3215 Luyung Drive
Rancho Cordova, CA 95827, USA
ph. (916) 368-4770
fax (916) 362-2579

RAVEM SYSTEM TECHNICAL SUMMARY

Christopher Weaver, P.E.

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The Ride-Along Vehicle Emissions Measurement (RAVEM) was among the first portable emission measurement systems (PEMS) to be developed, and is presently the only commercially-available PEMS that can measure emissions of PM as well as NOx, CO, and CO_2. Optional capabilities also allow the measurement and quantification of total hydrocarbons (THC), sulfur dioxide (SO_2), ammonia (NH_3), and nitrous oxide (N_2O), as well as individual species of volatile organic compounds (VOC) and carbonyls such as formaldehyde, acetaldehyde, and acrolein.

During the last four years, RAVEM systems have been applied to measure pollutant emissions from a wide variety of mobile sources, ranging from transit buses in Mexico City[1] to ferryboats on San Francisco Bay[2]. They have also been applied to the evaluation of emission control systems including selective catalytic reduction, diesel particulate filters, diesel oxidation catalysts, natural gas and LPG engines, and emulsion fuels.

Principles of Operation

The RAVEM system is described in two published papers[3,4], so its operating principles are summarized only briefly here. As Reference 3 explains in more detail, the RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the air dilution and total flow arrangements are such that the pollutant *concentration* in the CVS dilution tunnel is proportional to the pollutant *mass flow rate* in the vehicle exhaust. Gaseous pollutant concentrations can be measured readily, as can integrated concentrations of particulate matter. On the other hand, exhaust mass flow rates are difficult and expensive to measure accurately – especially under transient conditions.

The total pollutant mass emissions over a given driving cycle, such as the US Federal Test Procedure, European Transient Cycle, or Mexico City Bus Cycle, are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone. The CVS flow rate enters into the calculation as a constant multiplier. The integration of pollutant concentration can be accomplished either numerically or physically. The vehicle exhaust mass flow rate does not enter into the calculation, making it unnecessary to measure.

For gases, the RAVEM system uses both numerical and physical integration. Concentrations of NOx, CO_2, and CO in the dilute exhaust gas are recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in Tedlar® bags during the test, and analyzed afterward for NOx, CO_2, CO and (optionally) other pollutants.

In CVS sampling for particulate matter, sample integration is accomplished physically -- by passing dilute exhaust mixture through a pre-weighed filter at a constant, controlled flow rate. The weight gain by the filter is then divided by the volume of mixture passed through it to yield the average particulate concentration over the test cycle.

