# DIESEL EMISSION MEASUREMENTS ON TRANSIT BUSES

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**ABSTRACT**

**Modern diesel-powered transit buses are subject to increasingly stringent reductions in the permissible levels of exhaust emissions. This paper examines the mandated reductions in emission levels for transit buses and the existing and proposed methodologies for measuring vehicle emissions. A discussion of in-vehicle emission measurement efforts conducted at the Pennsylvania Transportation Institute (PTI) is included as is a description of a chassis dynamometer-based emissions test methodology proposed for emissions testing of transit buses at PTI.**

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## 1 INTRODUCTION

Significant progress has been made in reducing air pollution from heavy-duty diesel engines in the past thirty years [1]. These important emission reductions have occurred due to increasingly stringent emission standards mandated by the United States Environmental Protection Agency (EPA). In particular, particulate matter (PM) and nitrogen oxides ($NO_x$) emissions from heavy-duty diesel engines were progressively reduced through the 1980's and the 1990's and further reductions are mandated through 2010. Figure 1 illustrates the progressive tightening of the EPA emission standards for PM and $NO_x$ for heavy-duty diesel engines from 1988 to 2007-2010 [2].

The EPA mandates for PM and $NO_x$ for the model years 2007-2010 are an order of magnitude lower than the current mandates. In order to meet the stringent standards, engine manufacturers are investigating modifications to the combustion processes and treatment of the exhaust after it leaves the combustion chamber, such as homogeneous charge compression ignition, exhaust gas recirculation, urea injection, and the use of particulate traps [2]. It is anticipated that one or more of these methods will be used in heavy-duty diesel engines for the year 2007. Therefore the PM and gaseous emissions from these engines will be significantly lower than the current engines and will challenge the measurement capabilities of existing methods and instrumentation.

As emission levels reduced in response to these mandates, the EPA approved method of measurement remained the same; *i.e.*, diluting the entire engine exhaust in a full-scale dilution tunnel, and sampling a part of the diluted exhaust for emission measurements, although the requirements for full-scale dilution are substantially tighter for 2007. PM is currently measured by drawing a portion of the dilute exhaust sample through a filter and measuring the weight gain of the filter media, while gaseous emissions are measured using an array of gas analyzers. Alternate methods for measuring low levels of PM emissions from diesel engines have been investigated; however these methods have not been approved by EPA to date. Some of these

approaches include the use of diffusion charger and flame ionization detectors [3], light extinction measurements [4], and light extinction and scattering measurements [5].

EPA test methods are engine based, the tests are conducted using an engine dynamometer, and the emissions are measured in gms/bhp-hr. These tests are conducted using Federal Test Protocol (FTP) cycles and the results are used in engine certification. However, these results cannot be easily correlated to actual in-use emissions from vehicles. A chassis dynamometer based emissions test is more representative of actual driving conditions. This methodology provides emissions results in gms/mile basis that allows comparison of emissions between different vehicles.

The Pennsylvania Transportation Institute (PTI) of The Pennsylvania State University operates a transit bus testing facility for the U. S. Department of Transportation's Federal Transit Administration (FTA).  As part of this testing program, PTI and West Virginia University have been involved in the measurement of PM and gaseous emissions from transit buses. Initial efforts at PTI focused on in-vehicle sampling of emissions from buses and heavy-duty vehicles while they were run on simulated test cycles around PTI's closed-loop test track. WVU focused on building and operating a transportable chassis dynamometer and conducting emissions tests using a portable emissions laboratory.

