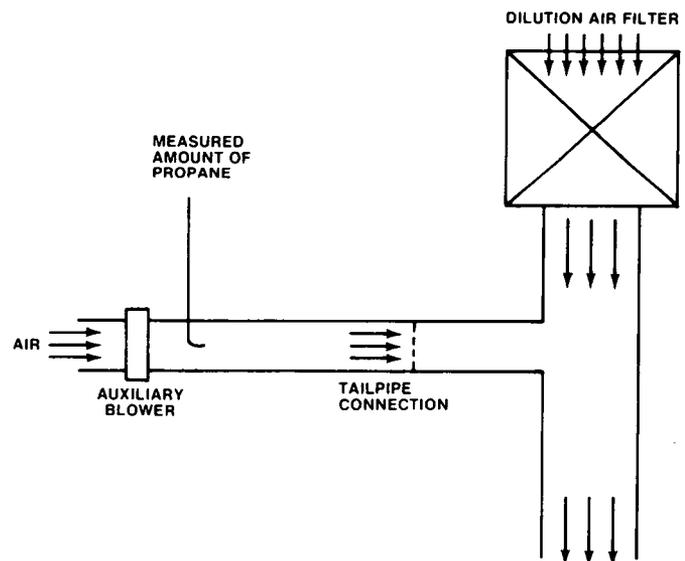

FIG. 11—CVS SYSTEM VERIFICATION

4.1.5.5 Critical Flow Orifice—A simpler alternative to the gravimetric procedure described above for CVS system verification is the use of a critical flow orifice (CFO). The advantage of a calibrated CFO is that the weighing steps are replaced by a single determination of a high pressure level reading. Appendix D is an example of a data and calculation sheet for use with a CFO. The CVS measurement is compared to the CFO measurement using the CFO measurement as the standard. Again, if the percent difference is greater than ±2%, investigate possible sources of error and repeat the verification.

4.2 Operating Procedure—A wide variety of CVS configurations are currently available. The detailed operating procedure for each configuration will be unique, and will depend upon the nature of the test being performed. Requirements for hot and cold weighting and inclusion of multiple background bags all necessitate changes in the detailed operating procedure. Furthermore, the required degree of operator attention to the CVS console during performance of an emission test varies from installation to installation. Fully automated systems require almost no attention to detail. Once the test is initiated, all functions including the diverting of exhaust gas into the appropriate sample bags at the correct times and even changing of the paper filters are all accomplished automatically. Other units may require the operator to perform each of these operations manually. As a result of these many factors (configuration of equipment, interfacing equipment for automatic control, and test procedure no attempt will be made here to provide a detailed step-by-step procedure Any such procedure would be specific for a particular unit and test objective, rather than of universal value. Each operator should, of course, follow the instructions of the CVS manufacturer and/or system designer as well as the test procedure outlined in the appropriate governmental regulations. The remainder of this section will be devoted to items which may be best described as "good operating practice" and are more universally applicable.

First, it should be pointed out that the concept of CVS sampling is still evolving. Areas of uncertainty still exist. Such an area is that of defining the acceptable "tailpipe depression" at idle or positive pressure during modes such as acceleration and cruise, which the CVS may exert upon the vehicle during the performance of an emissions test. The objective of the operator should be to employ his given CVS unit in a way which will minimize its effect upon vehicle operation. Actual CVS design has a large impact on tailpipe depression or pressurization. Above and beyond this the operator can minimize effects by insuring that connections between the vehicle and the CVS are relatively short (5–6 ft (1.5–1.8 m)), of large enough diameter (4 in. (100 mm) or larger) and that the inside wall of this flexible connection is relatively smooth (interlock type tubing).

A second area which deserves attention is that of preventing moisture condensation in the CVS or sampling lines. Condensation may remove soluble gas species from the sample stream and interfere with the accuracy of NO_x measurements. The dew point of concentrated exhaust gas is typically 120–130°F (49–54°C). Therefore, it is essential that the exhaust temperature not approach this range before dilution in the CVS mainstream. The use of a short (5–6 ft (1.5–1.8 m)) connection between the vehicle tailpipe and the CVS inlet will help prevent condensation in the connecting line. If the CVS configuration is such that the exhaust gas is cooled prior to mixing with the dilution air, it will be necessary to insure that condensation does not occur before dilution. Dilution of the exhaust gas should be sufficient to preclude condensation of moisture in the main flow stream.

Condensation of the dilute exhaust sample may occur in sample lines, pumps, filters, and meters, particularly when the relative humidity of the dilution air exceeds 50%. Unless bubbles appear in the flow meters, this condensation may be difficult to detect. Dampness in the paper filters in the sample streams is an indication that condensation is occurring. If condensation is a problem, it may be necessary to install drain lines to divert the condensation back into the main flow path of the CVS upstream of the positive displacement pump. Better approaches to avoid the condensation problem are to match the sample pump capacity more closely to the sampling system and to use back-pressure regulated sample pumps to reduce the maximum pressure to which the sample is exposed and thus reduce the tendency for condensation to occur. Usually, humidity is added to the test area so that the relative humidity is maintained near 50%, so that the NOx correction factor will be near unity.

Deposits will slowly build up in the CVS. These are most likely to occur in the heat exchanger. Good operating practice dictates regularly scheduled cleaning. Increase of depression at the pump inlet is a good indicator of deposit buildup. Even though the CVS flow conditions are corrected for the changing operating conditions, the deposit buildup is not uniform and consequently can cause stratification at the sample probe. Deposit buildup will

be a function of the number and type of tests. For a very active testing program, monthly cleaning would be recommended.

CVS pumps have been known to seize. Usually, this is due to deposits and moisture that remain in a CVS after a series of intermittent tests. This problem can be avoided by connecting the CVS outlet to a laboratory exhaust system that has sufficient capacity to rotate the blower slowly when the CVS is off. The laboratory exhaust is effective in removing the moisture.