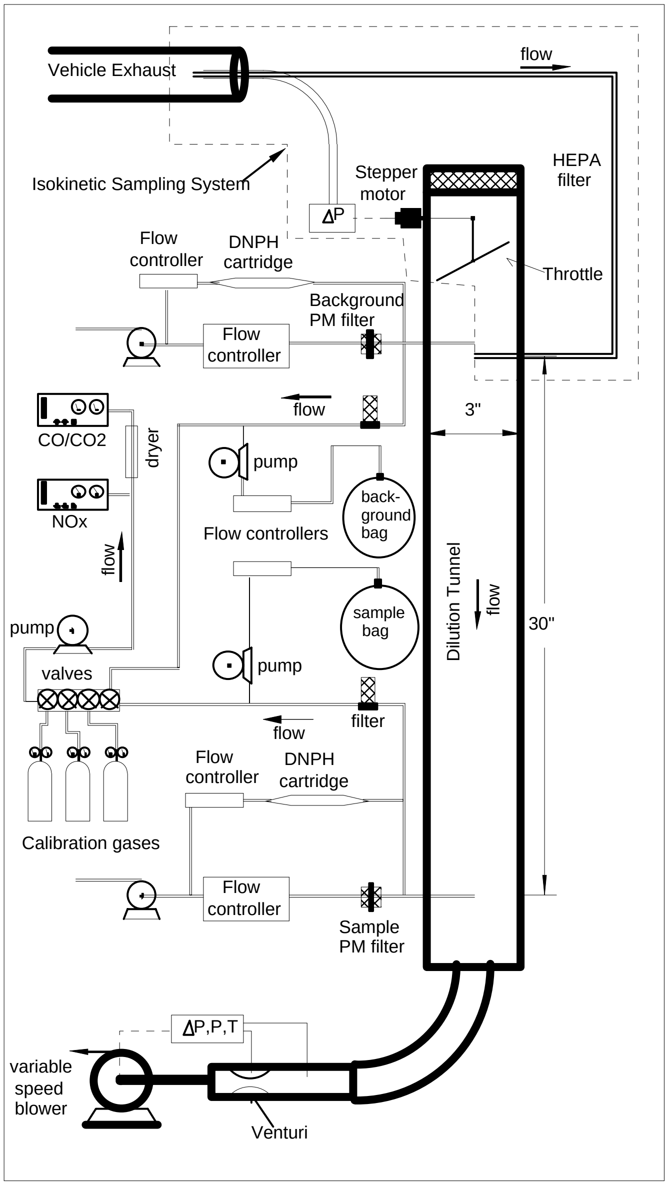

Figure 1: Schematic diagram of the RAVEM system

A schematic diagram of the RAVEM system is shown in Figure 1. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

Conventional emission laboratory methods defined by the U.S. EPA[5] and California ARB[6] utilize full-flow CVS, in which the entire exhaust flow is extracted and diluted with air. However, the large amounts of dilution air required make full-flow CVS impractical for portable systems.

The principle of the RAVEM sampling system is as follows: the RAVEM's sampling system extracts and dilutes only a small, constant fraction of the total exhaust flow. The dilution air requirements and dilution tunnel size can thus be reduced to levels compatible with portable operation. The patented isokinetic proportional sampling system[7] continuously adjusts the sample flow rate so that the flow velocity in the sample probe is equal to that of the surrounding exhaust. Since the velocities are equal ("isokinetic"), the ratio of the flow rates in the exhaust pipe and the sample probe is equal to the ratio of their cross-sectional areas.

Pollutant concentration measurements in the RAVEM system follow the methods specified by the U.S. EPA (US CFR Vol 40 Part 86) and ISO standard 8178. The pollutants measured are:

- Oxides of Nitrogen (NOx) by chemilumenescent analysis of the dilute exhaust sample;
- Carbon monoxide (CO) and carbon dioxide (CO_2) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample;
- Particulate matter (PM) by passing the dilute exhaust sample through pre-weighed 47 mm filters of Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing;
- (Optional) total hydrocarbons by flame ionization detection (FID). This option is most useful for gasoline and alternative fuels, since THC emissions from diesel engines are usually very low and of little concern. When used, the separate sample probe, sample line, and FID analyzer are all heated to 190 ^{o}C;
- (Optional) speciated volatile organic compounds (VOC) can be measured by gas-chromatographic (GC) analysis of the integrated bag samples, using flame ionization detectors in a method patterned on California Air Resources Board methods 102 and 103. This approach is especially useful with natural gas vehicles, as it is possible to distinguish unreactive methane and ethane from reactive VOC species;
- (Optional) aldehydes and other carbonyls by collection in silica-gel cartridges coated with di-nitro phenyl hydrazine (DNPH), followed by elution with acetonitrile and analysis of the eluate by high-pressure liquid chromatography, as specified in U.S. EPA method TO-11a;
- (Optional) sulfur dioxide (SO_2) by UV fluorescence or non-dispersive UV analysis;
- (Optional) ammonia (NH_3) and nitrous oxide (N_2O) emissions by Fourier transform infrared (FTIR) analyis, using a heated sample line, and sample cell.

RAVEM Subsystems and Operation

The RAVEM system comprises the following key subsystems.