PTI recently installed a large-roller (72 inch diameter), heavy-duty chassis dynamometer with inertia simulation capabilities.  This equipment provides the capability of performing closely controlled, stationary emissions tests using a variety of simulated test cycles. The following paragraphs discuss some results obtained with in-vehicle sampling and the challenges and potential approaches to measuring the low levels of emissions from 2007-2010 diesel engines.
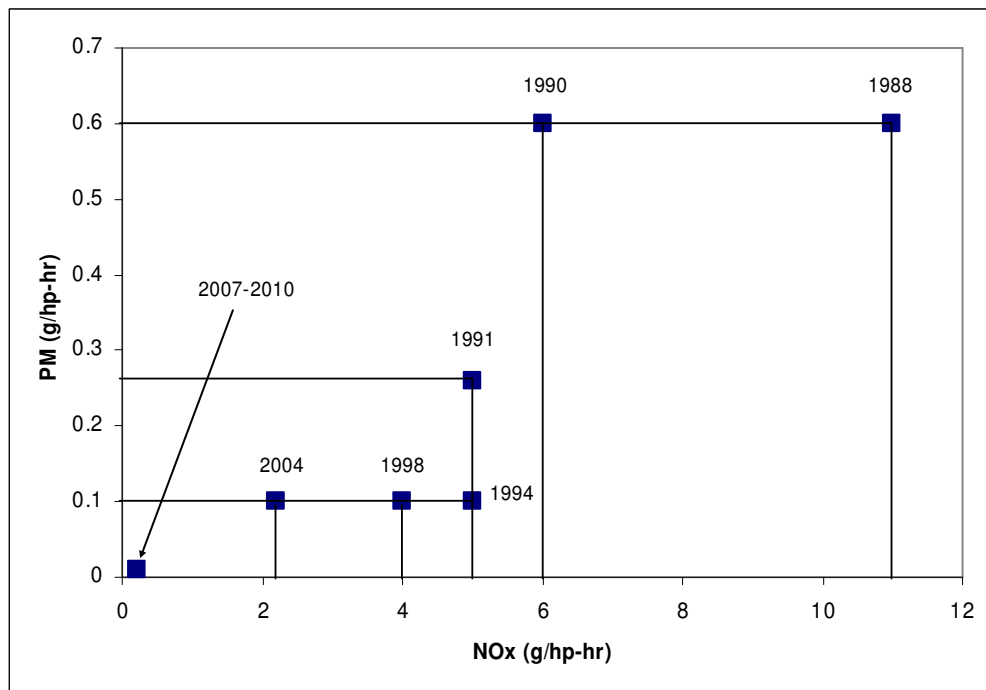


**Figure 1. U.S. EPA Standards for heavy-duty diesel emission levels for PM and NO$_x$ [2]**

**2 DILUTION AND SAMPLING SYSTEMS**

The species that are usually of interest during emission measurements are PM, $NO_x$, hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide ($CO_2$). While PM, $NO_x$, CO, and HC are measured for compliance with EPA regulations, the $CO_2$ measurement is useful for test validation. Fuel consumed during the test can be calculated from the total $CO_2$ using the carbon balance method. The calculated value for fuel consumption can then be compared with the actual measured value. As mentioned earlier, the EPA suggests full scale dilution where the entire engine exhaust is diluted with ambient dilution air in a dilution tunnel for certification purposes [6].

Full-scale dilution requires the use of large pumps and ducting to accommodate the high volume flow. Typically 2000 to 3000 scfm of dilute exhaust must be managed for heavy-duty engines. During this process, the total volume flow rate of the diluted exhaust is maintained constant, subject to temperature variations, (Constant Volume System-CVS) with the use of a critical flow device (CFD), usually a venturi. This type of setup results in a dilution ratio (ratio of dilution air flow rate to engine exhaust flow rate) that varies with engine exhaust flow rate. The dilution ratio will be the lowest when the engine exhaust flow is at its highest value, and vice-versa. The lowest value for the dilution ratio is usually about 6, and is dictated by the requirement that the water vapor in the engine exhaust must not condense in the diluted exhaust. This implies that the dilution ratio will be approximately 35 when the exhaust flow rate is at its lowest. In diesel engines, generally the concentration of pollutant emissions tends to be at its lowest at idle and increases with increase in load and speed. Therefore when diesel exhaust is diluted in a full-scale dilution system, the resultant concentration of emissions in the diluted exhaust will have a wide range with the least concentration at idle. This poses challenges in selecting the ranges for real time emission measurements. The concentration of some pollutants in the diluted exhaust such as HC may at times fall below that of the ambient air, necessitating the use of purified dilution air and measurement devices with high sensitivity. This situation will be exacerbated by the further mandated reduction in emission levels; in particular the emissions levels of $NO_x$.

