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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

abs	absolute	lb/h	pound per hour
atm	atmosphere, standard	L/min	liter per minute
°C	degree Celsius	mg/m^3	milligram per cubic meter
cm	centimeter	min	minute
ft•lbf	foot pound (force)	mm	millimeter
h	hour	N•m	newton meter
hp	horsepower	pct	percent
in	inch	ppm	part per million
in H_2O	inch of water (pressure)	r/min	revolution per minute
K	kelvin	s	second
kg/h	kilogram per hour	vol pct	volume percent
kPa	kilopascal	wt pct	weight percent

APPARATUS FOR MEASURING DIESEL TAILPIPE EMISSIONS IN UNDERGROUND MINES

By D. H. Carlson,[1] T. R. Taubert,[2] and J. H. Johnson[3]

ABSTRACT

The U.S. Bureau of Mines and Michigan Technological University (MTU) are collaborating to develop an apparatus for measuring diesel tailpipe emissions in underground mines. A tailpipe emissions measurement apparatus (EMA) is described that dilutes diesel exhaust and measures the concentrations of diesel particulate matter (DPM), CO, CO_2, NO, and NO_2 at known dilution ratios.

The EMA was evaluated by side-by-side comparison of its measurements with those by laboratory-grade instruments. Concentrations of CO and CO_2 measured by the EMA were usually within ±14 pct of concentrations measured by laboratory-grade instruments for CO and ±20 pct for CO_2. EMA-measured DPM concentrations were, on average, 29 pct lower than those measured by laboratory-grade instruments, with the differences being fairly consistent. The CO and CO_2 differences are related to the method of calculating the EMA's dilution ratio, and the difference in DPM concentrations is attributed to thermophoretic and/or condensation losses related to the EMA's unheated sample probe. Preliminary analysis of data obtained with a heated sampling probe and modifications in the sampling procedures have indicated reduced variability in DPM and in the calculated dilution ratios.

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INTRODUCTION

Diesel equipment is gaining popularity in underground coal mines[4] and is almost universally used in underground noncoal mines. From 1980 through 1990, the estimated number of underground coal mines using diesels has more than tripled to more than 200, and the number of diesels has quadrupled to more than 2,300. An estimated 6,000 pieces of diesel equipment are used in underground noncoal mines. The increased use is related to the recognition that diesel-powered vehicles are more flexible, which can contribute to increased productivity when compared to their electrically powered counterparts.

However, the use of diesel equipment in underground mines is controversial. The National Institute of Occupational Safety and Health (NIOSH) has recommended that "whole diesel exhaust be regarded as a "potential occupational carcinogen," as defined in the Cancer Policy of the Occupational Safety and Health Administration." NIOSH further stated that "though the excess risk of cancer in diesel-exhaust-exposed workers has not been quantitatively estimated, it is logical to assume that reduction in exposure to diesel exhaust in the work place would reduce the excess risk" (*1*).[5] In 1989, the International Agency for Research on Cancer also classified diesel exhaust as "probably carcinogenic to humans" (*2*). In 1988, the U.S. Mine Safety and Health Administration (MSHA) was directed by an advisory committee to establish a DPM standard and regulations to minimize exposure to all diesel pollutants in underground coal mines (*3*).

Diesel-exhaust-pollutant concentrations underground are dependent upon the quantity of ventilation air and exhaust emission rates. Inadequate maintenance, improper adjustments, and wear of the diesel engine, and other factors may cause changes in diesel-exhaust-emission rates. For example, measurements have shown that an improperly tuned diesel engine can increase concentrations of some pollutants by a factor of 10 (*4*). A method for detecting changes in emissions caused by poor maintenance and wear is needed to determine when corrective action is required. Additionally, such measurements would assure that tailpipe emissions control systems are functioning correctly.

An EMA that dilutes diesel exhaust and allows measurement of DPM, CO, CO_2, NO, and NO_2 concentrations was developed by MTU under contract to the U.S. Bureau of Mines.[7] The EMA enables the exhaust of diesel engines to be monitored on a regular basis so that engines producing excessive exhaust pollutants can be identified and taken out of service for maintenance. As part of the Bureau's program to improve safety of the underground worker, this report (1) describes the design and operation of the EMA and (2) presents results of preliminary laboratory tests designed to evaluate the accuracy of EMA measurements.

EMISSIONS MEASUREMENT APPARATUS DILUTION SYSTEM

The EMA dilution system (fig. 1) is designed to instantaneously dilute and cool a sample of hot, moist diesel exhaust with nitrogen or air at a predetermined dilution ratio.[6] The dilute sample is then passed through a preweighed particulate filter, and a portion of the filtered exhaust is collected in a gas-sampling bag for later analysis.

Instantaneous dilution simulates the situation where hot, raw diesel exhaust is rapidly emitted into the mine air. Because most chemical reactions are temperature and concentration dependent, instantaneous dilution and resultant cooling would be expected to greatly reduce the effect of such reactions on the measured concentrations.

The DPM concentration is determined gravimetrically. The concentrations of CO, CO_2, NO, and NO_2 are measured by connecting the gas-sampling bag to portable instruments immediately after collecting the sample. Measurements for NO and NO_2 are made first because the bag concentrations change over time (*5*). NO_2 is difficult to measure accurately because of the difficulty of preparing calibration standards.

The EMA is designed to be used during a stationary test of an underground mine vehicle and not on vehicles during production from actual mining operations. In-mine tests are conducted by operating the engine under high load at a single speed with the vehicle parked. This test condition is achieved by depressing the vehicle's brake, engaging the transmission in high gear, and pressing the accelerator pedal to the floor. It represents the condition of maximum torque on the engine. It is repeatable and operates the engine at a low air-to-fuel mass ratio (A/F) that results in the production of high CO and DPM

[4]Information obtained from R. W. Waytulonis, Twin Cities Research Center, in 1990.

[5]Italic numbers in parentheses refer to items in the list of referenes at the end of this report.

[6]Dilution ratio as used here is defined as the volume of the dilute mixture per unit volume of exhaust at the same temperature and pressure.

[7]Work done by MTU under Bureau of Mines contract J0199125.

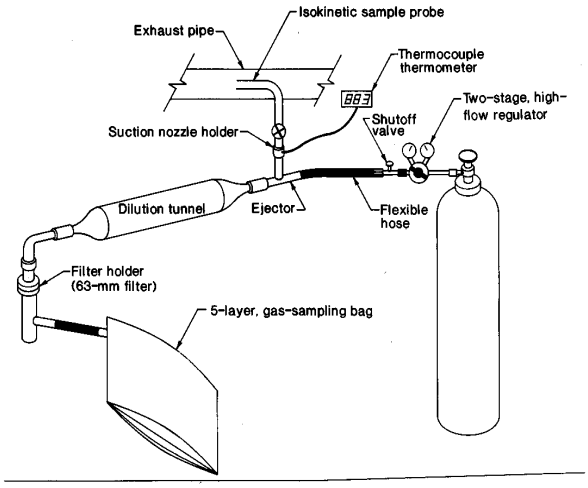

Figure 1.—EMA dilution system.

concentrations. Engine faults magnify these concentrations at this condition, and it has been reported that excessive CO production can only be detected at a high engine torque condition (*6*). The temperature of the transmission fluid is monitored and maintained within the manufacturer's recommended limits by adjusting the amount of time the engine is allowed to idle between repeat tests. Experience has indicated that when sampling times are less than 1 min, the fluid temperatures are maintained even after a number of repeat measurements.