- Miniature constant volume dilution system
- Isokinetic proportional sampling system
- Bag sampling system: a) exhaust sample; b) background air sample
- Gas analyzer system: a) CO/CO_2; b) NO_x
- Particulate sampling system
- Cartridge sampling system (not used in this test program)
- Data processing and handling system
- Auxiliary inputs

Miniature Constant-Volume Dilution System

This constitutes the heart of the RAVEM system. As diagrammed in Figure 1, the variable speed blower draws dilute air/exhaust gas mixture out of the dilution tunnel at a constant rate (expressed in standard liters per minute). The flow rate is controlled by a closed-loop system that measures volumetric flow rate via a venturi meter, corrects this to standard conditions of one atmosphere pressure and 20^o C, and then adjusts the blower speed to maintain the flow setpoint. The venturi meter is calibrated against a high-accuracy hot-wire mass flow meter (not shown) in order to compensate for any drift. High accuracy is needed, as any error in the mass flow will result in a proportional error in the final results.

Raw exhaust gas enters the dilution tunnel near the upper end, where it mixes with filtered dilution air. The relative proportions of exhaust gas and dilution air are controlled by the isokinetic sampling system, by means of the throttle in the air inlet.

Isokinetic Proportional Sampling System

The isokinetic sampling system comprises: a) the sampling probe in the exhaust pipe; b) an insulated sample line connecting the sampling probe to the raw gas inlet on the dilution tunnel; and c) the system for controlling the sample flow to maintain isokinetic conditions. The control system uses static pressure taps on the inside and outside surfaces of the probe, connected to a sensitive differential pressure sensor. When this sensor reads zero, the inside and outside pressures are the same. This requires that the velocities inside and outside the sample probe also be equal – i.e. isokinetic. Thus, exhaust gas entering the sampling probe is equal in velocity to that in the main engine exhaust stream ($v_1 = v_2$).

The throttle at the upstream end of the dilution tunnel is connected to a “smart” motor/controller combination. The controller responds to the signal from the differential pressure sensor by changing the throttle position to maintain isokinetic conditions. When the exhaust flow rate increases, the controller closes the throttle somewhat, increasing the pressure drop between the probe and the dilution tunnel, and thus increasing the flow velocity through the probe. When the exhaust flow decreases, the throttle opens, decreasing the pressure drop and the flow velocity in the probe. A fan upstream of the throttle (not shown) extends the possible range of dilution tunnel pressures to include slightly positive as well as negative values (compared to ambient atmospheric pressure).

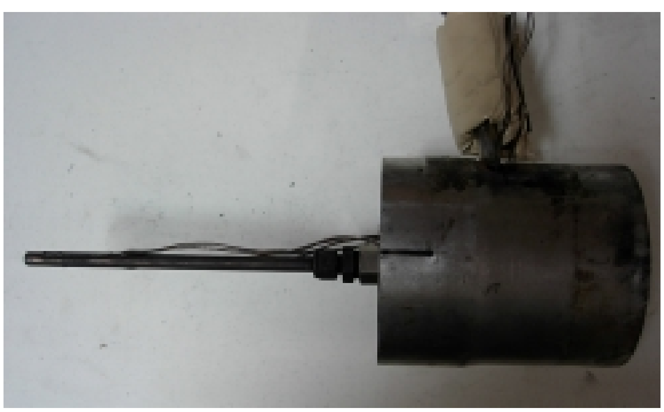

Figure 2: Exhaust probe, mount, and sample line

Since the control system depends on equalizing the static pressures measured inside and outside the probe, leaks or other problems in the pressure taps, pressure lines, or differential pressure sensor can affect the measured pressure difference, and thus the emission results. To aid in detecting this problem, the RAVEM incorporates a system for *in situ* leak checks on the differential pressure lines.

Bag Sampling System

The bag sampling system is designed to fill one pair of Tedlar bags for each test. One bag contains an integrated sample of the dilute exhaust from the dilution tunnel, and the other contains an integrated sample of the dilution air. Two choices are available with respect to the Tedlar bags: a pair of internal bags having a usable volume of about 10 liters, or a pair of 60 liter external bags fed through two quick-connect ports on the exterior of the system unit. The system is designed to allow the external bags to be exchanged quickly between tests, so that the bag samples for each test can analyzed off-board – e.g. by gas chromatograph. A pair of manually operated three-way valves selects the internal or external bags.