There are two alternate methods to full-scale dilution. One is partial dilution, where only a part of the engine exhaust is diluted and the emissions are measured from this diluted exhaust. The other method is sampling the raw exhaust without any dilution. Both of these methods offer the advantage of lower volumetric flow rates and consequently require smaller ducting and equipments, thus reducing cost.

The features of the full-scale dilution system, the partial dilution system, and raw exhaust sampling system for the measurement of different pollutants are compared in Table 1. For each of the above three dilution/sampling systems, the sampled exhaust may be measured for emissions in two ways; in real-time, where the instantaneous concentrations of the different emissions are integrated in time to obtain the emission value for the test, or post-test where a sample flow rate that is proportional to the engine exhaust flow rate may be collected in a bag which is then analyzed for the emission concentrations after the test. During a test, both methods may be used for validation purpose. It is important to note that during a bag measurement, the sample flow rate into the bag must be proportional to the engine exhaust flow rate. In the real time measurement method, the constituent gas concentrations in the sampled exhaust and the total exhaust mass flow rate are measured continuously (at discrete intervals in time). The data is then integrated to obtain the total mass emission values for the test.

**Table 1. Comparison of full-scale dilution and partial flow dilution systems**

| | | $CO_2$ | CO | NOx Dry | NOx Wet | HC Heated FID | PM Filter medium |
|---|---|---|---|---|---|---|---|
| Full scale dilution | Bag | 1.Cond./low conc. | 1.Cond./low conc. | X | 1.Cond./low conc. | X | |
| | Real Time | 1.Cond./low conc. 2. Instrum. response | 1.Cond./low conc. 2.Instrum. Response 3.Disparate Ranges | X | 1.Cond./low conc. | 1.Cond./low conc. | X |
| Partial dilution variable DR | Bag | 1.Cond./low conc. | 1.Cond./low conc. | X | 1.Cond./low conc. | X | |
| | Real Time | 1.Cond./low conc. 2. Instrum. response | 1.Cond./low conc. 2.Instrum. Response 3.Disparate Ranges | X | 1.Cond./low conc. | 1.Cond./low conc. | X |
| Partial dilution fixed DR | Bag | | | X | | X | |
| | Real Time | 1. Instrum. response | 1. Instrum. Response 2.Disparate Ranges | X | | | X |
| No dilution (raw exhaust) | Bag | 1.Water correction | 1.Water correction | 1.Water correction | X | X | X |
| | Real Time | 1.Water correction 2. Instrum. response | 1.Water correction 2. Instrum. Response 3.Disparate Ranges | 1.Water correction | X | | X |

Notes:
1. X denotes not applicable / not practical.
2. *Cond. /low conc*. denotes the condensation of water at high exhaust flow rates and the low concentration of a pollutant at engine idle conditions.
3. *Instrum. Response* denotes the limited response of the instrument to transient changes in concentration.
4. *Disparate ranges* denote wide ranges in concentration that poses challenges to selecting the appropriate range.

The above methods of dilution/sampling and measurement pose some challenges to the sensitivity and accuracy of measurement, depending upon the type of emission measured. These challenges are discussed below for the measurements of PM, $NO_x$, CO, HC, and $CO_2$. In full-scale dilution, the diluted exhaust flow rate is maintained constant, subject to temperature variations. This results in a low dilution ratio for large exhaust flows and as explained earlier, the lowest permissible dilution ratio is chosen such that water vapor in the engine exhaust does not condense in the diluted exhaust. Consequently, the dilution ratio is rather high when the engine is at idle which results in low concentrations of emissions in the diluted exhaust. Choosing an optimum CFD for an engine that would avoid condensation of water vapor at maximum engine exhaust flow rate and also avoid very low concentrations of emissions in the diluted exhaust at engine idle presents a challenge in full-scale dilution systems. This is especially true in view of the reduced emission mandates, and $NO_x$ is the pollutant most likely to be affected in this way. While the above condition presents a common challenge for all emissions (PM, NOx, CO, $CO_2$, and hydrocarbons), some of these emissions pose additional measurement challenges which are discussed in the following paragraphs.