FLOW RATE CONTROL

The EMA uses an air ejector (*7*) to mix compressed nitrogen or air with diesel exhaust. Under test conditions, the air or nitrogen flows into the ejector's venturi-shaped motive nozzle under a pressure that is maintained at more than twice atmospheric to maintain critical flow conditions (*7*). For a nozzle of given diameter under critical flow conditions, the flow rate (F) is controlled primarily by controlling the pressure upstream of the nozzle and is not affected by the downstream pressure. F is calculated by equation 1:

$$F\ (\text{L/min at } T_2,\ P_2) = \frac{56.77 \times C_d \times d^2 \times P_1 \times T_2}{P_2 \times \sqrt{T_1}}, \quad (1)$$

where T_2 = temperature at which volume F is expressed, K,

P_2 = pressure at which volume F is expressed, kPa (abs),

C_d = nozzle coefficient of discharge,

d = nozzle throat diameter, cm,

P_1 = nozzle inlet pressure, kPa (abs),

and T_1 = nozzle inlet temperature, K.

The low pressure created in the ejector draws a sample of diesel exhaust into the ejector's suction chamber. The EMA's ejector has a venturi-shaped nozzle in the suction inlet. The ejector and suction nozzle are sized to give critical flow conditions in the suction nozzle at upstream pressures as low as 1/2 atm. The exhaust flow rate through the suction nozzle is also calculated using equation 1. The dilution ratio can be varied by varying the sizes of the motive and suction nozzles.

Thus, in the EMA, controlled volumes of nitrogen and exhaust are mixed at known, controllable dilution ratios (usually about 20 volumes of mixture per volume of exhaust). The mixture passes through the ejector, then through a Pallflex T60A20[8] 64-mm-diameter (2-1/2-in) Teflon fluorocarbon polymer-coated glass-fiber filter, and finally through a splitter, which directs a portion of the dilute exhaust into a Calibrated Instruments five-layer, gas-sampling bag and rejects the remaining portion. Usually a 20-s sample collects adequate particulate for accurate determination of the increase in weight of the 64-mm filter and calculation of the DPM concentration.

EMISSIONS MEASUREMENT APPARATUS LABORATORY TESTS

LABORATORY DESCRIPTION AND PROCEDURES

The evaluation of the EMA dilution system was performed at the Bureau's Twin Cities Research Center (TCRC) diesel engine laboratory (fig. 2), which is described in detail in reference 8. A Caterpillar 3304 PCNA diesel engine was coupled to an eddy current dynamometer that can control engine speed to ±1 r/min and engine load to ±0.7 N•m (0.5 ft•lbf). The engine is rated at 86 hp at 1,800 r/min and 380 N•m (280 ft•lbf) torque at 1,200 r/min. A commercially available No. 2 diesel fuel was used (table 1).

[8]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

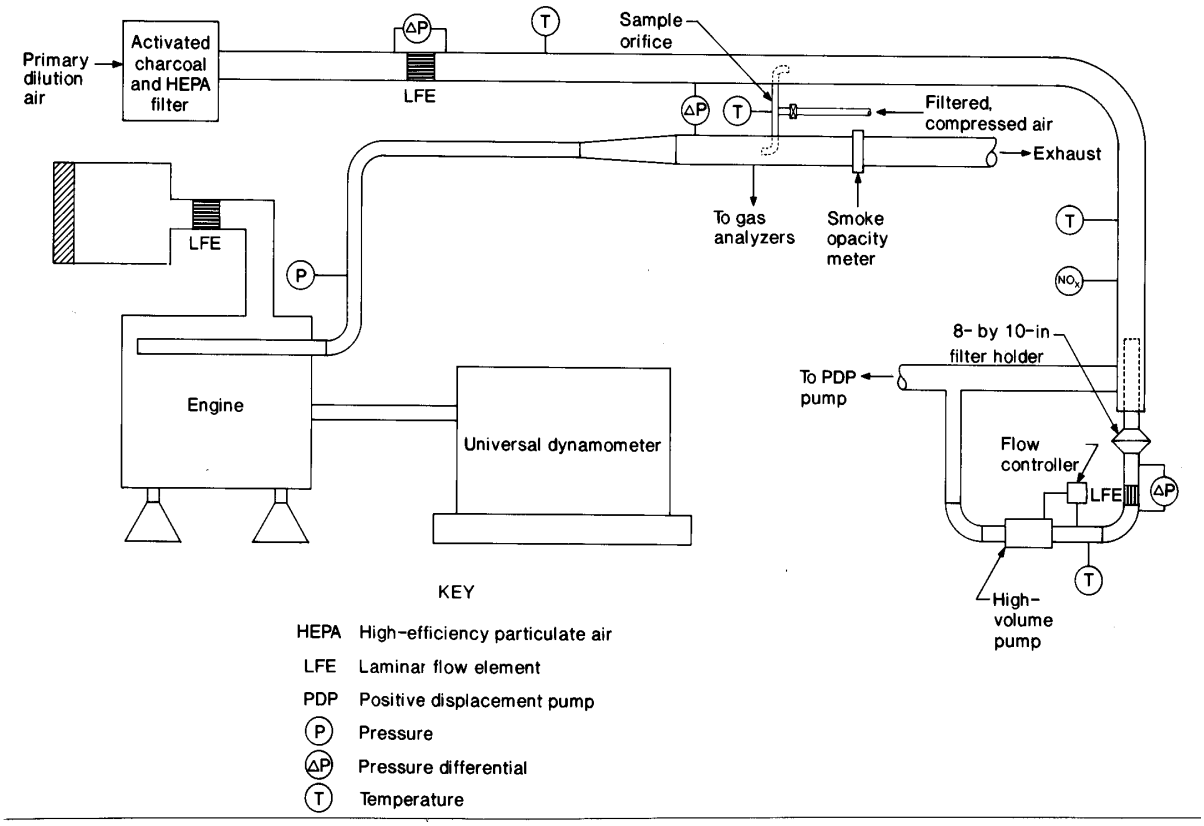

Figure 2.—Schematic of Bureau's dilution system.

Table 1.—No. 2 diesel fuel specifications

Cetane index	42.4	Total sulfur, wt pct	0.39
Gravity, API	31.5	Aromatics, FIA, vol pct	40.8
IBP, °C	169.4	Flash point, °C	71.0

API American Petroleum Institute.
FIA Fluorescent indicator absorption.
IBP Initial boiling point.