Foreign objects can enter the CVS inlet and effectively destroy mixing or cause severe stratification. Large mesh screens have been used effectively to prevent foreign objects from reaching the mixing area and the heat exchanger.

The dilution air filter is not intended to remove all hydrocarbons from the inlet air, but rather to stabilize their level. Precautions should be taken to insure that the dilution air is not contaminated with excessive HC vapor from spilled gasoline, etc. The dilution air filter package is normally a set of three 24 x 24 in (600 x 600 mm) filters. The first is a dust filter, the second a charcoal filter, and the third filter to remove charcoal particles from the dilution air stream. These filters can become loaded with dirt. An acceptable method for determining the useful life of these filters is to monitor the pressure drop across the filter when the CVS blower is operating at high speed. When the pressure drop across the three filters reaches 0.5 in H2O (125 Pa), the filter set should be changed. If desired the charcoal could be reactivated and reused.

A detailed calibrating procedure appears in another section. It should be noted that, while this procedure is intended to uncover mechanical and flow problems which may exist, it is not a cure-all. Actual operating conditions are somewhat different from calibrating conditions. For example, the temperature and flow rate entering the CVS during calibration is different than the temperature and flow rate of exhaust entering during vehicle emission testing. The degree of stratification under actual test conditions could differ from that observed during calibration. Mixing difficulties at other than calibrating conditions will lead to a situation where, even though a CVS checks out during the calibration, during actual operation the mass obtained by integrating the continuous diluted exhaust stream concentration does not agree with that collected in the bags. When a situation like this is observed, it will be necessary to repeat the stratification check outlined in the calibrating procedure with exhaust gas supplied by a vehicle operating at 50, 40, and 30 mph (80.5, 64, and 48 km/h) steady-states. If mixing is not complete it may be necessary to experiment with unique mixing devices to aid or replace those supplied with the CVS unit. Considerations such as those outlined above emphasize the importance of paying careful attention to each step of CVS operation even when the unit is completely automated. Each configuration has its unique advantages and problems. Furthermore, changes in a given unit may occur from time to time, so that what is not a problem at one moment may become one later.

5. Data Analysis—Two types of data analysis are possible, bag and modal. Bag analysis will yield emission values which are the composite for a complete test. This kind of analysis is simpler to perform, and is satisfactory for determining whether a vehicle will pass a given test. Therefore, bag analysis is used for surveillance or compliance testing. For development of emission control systems, modal analysis is necessary to determine the relationships between emissions and driving mode.

5.1 Bag Analysis—The HC, CO, NO_x (NO + NO_2), and CO_2 concentrations are measured in the diluted exhaust and the background bags. Depending upon the specific cycle used, more than one exhaust and one background bag may be needed. For the 1975 Federal Test Procedure, separate exhaust bags are needed for the cold transient, cold stabilized, and hot transient phases of the driving cycle, thus allowing weighting factors to be applied to the cold and hot transient phases of the test. It is good practice to use a separate background bag for each sample bag used, in case the background concentrations change during a test.

5.1.1 Exhaust Emission Calculations—One diluted exhaust sample bag and one background bag are required for each test phase. The concentrations of HC, CO, NO_x, and CO_2 in the bags are determined by passing the gases through the analyzers described in paragraph 3.2.

5.1.1.1 The final reported test results are computed as follows:

$$Y_{wm} = (X_1Y_1 + X_2Y_2 + X_3Y_3)/7.5 \text{ miles}$$

where: Y_{wm} = weighted mass emissions of each pollutant, that is, HC, CO, and NO_x, g/vehicle mile
X_1, X_2, X_3 = 0.43, 1.0, 0.57, respective weighting factors for each test phase
Y_1, Y_2, Y_3 = mass emissions for each phase, g/phase
  1 = cold transient test phase
  2 = cold stabilized test phase
  3 = hot transient test phase

5.1.1.2 The mass of each pollutant for each phase of the test is determined from the following:

(a) HC mass:

$$HC_{mass} = V_{mix} \times density_{HC} \times \frac{HC_{conc}}{1,000,000}$$

(b) CO mass:

$$CO_{mass} = V_{mix} \times density_{CO} \times \frac{CO_{conc}}{1,000,000}$$

(c) NO_x mass:

$$NO_{x_{mass}} = V_{mix} \times density_{NO_2} \times \frac{NO_{x_{conc}}}{1,000,000} \times Kh$$

(d) CO_2 mass:

$$CO_{2_{mass}} = V_{mix} \times density_{CO_2} \times \frac{CO_{2_{conc}}}{100}$$

5.1.1.3 *Meaning of Symbols*

HC_{mass} = hydrocarbon emissions, g/test phase

$Density_{HC}$ = density of hydrocarbons in the exhaust gas, assuming an average carbon-to-hydrogen ratio of 1:1.85, g/ft^3 at 68 °F (20 °C) and 29.92 in. Hg (101 kPa) pressure (16.33 g/ft^3)[4]

HC_{conc} = hydrocarbon concentration of the dilute exhaust sample corrected for background, ppm carbon equivalent, that is equivalent propane × 3

$HC_{conc} = HC_e - HC_d(1 - 1/DF)$

HC_e = hydrocarbon concentration of the dilute exhaust sample as measured, ppm carbon equivalent

HC_d = hydrocarbon concentration of the background as measured, ppm carbon equivalent

CO_{mass} = carbon monoxide emissions, g/test phase

$Density_{CO}$ = density of carbon monoxide g/ft^3 at 68 °F (20 °C) and 29.92 in. Hg (101 kPa) pressure (32.97 g/ft^3)

CO_{conc} = carbon monoxide concentration of the dilute exhaust sample corrected for background, water vapor, and CO_2 extraction, ppm

$CO_{conc} = CO_e - CO_d(1 - 1/DF)$

CO_e = carbon monoxide concentration of the dilute exhaust sample corrected for water vapor and carbon dioxide extraction, ppm. The calculation assumes the hydrogen-carbon ratio of the fuel is 1.85:1