PM is traditionally trapped on filter media and the filters are weighed to determine the mass PM emissions. It is necessary to obtain a measurable amount of PM on the filter paper during a test. It may be noted that the above gravimetric method is not able to provide real-time data and that only the total PM emissions for a test can be obtained as shown in Table 1. Further, in order to obtain accurate measurement of PM emissions, it is necessary to simulate the interaction that occurs when the hot exhaust mixes with the cool ambient air at the exit of the vehicle exhaust pipe. Gas-to-particle conversion takes place during the dilution process that occurs at the exit of the vehicle exhaust pipe as volatile hydrocarbons and sulfuric acid adsorb onto existing particles and nucleate to form new particles. Thus the measurement of PM is a method based concept, rather than an abstract concept, and the method is defined by EPA [6].

CO and $CO_2$ are usually measured using non dispersive infra-red absorption (NDIR) where the extent of absorption of infra-red light as it passes through a chamber containing the sample is a measure of the concentration of CO or $CO_2$ in the chamber. The volume of the chamber tends to average the concentration of gas flowing through it, thereby limiting the ability to detect and measure transient changes in concentration. This feature will not affect measurements from a bag because the bag concentration is already mixed and averaged and will be constant.

CO measurement poses an additional challenge. The typical concentration of the CO emission over time from a heavy-duty diesel engine is illustrated in Figure 2. It may be noted from Figure 2 that the dynamic range of this type of trace will present a challenge for measurement in real time. Selecting an appropriate range for the measuring equipment is complicated due to an order of magnitude difference in the values between constant throttle at idle and the acceleration phases. The bag measurement will not be sensitive to these disparate levels of emissions, because the sampled gas is collected in the bag during the test and the averaged, constant concentration of the pollutant is measured after the test is completed.

$NO_2$, one of the components of NOx, is soluble in water. Therefore it is important to ensure that the water does not condense in the sample before or during the measurement. There are two methods usually used for measuring $NO_x$. One is called wet measurement and the other is called dry measurement. In the wet measurement, the tail pipe exhaust is diluted with air to ensure that the water vapor does not condense. Heated sample lines are also used to insure that the water vapor in the diluted exhaust does not condense anywhere in the sample line. The

measurement is carried out on the diluted exhaust with the water in vapor form. In dry measurement, the heated sample is passed through a $NO_x$ converter and the soluble $NO_2$ component is converted to NO which is insoluble in water. After this conversion, the sample gas is passed through a chiller and the water vapor is condensed and separated. The dried sample is measured for the total $NO_x$ emissions. A correction is applied to the measured concentration to account for the water vapor that was separated from the sample exhaust. The dry measurement method is usually used for raw exhaust samples, while the wet method is more suited for diluted samples (Table1).

Hydrocarbons (HC) in diesel exhaust are usually measured with a Heated Flame Ionization Detector (HFID).  Sample lines are heated to avoid condensation of the heavier hydrocarbons before the sample reaches the analyzer. Due to this requirement, HC cannot be measured reliably using the bag sampling method (Table 1).
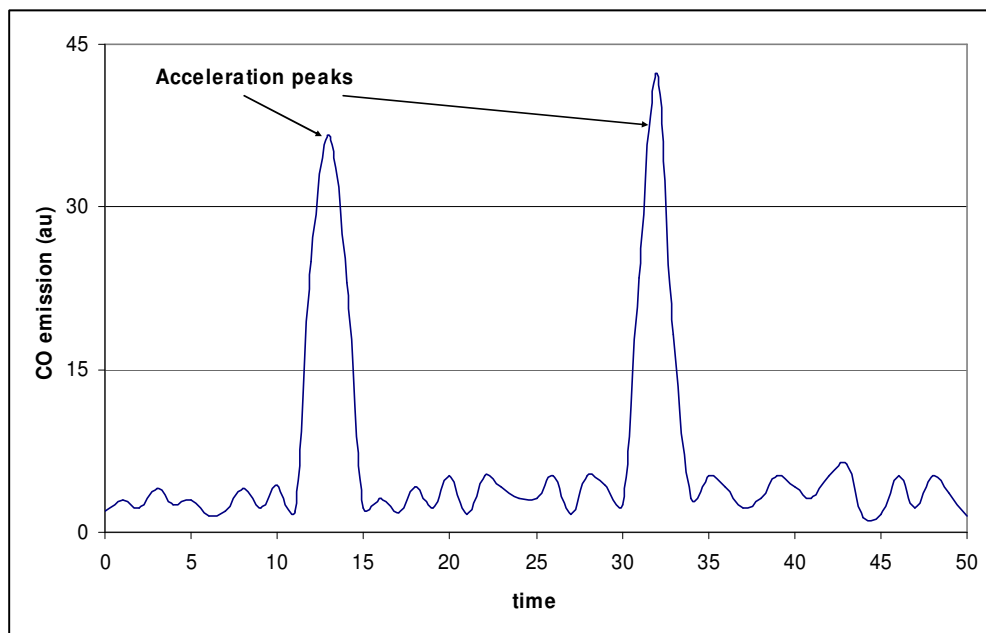