For each bag, gas is drawn from a sample port in the dilution tunnel, through a filter to a small pump. It then passes through a mass flow controller to the bag selector valve, and thence to the bag. The flow rate to the bags typically ranges from 0.25 to 1.5 standard liters per minute, and is kept constant during each emission test. The flow rate is normally calculated and set automatically, to capture a specified volume of gas over the length of the emission test. It can also be set manually by the RAVEM operator. The volume flowing to the sample bag is added to the total CVS flow in calculating the emission results.

Any leaks in the sample bag will directly affect the bag emission results. A leak check is therefore performed in the process of emptying the sample bags before each test.

Gas Analyzer System

The gas analyzer system comprises a sample pump, valve manifold, and conventional laboratory-grade heated NOx and ambient-temperature CO/CO_2 analyzers installed in a shock-mounted 19 inch rack inside a protective case. The standard NOx analyzer is a California Analytical Instruments HCLD 400 equipped with an NO to NO_2 converter using activated carbon. The analyzer is maintained at 60^oC, making it unnecessary to dry the sample to avoid condensation Dry, low-pressure compressed air for the ozone generator is supplied by an on-board pump by way of a filter and desiccant cartridge.

The standard CO/CO_2 analyzer is a California Analytical Instruments model ZRH using non-dispersive infrared (NDIR) analysis. Water vapor interferes with the NDIR measurement, especially for CO, and must be removed from the sample. This is accomplished by passing it through a Nafion™ semi-permeable membrane mass-exchanger. Dry gas for the other side of the mass exchanger is supplied by a small pump circulating air through a desiccant cartridge.

Figure 3: RAVEM gas analyzer system in shock-mounted case

The gas analyzer system valve manifold allows the analyzer sample feed to be drawn from any one of the following sources: the dilute exhaust mixture in the dilution tunnel, the dilution air entering the tunnel (for background measurements), the integrated sample bag, the integrated background bag, zero gas, CO/CO_2 span gas, or NOx span gas. The latter three gases are used for calibration, and are supplied to quick-connect ports on the exterior of the RAVEM system unit.

During an emission test, gas concentrations in the dilute exhaust are monitored continuously, and recorded about once per second. After the test ends, the analyzers are normally again calibrated prior to analyzing the concentrations in the sample and background bags.

Since the second-by-second pollutant readings can be affected by drift, vibration, and changes in background pollutant concentrations as the vehicle drives, the bag data are normally more accurate, and are generally the ones reported. The second-by-second data are useful for examining the variation in emissions over the driving cycle, and also provide a backup should the bag results be compromised – e.g. by bag failure during a test.

Particulate Sampling System

The particulate sampling system comprises a vacuum pump, two flow controllers, two shutoff valves, and two filter holders: one for the PM sample, and one for the background dilution air. Each filter holder contains two 47 mm filters in series. The filters should be composed of Teflon-coated borosilicate glass, and meet U.S. EPA (40 CFR 86.1311-90) and ISO 8178 specifications for diesel PM measurement. Two sets of filter holders are supplied with each RAVEM system. They are designed to be quickly connected and removed from the sampling system, thus allowing one emission test to go on while the filters from the last test are being exchanged for the filters for the next.

Figure 4: PM filter holder and exposed filters

During an emission test, the shutoff valves are opened, and the dilute exhaust gas and dilution air are drawn through their respective filter sets. The filtered gas then passes through the flow controllers to the vacuum pump, where it is exhausted. The flow controllers maintain a constant flow rate (typically 10 to 30 SLPLM, depending on the anticipated PM loading) throughout the emission test. Integrated flow volume is recorded during the emission test in order to calculate the particulate mass concentration in the dilute air/exhaust sample and in the background dilution air.

The filter set exposed to the dilution air provides a “blank” sample for each test, correcting for the effects of changing humidity, atmospheric pressures, and any ambient PM (including condensable species) present in the filtered dilution air. Experience has shown that such corrections can amount to 0.01 to 0.02 grams of PM per BHP-hr, which is of the same order as the PM emissions from some low-emission vehicles.