$CO_e = (1 - 0.01925\ CO_{2_e} - 0.000323\ R)CO_{e_m}$

$(CO_e = CO_{e_m}$, if instrument has no CO_2 or H_2O response)

CO_{e_m} = carbon monoxide concentration of the dilute exhaust sample as measured, ppm

CO_{2_e} = carbon dioxide concentration of the dilute exhaust sample, mol %

R = relative humidity of the dilution air, %

CO_d = carbon monoxide concentration of the background air corrected for water vapor extraction, ppm

$CO_d = (1 - 0.000323\ R)CO_{d_m}$

$(CO_d = CO_{d_m}$, if instrument has no H_2O response)

CO_{d_m} = carbon monoxide concentration of the background air sample as measured, ppm

$NO_{x_{mass}}$ = oxides of nitrogen emissions, g/test phase

$Density_{NO_2}$ = density of oxides of nitrogen in the exhaust gas, assuming they are in the form of nitrogen dioxide, g/ft^3 at 68 °F (20 °C) and 29.92 in. Hg (101 kPa) pressure (54.16 g/ft^3)

$NO_{x_{conc}}$ = oxides of nitrogen concentration of the dilute exhaust sample corrected for background, ppm

$NO_{x_{conc}} = NO_{x_e} - NO_{x_d}(1 - 1/DF)$

NO_{x_e} = oxides of nitrogen concentration of the dilute exhaust sample as measured, ppm

NO_{x_d} = oxides of nitrogen concentration of the background as measured, ppm

$CO_{2_{mass}}$ = carbon dioxide emissions, g/test phase

$Density\ CO_2$ = density of carbon dioxide g/ft^3 at 68 °F (20 °C) and 29.92 in. Hg (101 kPa) pressure (51.81 g/ft^3)

$CO_{2_{conc}}$ = carbon dioxide concentration of the dilute exhaust sample corrected for background, %

$CO_{2_{conc}} = CO_{2_e} - CO_{2_d}(1 - 1/DF)$

CO_{2_e} = carbon dioxide concentration of the dilute exhaust sample as measured, %

[4]Density of emissions are based on Ideal Gas Law. Density is equal to 1.17714 times the molecular weight.

CO_{2_d} = carbon dioxide concentration of the background as measured, %

$$DF = \frac{13.4}{CO_{2_e} + (HC_e + CO_e)\ 10^{-4}}$$

V_{mix} = total dilute exhaust volume, ft^3/test phase corrected to standard conditions (68 °F, 29.92 in. Hg) (528 R, 101 kPa)

$V_{mix} = V_0 \times N \times (P_p/29.92)(528/T_n)$

V_0 = volume of gas pumped by the positive displacement pump, ft^3/rev. This volume is dependent upon the pressure differential across the positive displacement pump

N = number of revolutions of the positive displacement pump during the test phase while samples are being collected

P_p = absolute pressure of the dilute exhaust entering the positive displacement pump, in Hg, that is, barometric pressure minus the pressure depression below atmospheric of the mixture entering the positive displacement pump

T_p = average temperature of dilute exhaust entering the positive displacement pump during test while samples are being collected

P_b = barometric pressure, in Hg

T_w = wet bulb temperature, °F

T_d = dry bulb temperature, °F

P_w = saturation water vapor pressure, in. Hg at wet bulb temperature

$P_w = -4.14438\ 10^{-3} + 5.76645\ 10^{-3}\ T_w - 6.32788\ 10^{-5}\ T_w{}^2 + 2.12294\ 10^{-6}T_w{}^3 - 7.85415\ 10^{-9}T_w{}^4 + 6.55263\ 10^{-11}T_w{}^5$. This equation is a least squares fit of the Keenan and Keyes "steam table." It reproduces steam table values within ±0.001 in. Hg for temperatures of 20–110 °F.

P_d = saturation water vapor pressure in. Hg at dry bulb temperature. Same equation as for P_w except T_d is used instead of T_w

A = experimentally derived constant for use in Ferrel's equation as recommended by NBS

$A = 3.67\ 10^{-4}\ (1 + 0.00064)\ (T_w - 32))$

P_v = partial pressure of water vapor, in. Hg (found from Ferrel's equation)

$P_v = P_w - A\ P_b\ (T_d - T_w)$, **Ferrel's equation**

H = absolute humidity, grains H_2O/lb dry air

$$H = \frac{4347.8\ P_v}{P_b - P_v}$$

K_h = humidity correction factor

$$K_h = \frac{1}{1 - 0.0047\ (H - 75)}$$

R = relative humidity, %

$$R = \frac{P_v}{P_d} \times 100$$

5.1.1.4 *Calculation of Mass Emission Values*—Computers are generally used to determine the mass emission values. To verify computer programs, Appendix E detailing hand calculations can be used.

5.2 Modal Analysis—Modal analysis is necessary for the development of emission controls because it relates cause and effect. The cause is the particular engine system at a specific operating point. The effect is the resulting emissions. Mode of operation can be defined as an idle, cruise, acceleration, and deceleration. The length of a mode could be several minutes or as short as 1 s. At least two methods of modal analysis are available: continuous analysis of diluted vehicle exhaust, and continuous analysis of undiluted exhaust using the CO_2 tracer technique.

5.2.1 CONTINUOUS ANALYSIS USING DILUTED VEHICLE EXHAUST—Any driving schedule can be broken down into arbitrary modes such as idle, acceleration, cruise, and deceleration. For each mode, the mass emission of each pollutant can be computed using the equations of paragraph 5.1.1.2 modified slightly. The modifications are: The HC, CO, and NO_x masses will be in grams per mode. Generally, a computer will be advantageous for performing the large amount of calculation required for continuous modal analysis.