**Figure 2.  Typical trace of CO emission from diesel engines**

In a partial dilution system, a part of the engine exhaust is sampled and diluted with air and the emission measurements are carried out using this diluted sample. The dilution ratio may be maintained constant or allowed to vary depending on the exhaust mass flow rate. If the dilution ratio is allowed to vary, the same issues that are applicable to full scale dilution systems have to be addressed (Table 1), for both real-time and bag measurements. An alternate approach in partial dilution is to use a constant dilution ratio which ameliorates the dilution related issues presented in Table1. The lowest possible dilution ratio is chosen such that the water vapor does not condense in the diluted exhaust and this value for the dilution ratio is held constant for the test. In this way the adverse effect of the value of the dilution ratio in reducing the emission concentrations in the diluted exhaust for low exhaust flow rates is reduced.

Another alternate method to full-scale dilution is sampling the raw (undiluted) exhaust. While this method ensures that the emission concentrations are not further diluted, the high temperature exhaust has to be cooled before it reaches some of the measuring instruments. The water vapor will condense when the exhaust is cooled and the condensed water has to be

separated. A correction to the measured concentration of emissions is applied to account for the water vapor that is removed. As mentioned earlier, the soluble $NO_2$ component of $NO_x$ emissions must be converted to NO before cooling the exhaust, *i.e.,* the dry measurement method for $NO_x$ is used. It is noted that this method is not suitable for measurement of PM because the interaction between the hot exhaust and the cool ambient air is not simulated as explained earlier.