Cartridge Sampling System

The DNPH cartridge sampling system is similar in design to the PM sampling system described above, comprising two shutoff valves, two holders for SKC 6 mm glass sampling tubes, two flow controllers, and two sample pumps. The DNPH sampling system differs from the PM sampling system in having much lower designed flow rates (i.e. 0 to 2 liters per minute, rather than 0 to 30), and in drawing from the filtered sample stream that also feeds the Tedlar bags, rather than directly from the dilution tunnel.

To measure the concentration of carbonyls such as formaldehyde, acetaldehyde, and acetone, the cartridge sampler is loaded with two 6 mm glass tubes containing DNPH-impregnated silica gel. Gas is drawn from the sample and dilution air ports, through filters, and then through the cartridges, where any carbonyls present react with the DNPH and are retained in the cartridge. The cartridges are then removed, placed in a cooler at approximately 4 ^{o}C, and transported to the laboratory, where they are kept in a freezer until analysis by high performance liquid chromatography (HPLC), as specified in EPA method TO-11a.

Data Processing and Handling System

The data processing and handling system comprises a laptop computer, connected to a National Instruments Fieldpoint system containing 24 analog-to-digital channels, 8 digital-to-analog channels, 36 digital outputs, 8 general-purpose digital inputs, and 4 counter inputs. These include a number of spare inputs and outputs beyond those required by the RAVEM system itself, making it easy to interface auxiliary sensors.

The RAVEM system measures and records numerous data on a second-by-second basis during each emission test, including the raw inputs and calculated concentrations of CO, CO_2, and NOx, the CVS flow rate, throttle position, and differential pressure sensor reading. Calibration data relating the raw inputs and calculated concentrations are also recorded, making it possible to recalculate the second-by-second results using the calibration at the end of the test. Exhaust temperature and up to two auxiliary temperatures are recorded second-by-second; in addition, the temperature, barometric pressure, and humidity are recorded at the beginning of each test. All of these are stored in separate data file for each test, in a compact binary format.

A data file reading utility is supplied with the RAVEM system. This utility can be used to review and correct the data collected for each test, and to add data developed later such as the post-test weights of the particulate filters. This utility can also copy the data to a Microsoft Excel worksheet file. This file is formatted to be “human readable”, and occupies much more space than the compact binary format. Copies of the Excel worksheets for each emission test are given in the CD ROM that accompanies this report, along with summary worksheets that combine the individual test results.

Auxiliary Inputs

Auxiliary inputs to the RAVEM system include a global positioning system (GPS) receiver, as well as user-specified pulse, voltage, and 4-20 ma current inputs. The GPS system provides three-dimensional location and velocity data, based on signals from the global positioning network. These are supplied and recorded at a frequency of 1 Hz.

Quality Control Measures

RAVEM operating procedures include a number of quality assurance measures. Two key QA procedures are CO_2 recovery tests and fuel consumption checks. The CO_2 recovery check injects CO_2 gas from a cylinder into the dilution tunnel, and compares the CO_2 mass measured to the change in weight of the CO_2 cylinder. This confirms the accuracy of the CVS flow measurement, as well as the gas sampling system and the CO_2 analyzer.

Fuel consumption checks compare the mass of fuel consumed by the vehicle under test to the fuel consumption calculated from the CO_2 and CO emissions by carbon balance. Given good data on the carbon content of the fuel, the two measures should normally agree within 4 to 5 percent. In addition to the CVS and gas sampling system, this procedure also checks that the isokinetic sampling system is working properly.

References

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[5] 40 CFR 86, Subpart N "Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures"

[6] "California Exhaust Emission Standards and Test Procedures for 1985 and Subsequent Model Heavy-Duty Diesel Engines and Vehicles" as amended on February 26, 1999, California Air Resources Board

[7] U.S. Patent No. 6,062,092. "System for Extracting Samples from a Stream", May 16, 2000.