5.2.1.1 *Calculation of V_{mix} for One Mode*—The diluted exhaust volume, ft^3/mode, can be calculated as in paragraph 5.1.1.3, except that N should be taken as the number of pump revolutions for the individual mode being calculated. The number of pump revolutions can be sensed with magnetic or photocell pickups and fed into the computer. For short modes, it may be

necessary to measure partial pump revolutions in order to obtain sufficient accuracy.

5.2.1.2 *Calculation of* HC_{conc}, CO_{conc}, *and* $NO_{x_{conc}}$—These quantities have the same meaning as in paragraph 5.1.1.2, except that they now are the average concentrations for each mode. The output of the HC, CO, NO_x, and CO_2 analyzers can be continuously monitored by a computer, with suitable provisions for time delays between the vehicle driver's mode changes and the corresponding analyzer output change. The computer can be programmed to time average the concentrations for the specified intervals corresponding to the individual modes, and make the required corrections. However, it is difficult to measure the background HC, CO, NO_x, and CO_2 concentrations continuously in the dilution air unless separate analyzers are available, which is not usually the case. Therefore, some approximation may be necessary, such as measuring the background before and after the test and assuming a linear relation in between, or collecting an average background dilution air sample for the entire test.

5.2.2 MODAL ANALYSIS USING CO_2 TRACER METHOD—There are many inherent difficulties in continuously analyzing diluted vehicle exhaust, primarily because of the very low diluted concentrations obtained for some modes. These problems can be avoided by continuously measuring the undiluted exhaust concentrations of HC, CO, NO_x, and CO_2. If the undiluted exhaust CO_2 concentration is also measured continuously, it is possible to calculate the vehicle exhaust volume for each mode. From the exhaust volume and the undiluted exhaust concentrations, the modal mass of each pollutant can be calculated. Actually, any constituent of the exhaust can be used as the tracer, but CO_2 is a good choice because it occurs in the largest and most constant concentration and, therefore, is easiest to measure accurately even after dilution.

5.2.2.1 Exhaust Modal Mass Flow Calculations Using CO_2 Tracer Method—Assume that the modal average undiluted exhaust HC, CO, NOx, and CO_2 concentrations are measured, and that the modal average CO_2 concentrations are measured in the diluted exhaust stream. The diluted exhaust volume $ft^3/mode$, V_{mix}, can be calculated as described in paragraph 5.2.1.1. Assuming a constant for background CO_2, the average exhaust dilution ratio for each mode can be calculated as follows:

$$DR = \frac{CO_2 \text{ exhaust} - CO_2 \text{ background}}{CO_2 \text{ CVS} - CO_2 \text{ background}}$$

The undiluted exhaust volume, $ft^3/mode$, is:

$$V_{und} = V_{mix}/DR$$

The modal mass is given by following:

$$HC_{modal\ mass} = \frac{HC_{conc\ und} \times V_{und} \times density_{HC}}{10^6}$$

$$CO_{modal\ mass} = \frac{CO_{conc\ und} \times V_{und} \times density_{CO}}{10^6}$$

$$NOx_{modal\ mass} = \frac{NOx_{conc\ und} \times V_{und} \times density_{NO_2}}{10^6}$$

The upper portion of Fig. 12 shows only a hot transient modal mass output. Several pages may be required for a complete test. The mass emissions for individual modes can then be summed for the complete test, and these values compared with the mass emissions computed from the bags. Theoretically, the total of the modal masses should be equal to the mass emissions calculated from the bag data. In practice, there will not usually be perfect agreement, but the bags should agree with the modal total for each phase within a few percent. Fig. 13 is an example of a computer mass summary. The weighted mass values of Fig. 13 can be compared to the weighted modal data of Fig. 12. Fig. 14 shows the results of the bag versus modal NO_x comparison when the chemiluminescent NO_x analyzer was used.

5.3 Background—The exhaust dilution inherent in the operation of the constant volume sampler results in low concentrations of pollutants being presented to analyzers. Under some conditions, such as testing vehicles with very low emission levels, the diluted exhaust concentrations are not far above the background level of pollutants found in the dilution air. Therefore, it is important that background levels of pollutants be taken into account when measuring vehicle emissions.

Fig. 15 is a partial schematic diagram of a constant volume sampler. The following equations apply:

$$V_E + V_D = V_{mix} \tag{1}$$

where:

V_E = volume of vehicle exhaust

V_D = volume of dilution air

V_{mix} = volume of diluted exhaust

$$V_E\ C_E + V_D\ C_D = V_{mix}\ C_{mix} \tag{2}$$

where:

C_E = concentration of a given pollutant in the undiluted exhaust

C_D = concentration of same pollutant in the dilution air (background)

C_{mix} = concentration of the same pollutant in the diluted exhaust

$$V_E\ C_E = V_{mix}\ C_{mix} - V_D\ C_D = V_{mix}\ C_{mix} - (V_{mix} - V_E)\ C_D$$

$$V_E\ C_E = V_{mix}\ (C_{mix} - C_D) + V_E\ C_D \tag{3}$$

Eq. 3 expresses the correct way of calculating the true mass emission of the test vehicle, which is the quantity, $V_E\ C_E$. However, the application of Eq. 3 requires that V_E be measured, which is not done in practice. An approximation to the correct value of $V_E\ C_E$ can be obtained by neglecting the $V_E\ C_D$ term in the right-hand side of Eq. 3. The background concentration is merely substracted from the diluted exhaust concentration of the same pollutant. This method may be satisfactory if the background concentration and/or V_E is small compared to V_{mix}. However, for very low emitting vehicles whose diluted exhaust concentrations approach the background concentrations, it is necessary to apply Eq. 3 more rigorously, which requires the determination of either vehicle exhaust or the dilution air flow. The procedure of paragraph 5.1.1 may be used, wherein the exhaust dilution factor is estimated by means of the empirical equation:

$$DF = \frac{13.4}{CO_{2_e} + (HC_e + CO_e)\ 10^{-4}}$$

Then V_E is approximately equal to V_{mix} divided by DF. With V_E known, Eq. 3 can be used. This technique avoids the need to measure either the exhaust flow or the dilution air flow, and may be satisfactory for all but the most rigorous testing. Eq. 3 is applicable to continuous modal analysis as well as to bag samples.