The engine was operated under steady-state conditions. Exhaust was transferred continuously from the 10.2-cm-diameter (4-in) exhaust pipe to the 15.2-cm-diameter (6-in) dilution tunnel through a 2.5-cm (1-in) sample line. The sample line contained a 1.0-cm-diameter (0.41-in) orifice for flow calculations. The temperature and static pressure of the exhaust and the pressure drop across the orifice were recorded, and these data were used to calculate the raw exhaust flow rate to the dilution tunnel. In the dilution tunnel, the raw exhaust was mixed with dilution air that was cleaned by passage through activated charcoal and a high-efficiency particulate air (HEPA) filter to remove organics and DPM. The residence time of the exhaust in the dilution tunnel was about 1 s under turbulent flow conditions (Reynolds number = 45,000). The volume flow rate of primary air mixed with the exhaust was measured using a laminar flow element.

The dilution ratio was typically 22:1 and was calculated from the raw exhaust and dilution air flow rate's. The dilution flow ratio was verified by comparison of the ratio of the NO_x concentration measured in the raw exhaust to the NO_x concentration measured in the dilute exhaust.

A constant mass flow sampler draws a portion of the dilute exhaust through a preweighed, 20.3- by 25.4-cm (8- by 10-in) Pallflex TX40HI20-WW glass-fiber filter. Prior to the initial weighing, the filter is stored overnight in a desiccator containing Drierite calcium sulfate desiccant. Final weighing of the loaded filter followed 2 h of storage in the same desiccator.

The air and fuel flow rate's to the engine were measured continuously and the A/F was calculated. The air flow rate was measured using a laminar flow element, and the fuel flow rate was measured using a Flow-Tron model 22 flow measurement system capable of an accuracy of ±0.23 kg/h (0.5 lb/h). The raw exhaust concentrations of CO and CO_2 were measured using separate Beckman model 864 nondispersive infrared analyzers. The raw

exhaust concentration of NO_x was measured using a Beckman model 955 chemiluminescence analyzer, and the dilute exhaust NO_x concentration was measured using a CSI Meloy model NA 510-2 chemiluminescence analyzer.

ENGINE CONDITIONS

A single test series involved using the EMA to measure the concentrations of DPM, CO, and CO_2 at six engine modes (table 2), while simultaneous measurements were made using laboratory-grade instruments.

Table 2.—Six steady-state operating conditions representing LHD duty cycle (9)

Mode	Engine speed	Load, pct
1	Peak torque	50
2	..do.	75
3	..do.	100
4	Rated	50
5	..do.	75
6	..do.	100

These engine load and speed combinations were selected based on earlier measurements (*9*) made on a commercial, diesel-powered load-haul-dump (LHD) vehicle while a simulated mucking operation in an underground mine was performed. Modes 1 to 6 represent different parts of the LHD cycle, as follows: (1) with the bucket empty, (2) mucking at the face, (3) backing out of the drift with the bucket loaded, (4) traveling to the dumpsite, (5) dumping the load, and (6) traveling from the dumpsite to the drift with the bucket empty.

Four series of comparison tests were performed over a 4-day period, but condensation problems in the EMA's sample probe limited the amount of meaningful data that were collected. Only data from tests 102, 103, and 104 are presented. Tests 102 and 104 were performed over a 2-day period under normal engine conditions. During test 103, a large intake air restriction was applied to the engine to simulate a clogged air filter. This broadened the pollutant level ranges and provided an opportunity to determine if the EMA could detect this engine fault.

EMISSIONS MEASUREMENT APPARATUS TEST PROCEDURE

Sampling of particulate and gaseous emissions with the EMA involved inserting the particulate filter and connecting the filter holder and gas-sampling bag to the ejector and dilution tunnel. The motive gas valve was opened and the time recorded. A thermocouple positioned in line, immediately upstream from the suction nozzle, measured the exhaust temperatures. These temperatures were recorded manually at 5-s intervals, and the average temperature was used in the calculation of the exhaust flow rate entering the nozzle. When the predetermined sampling time was complete (20 to 90 s), the motive gas valve was closed and the sample bag and particulate filter were removed. The concentrations of CO and CO_2 in the bag were read out immediately by portable, battery-powered Ecolyzer 2600 electrochemical CO and Fuji ZFP5 NDIR CO_2 instruments. The particulate filter was stored in a petri dish and conditioned 24 h in a controlled, relative humidity environment prior to reweighing, a procedure similar to that, which had been followed in determining the filter tare weights. NO and NO_2 were not measured during these tests because of inadequate calibration gases.

From two to five repeat samples were taken at each engine load-speed condition. The total available EMA sampling time at each load-speed condition was determined by the time required to load the particulate filter used for sampling the laboratory's dilution system, typically about 20 to 30 min.

PROCEDURAL MODIFICATIONS MADE DURING TESTS

The EMA was initially suspended directly below the ceiling-mounted engine exhaust pipe to make it accessible during tests. This location was later found unacceptable because condensation from the exhaust pipe dripped into the suction port of the ejector between tests, causing large variability in the DPM weights. This variability occurred even though the filters were conditioned (that is, allowed to come to equilibrium in a controlled, relative humidity environment) prior to reweighing, indicating that substances other than water, such as high-boiling-point hydrocarbons, were present. To correct this problem, a valve was inserted between the exhaust pipe and ejector suction inlet. Even with the valve closed between tests, variable results were observed.

The sample procedure was further modified by incorporating a pretest purge. This involved opening the suction inlet valve and turning on the motive nitrogen gas for 5 s prior to installing the filter and gas collection bag, then installing the filter and bag and immediately beginning the test. The objective was to remove any condensed material that had dripped into the suction line prior to collecting the samples. This procedure greatly reduced the amount of visible condensation material.

RESULTS AND DISCUSSION

COMPARISON OF EMISSIONS MEASUREMENT APPARATUS VERSUS LABORATORY-GRADE INSTRUMENTS

The data from the EMA measurements are compared with the values from the measurements by laboratory-grade instruments in table 3 and in figures 3 through 8. Figures 3 and 5 show EMA-measured CO and CO_2 concentrations versus those measured by laboratory-grade instruments for tests 102 and 104. A least squares regression line is drawn through the data and reveals that while the data correlate very well, the EMA-measured concentrations average differences of 8.5 pct for CO and 4.1 pct for CO_2 from those of the laboratory-grade instruments, with most of the EMA values being lower. One possible explanation for these differences is particulate filter plugging. The EMA requires sonic flow in both the motive and exhaust venturi nozzles for equation 1 to accurately calculate flow rate. As the particulate filter becomes loaded, pressure in the ejector increases, and if it reaches a high enough value, the critical pressure ratio is not maintained over the exhaust venturi nozzle and flow becomes subsonic. This results in higher-than-calculated dilution ratios and lower gas and particulate concentrations. To identify and correct this condition, the following approach to sample the exhaust and measure the emission concentrations has been tried with some success:

1. Collect a bag sample of exhaust gas diluted by the EMA without the particulate filter installed.
2. Collect a bag sample of exhaust gas diluted by the EMA with the particulate filter installed.
3. Measure the CO_2 concentration in the first bag and measure the concentrations of all gases in the second bag (CO, CO_2, NO, and NO_2).