## 3 INITIAL EMISSION MEASUREMENT EFFORTS AT PTI

Initial emission measurement efforts at PTI focused on an in-vehicle emissions sampling system in which a portion of the tail pipe exhaust was sampled and diluted. The Mobile Vehicle Sampling System (MVESS) was developed for PTI by Southwest Research Institute [7]. In this system, the dilution ratio varies to keep the sampling rate proportional to the tail pipe exhaust flow rate. This method is classified as a system with partial dilution and variable dilution ratio in Table 1. A schematic diagram of this equipment is provided in Figure 3.
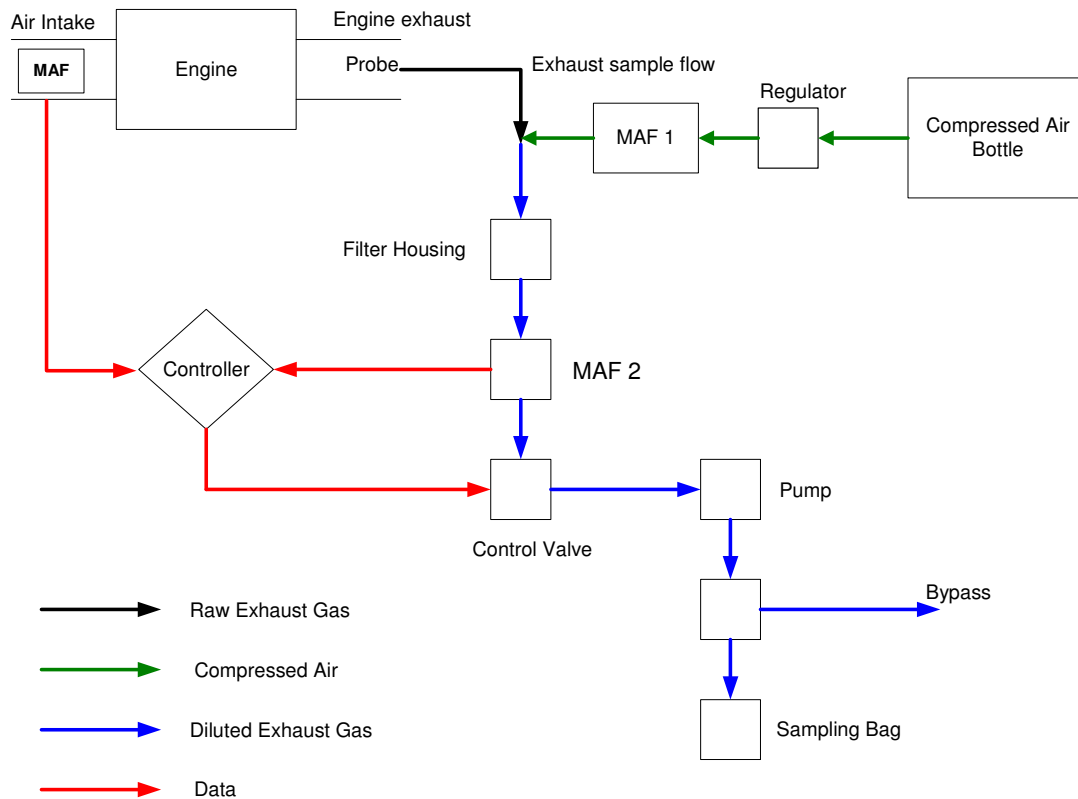
**Figure 3. Schematic of the Mobile Vehicle Emission Sampling System (MVESS)**

The MVESS system has a constant dilution air flow rate and a varying exhaust sample rate. The exhaust sample flow rate is varied in proportion to the mass of air inducted into the engine, measured using a mass airflow sensor (MAF), thereby varying the dilution ratio and insuring proportional sampling. This results in a higher dilution ratio at low engine air flow rates and a lower dilution ratio at larger engine air flow rates, as explained earlier. A constant supply of dilution air supply is obtained using a critical flow orifice that regulates the air flow from a

compressed air bottle. The engine intake air is measured in real time using a mass air flow sensor (MAF1). The dilution air lines are illustrated in green in Figure 3. Raw exhaust, illustrated in black, is collected from the tail pipe by an instrumented sample probe and is mixed with the dilution air in the probe. The diluted exhaust, illustrated in blue, is then drawn through a filter housing, mass flow sensor (MAF2) and a control valve by a pump. Two pre-weighed removable filter elements, one primary and the other secondary, are assembled in the filter housing for gravimetric analysis of particulate matter. The controller calculates the flow rate of diluted exhaust necessary to maintain proportional sampling, uses the feedback from MAF2 to modulate the control valve, and thus insures real time proportional sampling. The data flow paths are illustrated in red in Figure 3. The diluted exhaust sample is collected in a Tedlar bag during a test, or discarded through a bypass during other times. Control software is written in LabVIEW and the data acquisition is accomplished using a National Instruments data acquisition card (NI DAQ AI-16E-4). After a test, the mass of particulate matter is determined by measuring the weight gain of the filter media and the gaseous emission concentrations are measured by analyzing the bagged, diluted exhaust with laboratory grade gas analyzers.

A sample test result obtained from the MVESS is presented in Table 2 [8]. Over 10 runs of the Central Business District Cycle on four different days, the standard deviation of the results for the measured emissions, including PM, was less than 11%. Thus it was concluded that the results were consistent and that this system could be used for comparison of emissions from different vehicles.