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*** MASS BAG RESULTS ***

*** EPA MASS TEST RESULTS ***

*** TEST VARIABLES ***

—TAILPIPE CONC—TAILPIPE MASS—

*** MODAL TEST SUMMARY ***

COLD TRANSIENT

COLD STABILIZED

HOT TRANSIENT

WEIGHTED TOTAL

FIG. 12—EXAMPLE OF HOT TRANSIENT MODAL DATA AND MODAL TEST SUMMARY
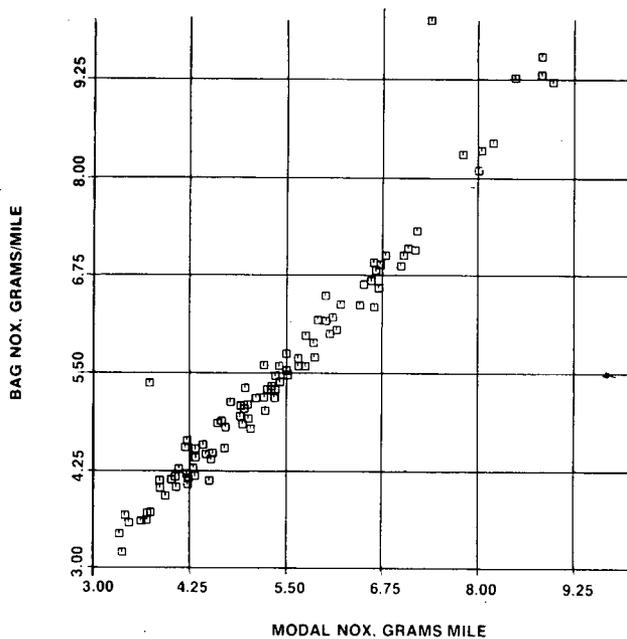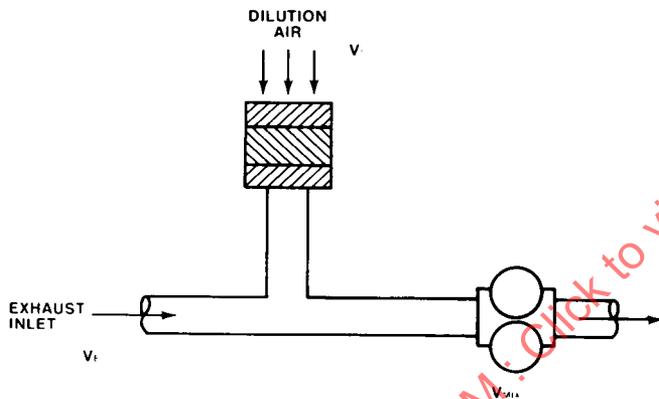
FIG. 13—EXAMPLE OF BAG DATA

FIG. 14—BAG NOx VERSUS MODAL NOx

FIG. 15—CONSTANT VOLUME SAMPLER SCHEMATIC

5.4 Fuel Economy Calculation from Exhaust Emissions—It is possible to calculate fuel economy from a vehicle's exhaust emissions using a form of carbon balance. The carbon in the fuel can be calculated as follows:

Fuel density, g/gal = $8.331 \times 0.7404 \times 453.6 = 2798$

$\qquad$ 8.331 lb/gal = density of water
$\qquad$ 0.7404 = specific gravity of typical gasoline
$\qquad$ 453.6 g/lb = conversion factor

Weight fraction of carbon in fuel, assuming fuel of composition
$CH_{1.85} = 12.011/((12.011 + (1.85 \times 1.008)) = 0.866$

$\qquad$ 12.011 = atomic weight of carbon
$\qquad$ 1.008 = atomic weight of hydrogen

Grams of carbon per gallon of fuel = (fuel density, g/gal)(wt% C in fuel) = $2798 \times 0.866 = 2423$
The carbon in the exhaust can be calculated as follows:

Mass C in HC = (HC g/mile)(wt% C in HC molecule, assume $CH_{1.85}$)
$\qquad$ = (HC g/mile)**(0.866)**
Mass C in CO = (CO g/mile)(wt% C in CO molecule)
$\qquad$ = (CO g/mile)(12.011/12.011 + 16)
$\qquad$ = (CO g/mile)(0.429)

Mass C in CO_2 = (CO_2 g/mile)(wt% C in CO_2 molecule)
$\qquad$ = (CO_2 g/mile)(12.011)/(12.011 + (2 $\times$ 16))
$\qquad$ = (CO_2 g/mile)(0.273)

Total mass of C in the exhaust, g/mile = 0.866 HC g/mile + 0.429 CO g/mile + 0.273 CO_2 g/mile
The vehicle fuel economy can be calculated as follows:

$$\text{miles/gal} = (\text{g C/gal fuel})/(\text{g/mile C in exhaust})$$

$$= \frac{2423}{0.866\, HC + 0.429\, CO + 0.273\, CO_2}$$

$$= \frac{2798}{HC + 0.495\, CO + 0.315\, CO_2}$$

where HC, CO, and CO_2 represent the grams/mile of these respective exhaust emissions for the vehicle.

Different values for fuel density and/or fuel H/C ratio will yield a slightly different equation.