Table 3.—Comparison of tailpipe concentrations measured by EMA and laboratory-grade instruments with and without engine intake air restriction

Engine condition		No intake restriction				38 in H_2O intake restriction			
		EMA			Laboratory	EMA			Laboratory
Speed	Load, pct	Av conc[1]	SD	Number of samples	conc[1]	Av conc[1]	SD	Number of samples	conc[1]
				CO_2					
Peak torque ..	50	5.4	0.0	5	5.5	6.8	0.1	5	6.2
Do	75	7.8	.2	2	7.3	9.0	.0	3	8.4
Do	100	9.0	.0	2	9.6	11.6	.5	4	10.7
Rated	50	5.3	.0	3	5.2	6.9	.0	3	5.8
Do	75	6.6	.0	4	6.8	9.0	.0	3	7.7
Do	100	8.0	.0	4	8.4	11.1	.1	3	9.4
				PARTICULATE					
Peak torque ..	50	38.9	15.0	4	50.5	45.8	5.7	6	76.1
Do	75	59.0	7.2	2	84.9	102	4.3	3	142.1
Do	100	162	1.1	2	240.6	602	29.8	4	732.7
Rated	50	111	21.0	3	99.5	94.6	14.5	3	130.0
Do	75	73.5	4.8	3	99.6	86.1	2.5	3	142.4
Do	100	66.8	3.5	4	104.3	100	3.6	3	144.1
				CO					
Peak torque ..	50	120	0.7	5	139	240	4.4	5	223
Do	75	228	12.0	2	231	497	2.1	3	485
Do	100	461	ND	1	531	1,850	4.1	3	1,746
Rated	50	200	6.1	3	223	365	.0	2	326
Do	75	256	8.3	4	272	465	6.5	3	411
Do	100	282	1.1	4	302	873	21.7	3	374

SD Standard deviation.

[1]EMA average concentrations and laboratory concentrations were measured as follows: for CO_2, by percent; for particulate, by milligrams per cubic meter; and for CO, by parts per million.

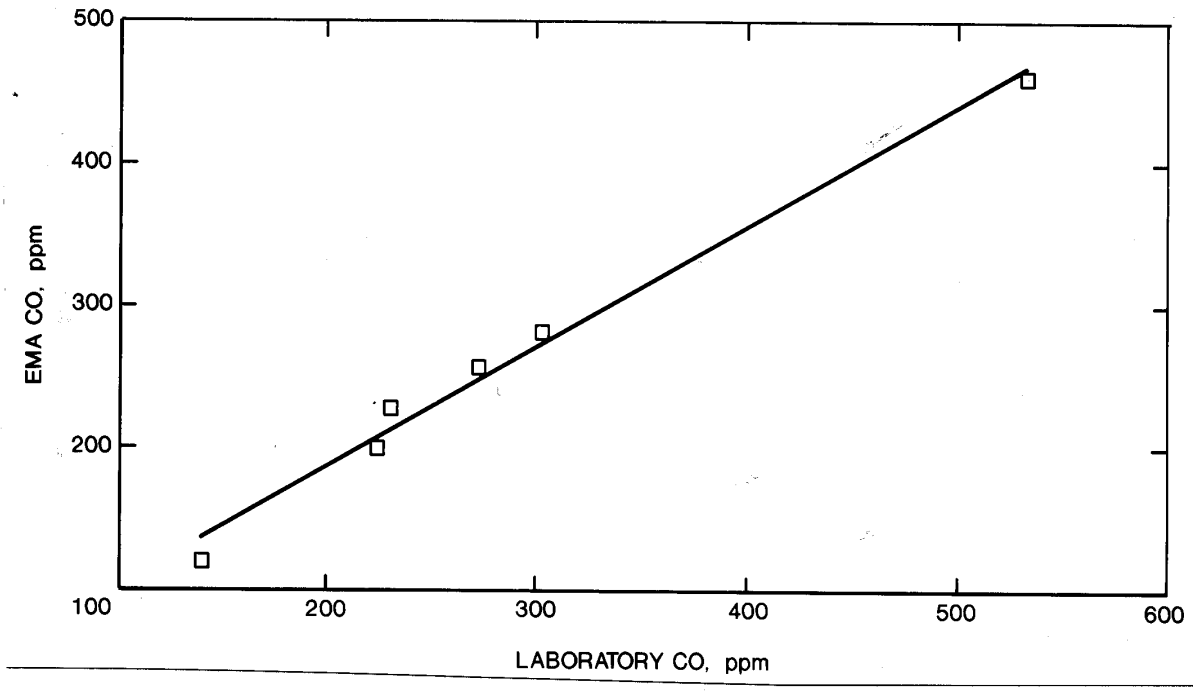

Figure 3.—CO by EMA versus laboratory-grade instruments for six engine load-speed conditions at normal engine operation for tests 102 and 104. (Slope = 0.85; correlation coefficeint = 0.99.)

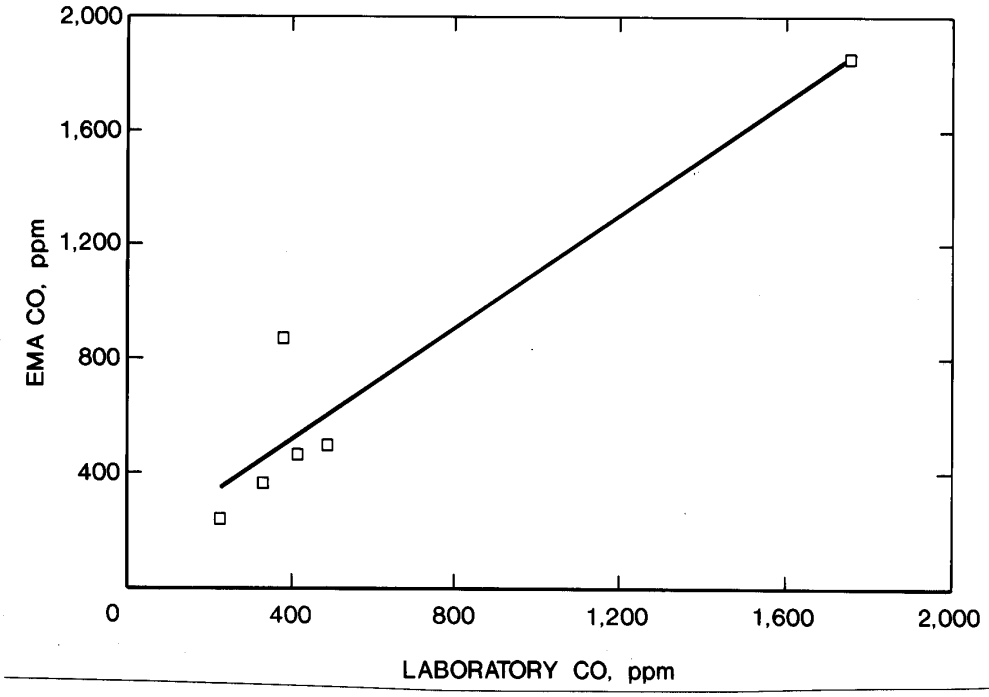

Figure 4.—CO by EMA versus laboratory-grade instruments for six engine load-speed conditions at restricted engine air intake operation for test 103. (Slope = 0.99; correlation coefficient = 0.95.)