## 4 PROPOSED EMISSION MEASURING SYSTEM FOR PTI

Although the emission measurements obtained with the MVESS were consistent, in-vehicle emission measurements were subject to limitations in the size and power rating of the equipments, use of very small sampling flow rates, and variations in the outdoor temperature and humidity. A new, large-roller chassis dynamometer has recently been installed at PTI and it is now possible to measure the emissions using stationary equipment. The stationary test vehicle is run on simulated test cycles using the dynamometer, without the constraints of in-vehicle sampling, and under more controlled ambient conditions. The proposed system will have separate sampling branches based on the exhaust pre-conditioning requirements for each type of emission measured. The pre-conditioning requirements are different for measurements of PM, $NO_x$, HC and the oxides of carbon namely, CO and $CO_2$. The partial flow PM sampling system was designed by PTI while the raw exhaust gaseous emissions measurement system was designed by West Virginia University (WVU) [9]. Details of both measuring systems are described in this section.

### 4.1 Particulate Matter

Particulate emissions measurement will consist of two stages; the collection (trapping) of the particulate matter (PM) sample in the filter, and the analysis (weighing) of the collected samples. The proposed particulate sampling system is a partial flow system that uses a constant value for the dilution ratio (Table 1). In the Partial Flow Sampling system, the mass flow rate of the exhaust sample is kept proportional to the total mass flow rate of the engine exhaust to insure that the sample collected for analysis is representative of the tail pipe exhaust flow rates. Use of a constant dilution ratio helps in preventing very low concentrations of a pollutant in the diluted exhaust at low exhaust flow rates, as explained earlier.

**Table 2. Typical results obtained from the MVESS (g/mile) [8]**

| No. | | CO | $CO_2$ | HC | $NO_x$ | PM |
|---|---|---|---|---|---|---|
| 1 | Temp: 60F | 3.96 | 1120 | 0.71 | 5.63 | 1.20 |
| 2 | Humidity: 49.7% | 4.82 | 1299 | 0.80 | 6.36 | 1.16 |
| 3 | | 4.57 | 1331 | 0.77 | 6.52 | 1.12 |
| 4 | Temp: 53.6F Humidity: 50.6% | 4.35 | 1216 | 0.72 | 6.17 | 1.15 |
| 5 | | 4.05 | 1076 | 0.76 | 5.68 | 1.35 |
| 6 | Temp: 66.5F | 4.77 | 1319 | 0.75 | 6.64 | 1.11 |
| 7 | Humidity: 53.5% | 4.05 | 1132 | 0.65 | 5.79 | 0.96 |
| 8 | | 4.12 | 1230 | 0.66 | 6.25 | 1.03 |
| 9 | Temp: 66F | 4.91 | 1402 | 0.80 | 7.29 | 1.11 |
| 10 | Humidity: 57.2% | 5.41 | 1506 | 0.76 | 7.81 | 1.32 |
| Mean | | 4.50 | 1263 | 0.74 | 6.41 | 1.15 |
| Standard Deviation (Std.Dev) | | 0.48 | 134.6 | 0.05 | 0.70 | 0.12 |
| % Std.Dev/Mean | | 10.6 | 10.7 | 7.2 | 10.9 | 10.3 |

There are two important requirements that have to be met by the sampling system. A cyclone is used to separate and eliminate particles over 10 microns in ($PM_{10}$ measurement), or 2.5 microns (in $PM_{2.5}$ measurement). The cut off point of the cyclone is a function of the flow velocity through the cyclone, and therefore the volumetric flow across the cyclone must be maintained constant. The second requirement is that the mass flow rate through the sample filters must be proportional to the mass flow rate of the bus exhaust, as mentioned earlier.