5.4.1 WEIGHTED FUEL ECONOMY—"Weighted" fuel economy is the carbon balance fuel economy based on weighted emission values found from the 1975 Federal Test Procedure. This weighted fuel economy is identical to the fuel economy that would be obtained if the fuel economies were calculated for each of the three phases of the 75 FTP, and then weighted in the same manner as the emissions. The proof follows: Subscript w refers to the 75 FTP weighted emissions, subscript 1, 2, and 3, refer to the 75 FTP phase. The distance for phase 1 and phase 3 is 3.59 miles, and the distance for phase 2 is 3.91 miles. The weighting factor for phase 1 is 0.43 and for phase 3 is 0.57.

$$FE_w = \frac{2423}{0.866\, HC_w + 0.429\, CO_w + 0.273\, CO_{2_w}} \tag{1}$$

$$HC_w = \frac{0.43(3.59)\, HC_1 + 3.91\, HC_2 + 0.57(3.59)\, HC_3}{7.5} \tag{2}$$

$$CO_w = \frac{0.43(3.59)\, CO_1 + 3.91\, CO_2 + 0.57(3.59)\, CO_3}{7.5} \tag{3}$$

$$CO_{2w} = \frac{0.43(3.59)\, CO_{21} + 3.91\, CO_{22} + 0.57(3.59)\, CO_{23}}{7.5} \tag{4}$$

Substituting Eqs. 2, 3, and 4 into Eq. 1 and rearranging terms gives:

$$FE_w = \frac{2423(7.5)}{\begin{array}{c}0.43(3.59)(0.866 HC_1 + 0.429\, CO_1 + 0.273\, CO_{21}) + \\ (3.91)(0.866\, HC_2 + 0.429\, CO_2 + 0.273\, CO_{22}) + \\ 0.57(3.59)(0.866\, HC_3 + 0.429\, CO_3 + 0.273\, CO_{23})\end{array}} \tag{5}$$

The carbon balance formula applied to the emissions for each test phase is given by:

$$FE_n = \frac{2423}{0.866\, HC_n + 0.429\, CO_n + 0.273\, CO_{2n}} \tag{6}$$

where: n indicates the test phase. Substituting Eq. 6 into Eq. 5 gives

$$FE_w = \frac{7.5}{0.43\dfrac{3.59}{FE_1} + \dfrac{3.91}{FE_2} + 0.57\dfrac{3.59}{FE_3}} \tag{7}$$

The denominator is simply the gallons for each test phase weighted in the same manner as emissions.

5.4.2 FUEL ECONOMY CYCLE—The carbon balance fuel economy can be determined from any cycle, where emissions have been measured and are expressed in grams/mile. Recently EPA has developed a Highway Driving Cycle for fuel economy measurements. The driving sequence for this cycle is shown in Appendix F. This 12.75 min cycle has an average speed of 48.20 mph (77.6 km/h) and covers 10.24 miles (16.5 km).

6. Safety Recommendations

6.1 Dynamometer—The test vehicle should be restrained on the dynamometer by using tie-downs or other suitable means. The maximum speed and acceleration/deceleration rates of the dynamometer must not be exceeded.

6.2 Calibration Gas Cylinders

6.2.1 HANDLING—Gas cylinders must not be moved unless the safety cap is securely screwed on the cylinder. Gas cylinders must always be supported by chains or other suitable means when in use, transported, or in storage.

6.2.2 TOXIC OR DANGEROUS GASES—Gases such as CO and NO_x must be used in an area with adequate ventilation. An ambient CO monitor for the emissions laboratory area is suggested.

6.3 Vehicle Fuel (Gasoline)—Vehicle fuel must always be contained in safety containers.

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APPENDIX A
NO$_x$ CONVERTER EFFICIENCY CHECK
SEE FIG. 4

1. Attach NO/N$_2$ supply to NO inlet on NO$_x$ generator at C2 (NO concentration approximately 95% of full-scale), O$_2$ or air supply at C1 and efficiency checker to analyzer at C3.

2. With ozonator of NO$_x$ generator off, oxygen or air supply off, and analyzer in bypass mode, adjust NO/N$_2$ flow to analyzer. Zero analyzer and adjust span calibration to indicate approximately 100% of full-scale while flowing NO from NO$_x$ generator.
   Record actual reading _____

3. Turn oxygen or air supply of NO$_x$ generator and adjust MV1 to obtain analyzer reading of approximately 90% of full-scale.
   Record actual reading _____

4. Turn on ozonator power and adjust variac to obtain approximate 20% full-scale reading.
   Record actual reading _____

5. Place analyzer in converter mode.
   Record actual reading _____

6. Turn off ozonator.
   Record actual reading ——_____

7. Repeat steps 4 through 6 as necessary.

8. Calculate efficiency as follows:

$$\% \text{ Efficiency} = \frac{5-4}{6-4} \times 100\%$$

$$\% \text{ Efficiency} = \underline{\hspace{4cm}}$$

Note: Converter efficiency must be greater than 90% and should be greater than 95%.
   Check efficiency weekly.
   Record Test Cell, Analyzer, Date and Operator

APPENDIX B
STANDARD REFERENCE GASES
FOR
AUTOMOTIVE EMISSIONS ANALYSIS

The NBS Office of Standard Reference Materials announces the availability of Nitric Oxide in Nitrogen SRMs as its fourth series of SRMs for mobile source emission analysis. These SRMs are individually certified, and are available at the following *nominal* concentrations:

SRM 1683—Nitric Oxide in Nitrogen, 50 ppm
SRM 1684—Nitric Oxide in Nitrogen, 100 ppm
SRM 1685—Nitric Oxide in Nitrogen, 250 ppm
SRM 1686—Nitric Oxide in Nitrogen, 500 ppm
SRM 1687—Nitric Oxide in Nitrogen, 1000 ppm

The availability of the first two series, Propane in Air and Carbon Dioxide in Nitrogen, were announced in February 1973, and consist of the following *nominal* concentrations:

SRM 1665—Propane in Air, 2.8 ppm
SRM 1666—Propane in Air, 9.5 ppm
SRM 1667—Propane in Air, 48 ppm
SRM 1668—Propane in Air, 95 ppm
SRM 1669—Propane in Air, 475 ppm

SRM 1673—Carbon Dioxide in Nitrogen, 0.95%
SRM 1674—Carbon Dioxide in Nitrogen, 7.2%
SRM 1675—Carbon Dioxide in Nitrogen, 14.2%

The availability of the third series, Carbon Monoxide in Nitrogen, was announced in January 1974, and consists of:

SRM 1677—Carbon Monoxide in Nitrogen, 9.74 ppm
SRM 1678—Carbon Monoxide in Nitrogen, 47.1 ppm
SRM 1679—Carbon Monoxide in Nitrogen, 94.7 ppm
SRM 1680—Carbon Monoxide in Nitrogen, 484 ppm
SRM 1681—Carbon Monoxide in Nitrogen, 957 ppm

The development of these SRMs is a cooperative effort by National Bureau of Standards and the Environmental Protection Agency to provide standards that are needed to monitor compliance with automotive emission laws.