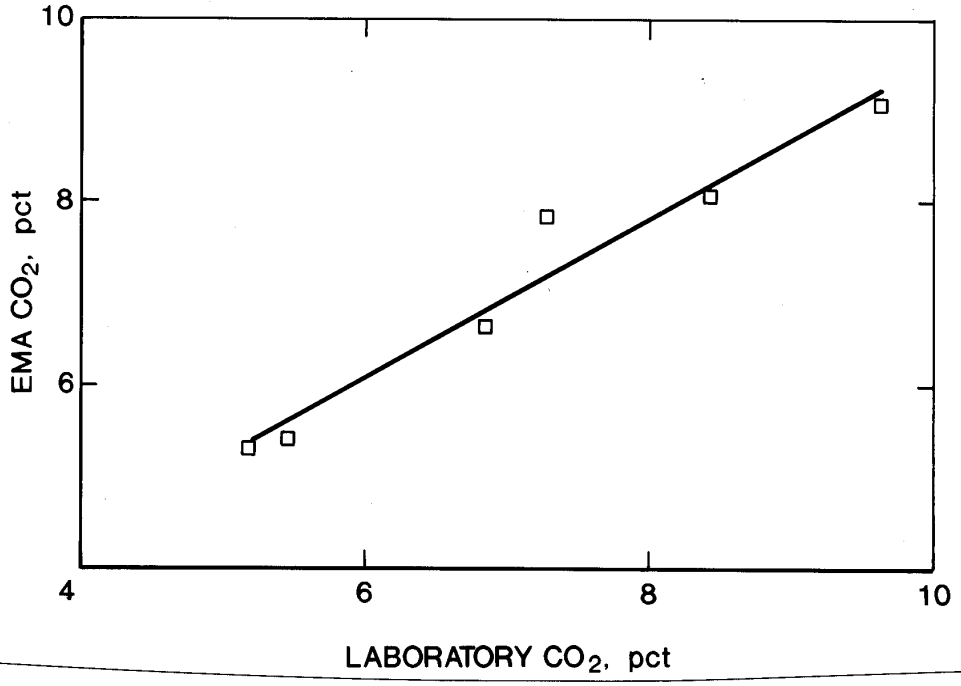

Figure 5.—CO_2 by EMA versus laboratory-grade instruments for six engine load-speed conditions at normal engine operation for tests 102 and 104. (Slope = 0.86; correlation coefficient = 0.98.)

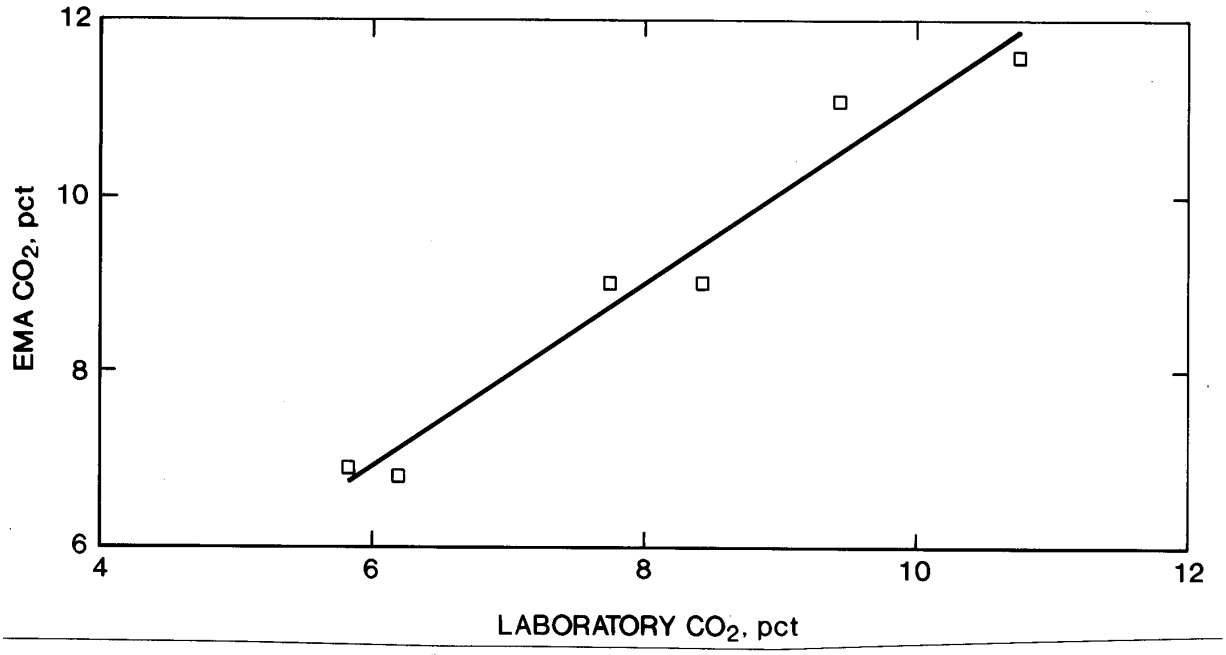

Figure 6.—CO_2 by EMA versus laboratory-grade instruments for six engine load-speed conditions at restricted engine air intake operation for test 103. (Slope = 1.05; correlation coefficient = 0.98.)

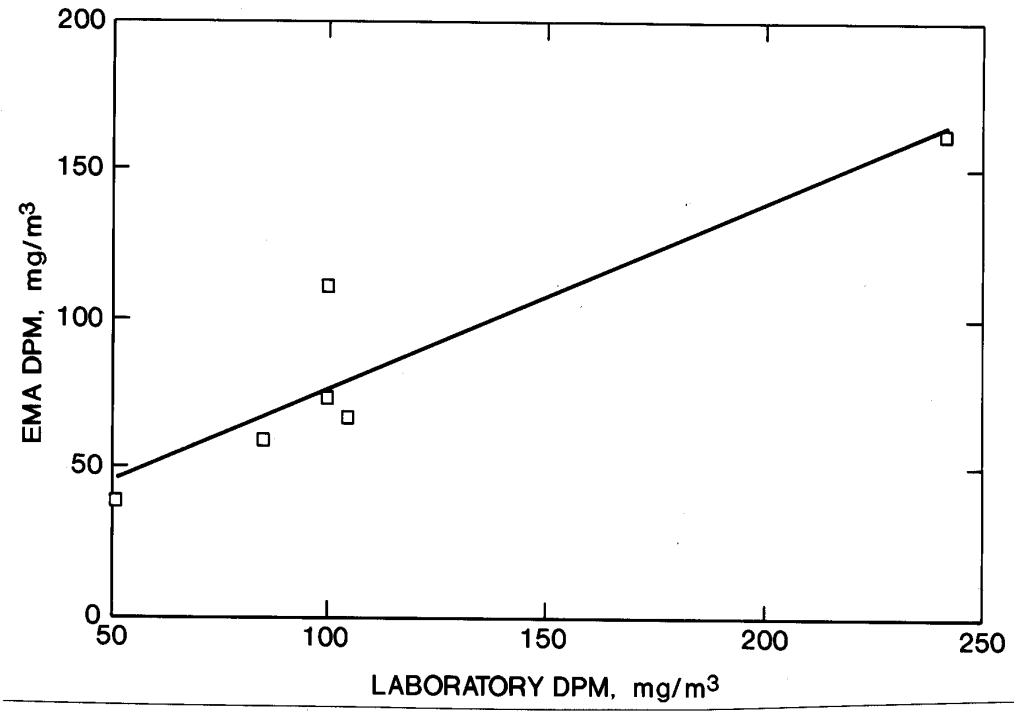

Figure 7.—DPM by EMA versus laboratory-grade instruments for six engine load-speed conditions at normal engine operation for tests 102 and 104. (Slope = 0.63; correlation coefficient = 0.92.)

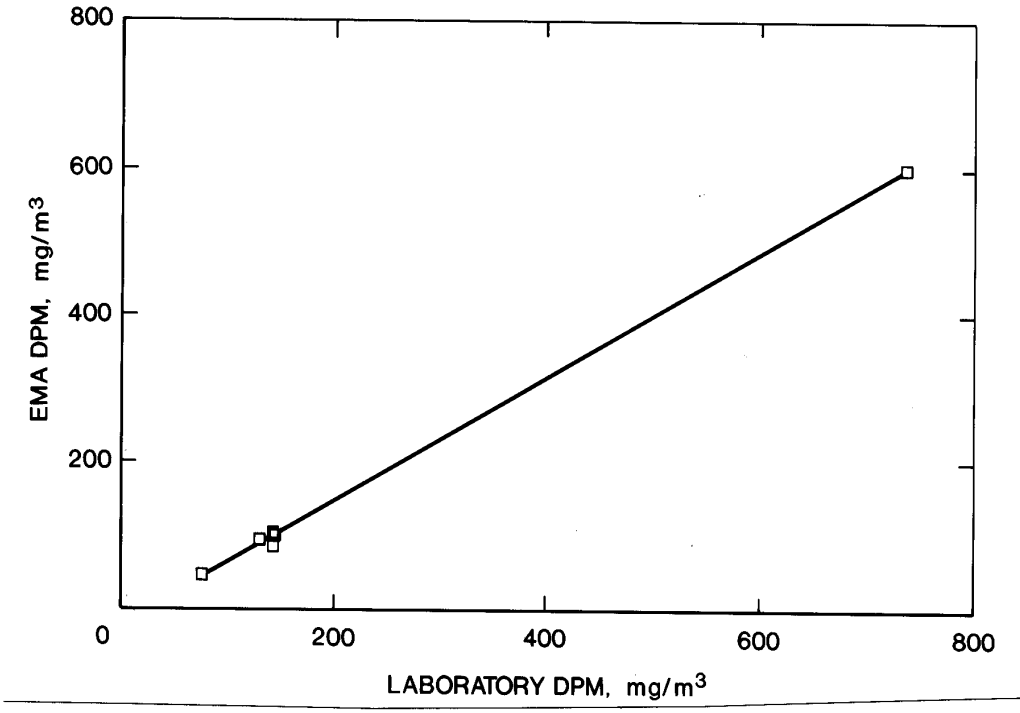

Figure 8.—DPM by EMA versus laboratory-grade instruments for six engine load-speed conditions at restricted engine air intake operation for test 103. (Slope = 0.85; correlation coefficient = 0.99.)

Because there can be no filter plugging while the first bag is collected, the exhaust flow rate and the dilution ratio should be equal to that calculated by equation 1. The exhaust flow rate may decrease with the filter installed because of plugging with a resulting lower CO_2 concentration in the dilute exhaust sample (higher dilution ratio). The actual dilution ratio can be determined by multiplying the calculated dilution ratio by the CO_2 ratio (CO_2 without filter divided by CO_2 with filter) as shown in equation 2.

$$DR_{act} = DR_{calc} \times \frac{CO_{2\ W/OFilter}}{CO_{2\ W/Filter}}, \qquad (2)$$

where DR_{act}, DR_{calc} = actual and calculated dilution ratios, respectively,

and $CO_{2\ W/Filter}$, $CO_{2\ W/OFilter}$ = CO_2 concentrations measured with and without filter installed, respectively.

Figures 4 and 6 show the relationship between CO and CO_2 concentrations measured by the EMA and laboratory-grade instruments for test 103. Results show that the concentrations measured by the EMA are higher than those by laboratory-grade instruments, with average percentage differences of 29.1 and 13.2, respectively. This discrepancy cannot be explained by filter plugging and is, at present, not understood.

Figures 7 and 8 show the DPM measurements by the EMA versus those by laboratory-grade instruments for tests 102 and 104 and test 103, respectively. Analysis indicates that all DPM concentrations measured by the EMA are lower than those by laboratory-grade instruments, except for mode 4, tests 102 and 104. The average percentage differences are 22.6 and 30.6. The fact that EMA-measured DPM concentrations are consistently lower than those measured by laboratory-grade instruments is probably due to DPM losses in the EMA as a result of cooling, condensation, and thermophoresis. Thermophoresis results in particles being repelled by a hot gas and deposited onto a cold surface. It is likely that these losses occurred because an unheated sample probe was used.

In the original EMA design, the use of a hot probe was avoided because the EMA was intended to be used underground where electrical power supplies are limited and because it was believed that the probe would be heated sufficiently by the exhaust prior to taking a sample. The present data indicate that losses are obtained with an insufficiently heated probe; thus, in the future, the probe will be wrapped with heating tape.

Thermophoresis and/or condensation-related particulate deposition on the cold surfaces of the unheated EMA sampling probe is the apparent cause for particulate concentrations that were consistently lower than those obtained by laboratory-grade instruments (about 30 pct lower on average). A heated probe has been incorporated in the apparatus, and recent laboratory measurements indicate that the particulate concentrations now agree with the values by laboratory-grade instruments.

CALCULATION OF AIR-TO-FUEL MASS RATIO FROM CO_2 CONCENTRATIONS MEASURED BY EMISSIONS MEASUREMENT APPARATUS AND LABORATORY-GRADE INSTRUMENTS

Equation 3 is the mass balance equation developed by the authors to calculate the CO_2 A/F's of the EMA and laboratory-grade instruments presented in table 4. The equation assumes complete combustion of fuel to CO_2 and water and calculates the engine intake A/F from the wet exhaust CO_2 concentration.

Table 4.—Comparison of A/F's calculated by EMA and measured and calculated by laboratory-grade instruments with and without engine intake air restriction

Engine condition		No intake restriction					38 in H_2O intake restriction				
		EMA			Laboratory		EMA			Laboratory	
Speed	Load, pct	Calc av ratio	SD	Number of samples	Measured ratio	Ratio from calc CO_2	Calc av ratio	SD	Number of samples	Measured ratio	Ratio from calc CO_2
Peak torque ..	50	38.0	0.2	5	39.0	37.3	30.0	0.5	5	34.3	33.0
Do	75	26.0	.7	2	29.5	27.9	22.4	.1	3	24.4	24.1
Do	100	22.4	.0	2	21.4	21.0	17.2	.6	4	19.2	18.7
Rated	50	38.7	.0	3	43.0	39.5	29.6	.1	3	36.4	35.3
Do	75	30.9	.1	4	32.9	30.0	22.5	.2	3	27.6	26.4
Do	100	25.4	.1	4	25.6	24.1	18.0	.2	3	23.0	21.5

SD Standard deviation.

$$A/F = \frac{(138.2 - 52.2Q)(400 - R\%CO_2)}{(229.3 + 19.3R)\%CO_2}, \quad (3)$$

where CO_2 = percentage by volume of CO_2 in exhaust-measured wet basis,

and R = number ratio of atoms of hydrogen to carbon in fuel.

$$Q = RH \times 0.00004066 \times (TDC + 273) \times e^{\frac{-(TDC-152)^2}{4,481}}, \quad (4)$$

where RH = relative humidity of air taken into engine, pct,

and TDC = temperature of air taken into engine, °C.