These standard reference gases are not to be considered as daily working standards, but rather as *primary* standards to be used in the calibration of daily working standards obtained from commercial sources, and by gas manufacturers to help control the quality of the working standards during processing. Thus, they provide a traceability of all gas standards used in mobile-source emission analysis back to a central reference point, the National Bureau of Standards.

These gases are supplied in cylinders with a delivered volume of 31 ft^3 at STP. The cylinders conform to the DOT 3AA-2015 specification.

The certified concentration of gas in each cylinder is given on the certificates issued at the time of purchase. For propane, carbon dioxide, and nitric oxide, cylinder labels list only the *nominal* concentration and these SRMs should be used only in conjunction with the printed Certificate of Analysis. Because the Certificate of Analysis may not accompany the cylinders, purchasers are requested to list the name of the actual user on the purchase order so that the Certificate of Analysis can be mailed directly to the user.

The cost of these SRMs includes the cost of the cylinder: for Propane in Air (SRMs 1665–1669) and Carbon Dioxide in Nitrogen (SRMs 1673–1675) the cost is $280 per cylinder; for Carbon Monoxide in Nitrogen (SRMs 1677–1681) the cost is $303 per cylinder; and for Nitric Oxide in Nitrogen (SRMs 1683–1687) the cost is $303 per cylinder. Purchase orders for these SRMs should be sent to the Office of Standard Reference Materials, B311 Chemistry, National Bureau of Standards, Washington, DC 20234.

APPENDIX C
PROCEDURE FOR AUTOMATIC LOADING
DIRECT-DRIVE DYNAMOMETER

Procedure:

1. Verify dynamometer speed and indicated horsepower calibrations.
2. Use typical weight car to run coastdowns after verifying speed calculation
3. Set inertia weight to 1750, horsepower to 7.7 (indicated about 6 hp)
4. Run coastdown recording time between 55 mph and 45 mph
   (a) Read horsepower directly with computer if available, or
   (b) Determine coastdown time between 55 and 45;
5. If necessary adjust internal pot on auto. dyno. Repeat coastdowns until horsepower or time (depending upon your system) is within 0.1 hp or 0.1.
6. Repeat coastdown without further pot adjustment.
7. Record FINAL repeated HORSEPOWER or TIME value.
8. Drive vehicle at 50 mph. Record INDICATED HORSEPOWER as observed on meter.
9. Repeat above for all inertia weights.
10. Check 1 or 2 coastdowns W/AC set point. Friction should be the same at each inertia weight.
11. Find friction horsepower at each inertia weight, plot and compare with previous coastdown results.

LOCATION_____ ROLLS_____ ENGINEER_____

ROLLS S/N_____ COASTDOWN DATE_____

INERTIA WEIGHT, lb	ABS HP AT 50 MPH WO/AC	COAST DOWN TIME S	FINAL HP FROM Comp.	FINAL TIME OF COAST DOWN	INDICATED HP AT 50 MPH	FRICTION HP AT 50 MPH	ABS HP AT 50 MPH W/AC
1750	7.7	13.80	____	____	____	____	8.47
2000	8.3	14.63	____	____	____	____	9.13
2250	8.8	15.53	____	____	____	____	9.68
2500	9.4	16.15	____	____	____	____	10.34
2750	9.9	16.87	____	____	____	____	10.89
3000	10.3	17.86	____	____	____	____	11.33
3500	11.2	18.98	____	____	____	____	12.32
4000	12.0	20.24	____	____	____	____	13.20
4500	12.7	21.52	____	____	____	____	13.97
5000	13.4	22.66	____	____	____	____	14.74
5500	13.9	24.03	____	____	____	____	15.29
over 5500	14.4	23.20	____	____	____	____	15.84

Run a sufficient number of coastdowns to verify that W/AC switch is increasing horsepower by 10%, as indicated in Table 2.

____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____

APPENDIX D
CRITICAL FLOW ORIFICE (CFO) PROPANE INJECTION
DATA AND CALCULATION SHEET

CVS (MANF. - NUMBER) = _____ DATE _____

ENGINEER _____ REMARKS _____

Barometer = _____ in Hg

CVS Inlet Depression (pressure) = $\dfrac{}{13.596}$ in H_2O = $\dfrac{}{\text{Enter Dif. of above in}}$ in Hg

STD. CVS FLOW equation

CVS Delta P = _____ in H_2O: CVS Flow at Operating Conditions found
from LFE Calibration Curve

STD. CVS FLOW = $\dfrac{}{} \times \dfrac{}{29.92} \times \dfrac{528}{460 + \underline{}}$ °F

Sample _____ ppm
– Bkg. _____ ppm

CVS G = _____ ft^3/rev × 51.908 × _____ × 10^{-6} _____ rev

CVS G = _____

Barometer = _____ in Hg

CFO Gage – _____ PSIG
0.4912 × Barometer = _____

P_a = _____

A, B, and C below are constants for a particular CFO. Each CFO would have its own constants.