A/F's determined by measurements by laboratory-grade instruments of the engine intake air and fuel mass flow rate's (abscissa) compare quite well with those obtained by equation 2 using the CO_2 concentrations measured by laboratory-grade instruments (figs. 9-10). Analysis shows that the A/F measured by laboratory-grade instruments for both tests was slightly higher, with an average percentage difference of 5.8 and 3.6, respectively.

Plots of the measured A/F by laboratory-grade instruments versus the calculated A/F by the EMA (figs. 11-12) show good correlation and indicate that the A/F's are being calculated correctly from the EMA-measured CO_2 concentrations. Average percentage differences of 6.0 and 15.0 were measured.

During test 103, a restriction was applied to the engine's air intake system to simulate a dirty intake air filter and to determine if the EMA could detect this engine fault. Results show that the EMA-measured CO and DPM concentrations for test 103 are considerably higher than those for the normal engine condition (tests 102 and 104) for all six engine modes, indicating that the EMA was able to detect an engine fault. These increases were especially noticeable at peak torque speed, the peak torque where CO and particulate emissions increased by 300 and 270 pct, respectively.

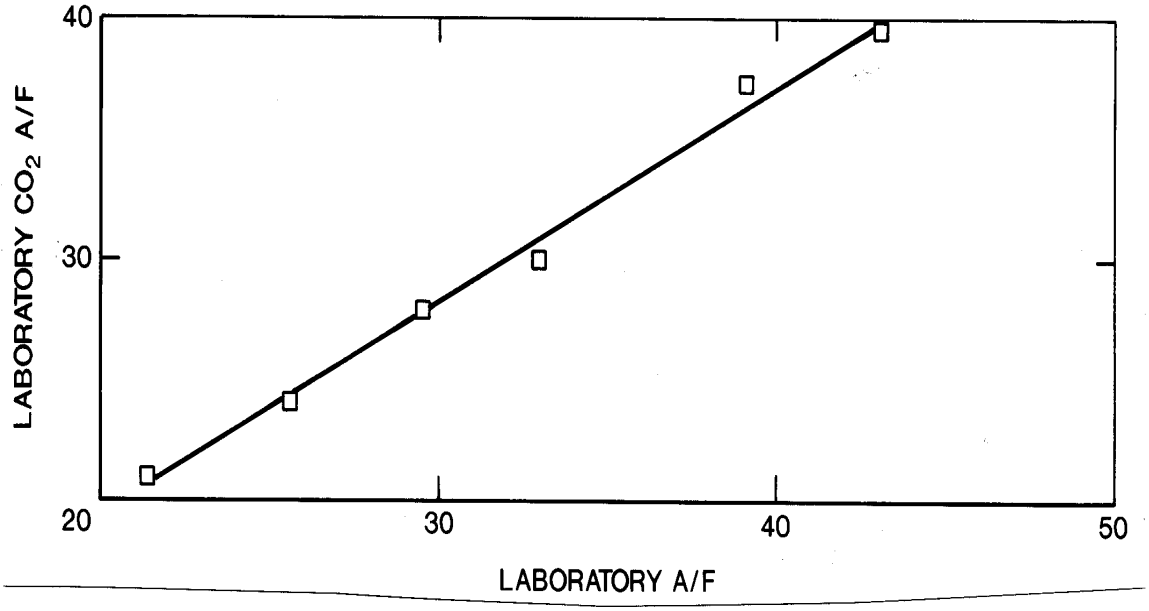

Figure 9.—A/F by laboratory-grade instruments versus A/F calculated from laboratory CO_2 concentrations for six engine load-speed conditions at normal engine operation for tests 102 and 104. (Slope = 0.89; correlation coefficient = 0.99.)

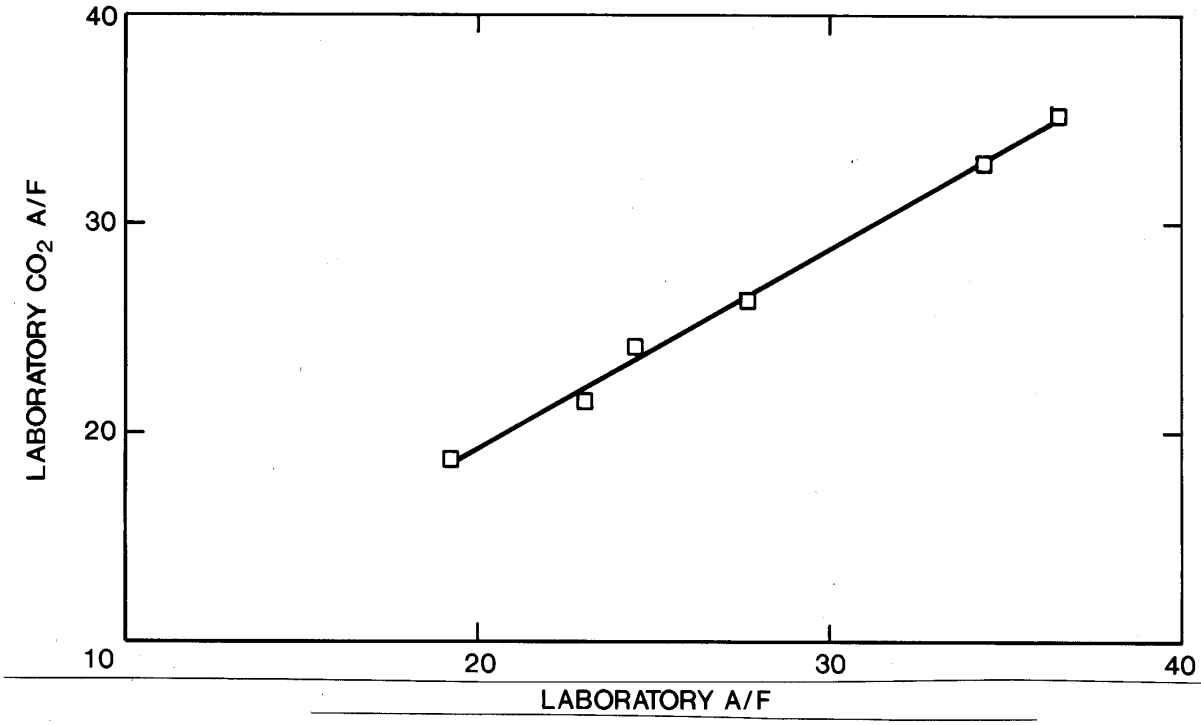

Figure 10.—A/F by laboratory-grade instruments versus A/F calculated from laboratory CO_2 concentrations for six engine load-speed conditions at restricted engine air intake operation for test 103. (Slope = 0.97; correlation coefficient = 1.0.)

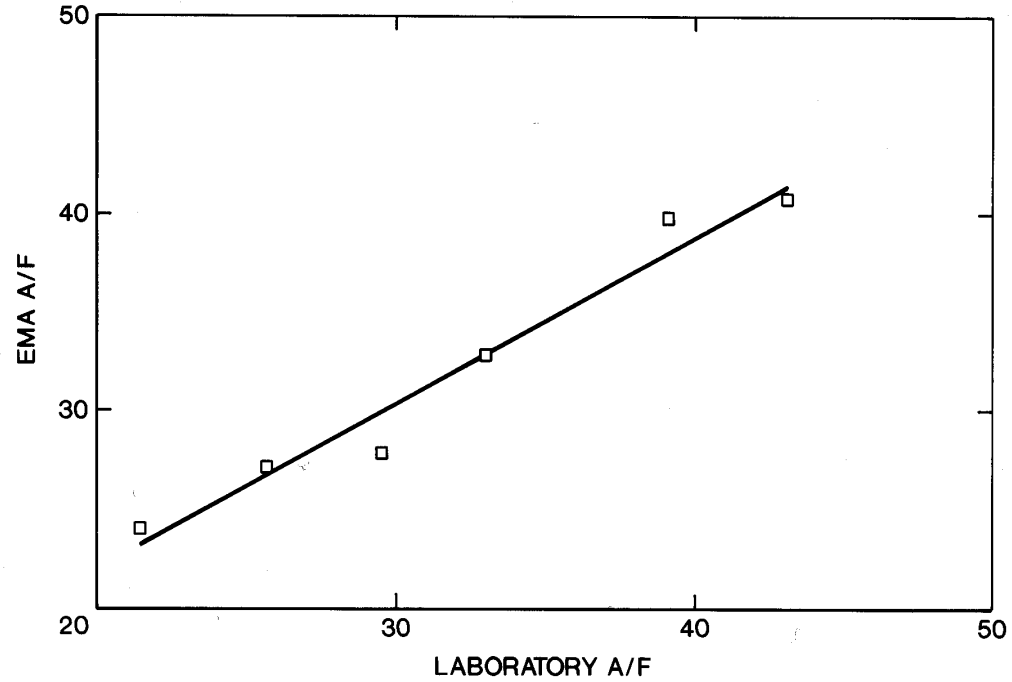

Figure 11.—A/F by EMA versus laboratory-grade instruments for six engine load-speed conditions at normal engine operation for tests 102 and 104. (Slope = 0.84; correlation coefficient = 0.98.)

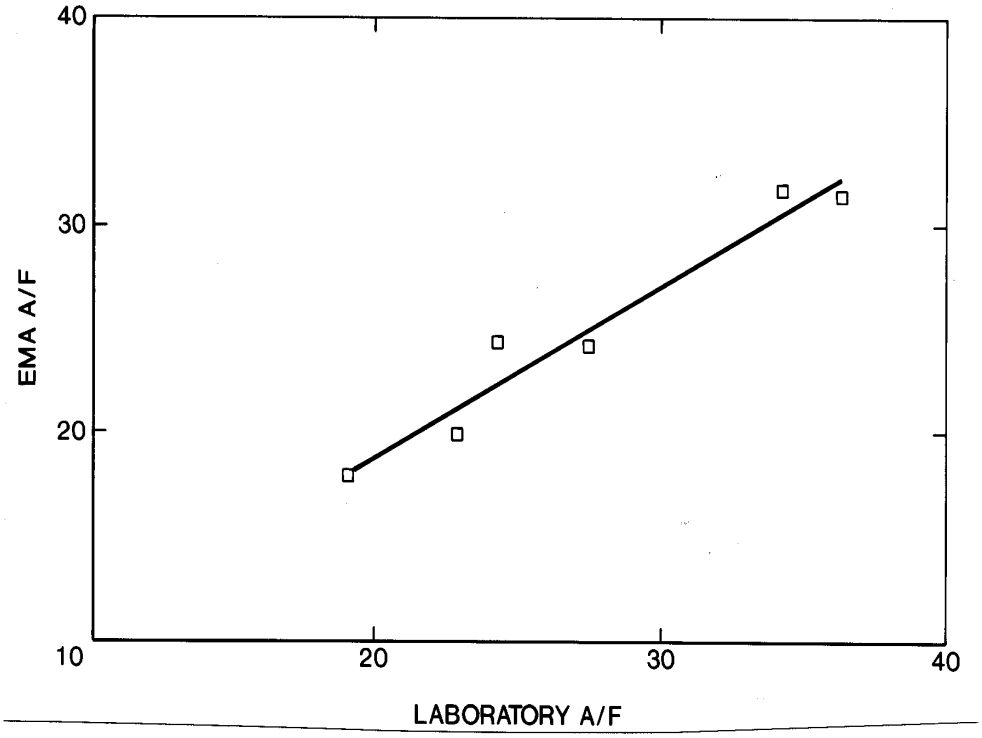

Figure 12.—A/F by EMA versus laboratory-grade instruments for six engine load-speed conditions at restricted engine air intake operation for test 103. (Slope = 0.83; correlation coefficient = 0.97.)

SUMMARY

In conclusion, the EMA can sample and dilute hot, moist, diesel exhaust, filter the dilute sample for determination of the DPM concentration, and provide an exhaust sample to portable CO, CO_2, NO, and NO_2 instruments at a known dilution ratio. Raw exhaust CO and CO_2 concentrations obtained by measuring the dilute exhaust concentrations with portable instruments and multiplying by the known dilution ratio were compared with laboratory-grade-instrument measurements and were within about ±14 pct for CO and ±20 pct for CO_2.

Variability in measured DPM, CO, and CO_2 concentrations is attributed primarily to a problem associated with condensate flowing from the exhaust system into the sample probe. In some instances, condensation droplets were visually observed on the filter holder. This source of variability has now been eliminated by making sure that gravity tends to empty rather than fill the probe. This involves simply making sure that the end of the probe is always lower than the first few inches of length.

Filter plugging was found to reduce the raw exhaust flow rate, thereby increasing the dilution ratio above the calculated value and giving minor errors in some of the calculated raw exhaust concentrations. A simple procedural modification by which to determine the actual dilution ratio involves the collection of two bags of dilute exhaust, one with and one without the particulate filter. The correct dilution ratio can be obtained by multiplying the calculated value by the ratio of the CO_2 concentration without the filter to the CO_2 concentration with the filter. Recent tests indicate that this new procedure has eliminated this source of error.

An intake air restriction fault was applied to the engine to determine if the EMA could detect the effects of this fault by measuring an increase in emissions. Results show that the EMA-measured CO and DPM concentrations are considerably higher than those for the normal engine condition, indicating that an engine fault was present.

Additional laboratory testing has been undertaken to verify the accuracy and precision of the EMA after making the recommended changes.

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