A = 0.004 105 79 = 0. _____

$B P_a$ = 0.006 811 90 P_a = 0. _____

CP_a^2 = 0.000 004 652 42 P_a^2 = 0. _____

SUM = 0. _____

CFO GRAMS = 51.908 × $\dfrac{}{60}$ × _____

CFO Temperature = _____ °F; $(460 + T_o)^{½}$ = _____ from Table

CFO G = _____

TEST ERROR = $\dfrac{\text{CVS CALCULATED G} \underline{} - \text{CFO CALCULATED G} \underline{}}{\text{CFO CALCULATED G} \times 10^{-2}}$

= _____ % POSITIVE ERROR or NEGATIVE ERROR   (circle)
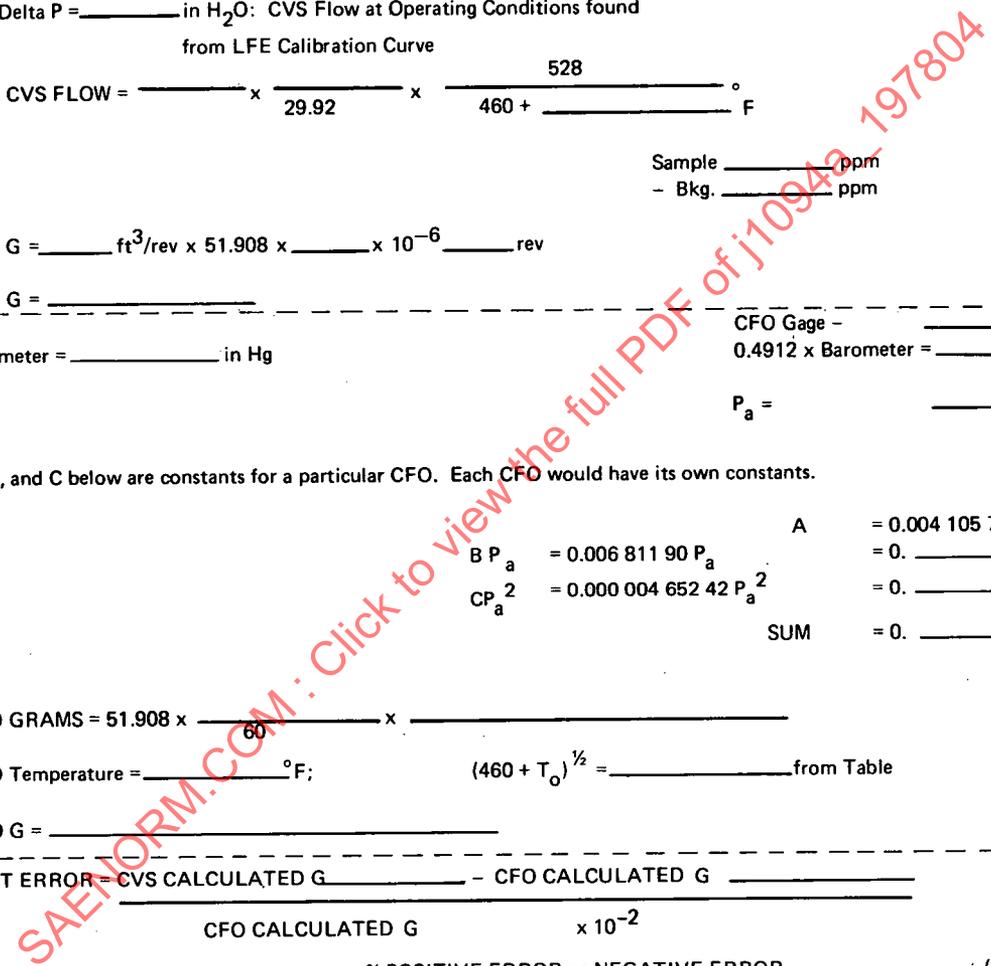
APPENDIX E
HAND CALCULATION FORM—1975 FEDERAL TEST PROCEDURE

AMBIENT CONDITIONS

Corrected Barometric Pressure (P_b) = _____ in. Hg
Wet Bulb Temperature (T_w) = _____ °F
Dry Bulb Temperature (T_d) = _____ °F

CONSTANT VOLUME SAMPLER PARAMETERS

	Phase 1	Phase 2	Phase 3
Average Delta P, in H_2O			
Average Flow, ft^3/rev			
Average P_{in}, in H_2O			
Average T_{in}, °F			
T_{obs}, T_{in} + 460, R			
Dilution Air Temp, Dry Bulb			
Dilution Air Temp, Wet Bulb			
Dilution Air Relative Humidity (R), %			
CVS Revolutions, rev			

BAG CONCENTRATIONS

	Phase 1	Phase 2	Phase 3
Dilution Bag			
HC_d, ppm			
CO_{d_m}, ppm			
NO_{xd}, ppm			
$CO2_d$, %			
Sample Bag			
HC_e, ppm			
CO_{e_m}, ppm			
NO_{xe}, ppm			
$CO2_e$, %			

CORRECTED BAG CONCENTRATIONS $CO_d = (1 - 0.000323\ R)\ CO_{d_m}$

Dilution Bag	Phase 1	Phase 2	Phase 3
R			
0.000323 R			
1 - 0.000323 R			
CO_{d_m}			
CO_d', ppm			

Sample Bag $CO_e = (1 - 0.01925\ CO2_e - 0.000323\ R)\ CO_{e_m}$

	Phase 1	Phase 2	Phase 3
$CO2_e$			
$0.01925\ CO2_e$			
$1 - 0.01925\ CO2_e - 0.000323R$			
CO_{e_m}			
CO_e, ppm			

DILUTION FACTORS

$$DF = \frac{13.4}{CO2_e + (HC_e + CO_e)\ 10^{-4}}$$

HC_e enters into this equation as ppm carbon equivalent.

	Phase 1	Phase 2	Phase 3
$HC_e + CO_e$			
CO_e			
$HC_{e_m} + CO_e$			
$CO2_e + (HC_{e_m} + CO_e) 10^{-4}$			
DF			

Facility _____   Date _____

Facility _____   Date _____