Figure 4 presents the schematic of the proposed sampling system. The engine exhaust is measured using an annubar which is calibrated to measure exhaust mass flow rate. A sample from the tail pipe exhaust is drawn into the probe where it mixes with dilution air supplied by a zero-air generator. Use of dilution air from a zero-air generator is preferred over ambient air or
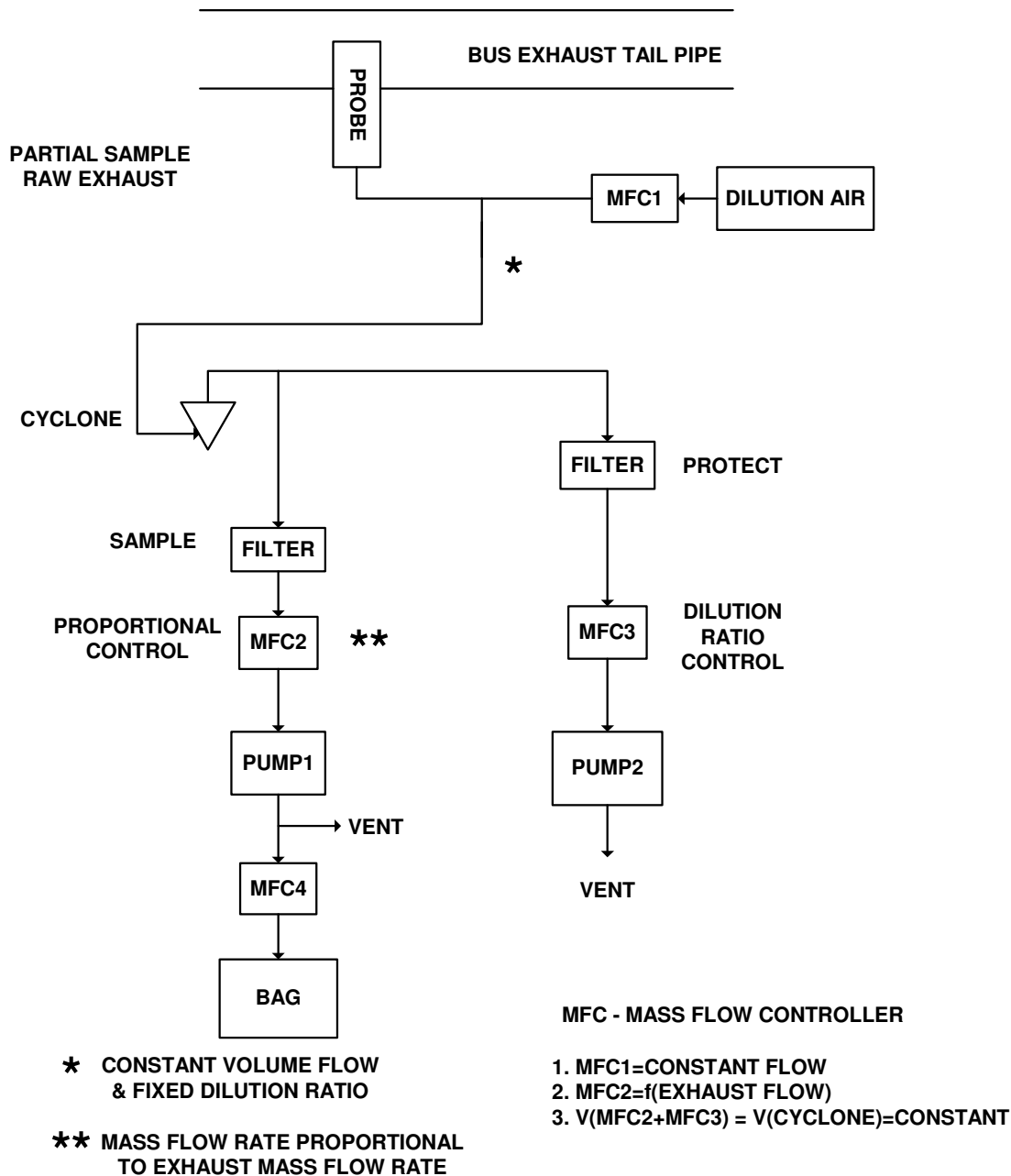
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          SAMPLE   ┌────────┐    │                    │          DILUTION
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                   └────────┘    │                │ MFC3 │       CONTROL
                       │         │                └──────┘
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            & FIXED DILUTION RATIO       3. V(MFC2+MFC3) = V(CYCLONE)=CONSTANT

      ★★  MASS FLOW RATE PROPORTIONAL
          TO EXHAUST MASS FLOW RATE
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**Figure 4. Schematic layout of the proposed PM sampling system**

bottled air to reduce the effects of background contamination, particularly with reference to
measurements of PM, HC, and $NO_x$. The dilution air flow rate is controlled by the mass flow
controller MFC1, which keeps the dilution ratio constant during the test. The diluted exhaust is
then drawn through a cyclone that separates and eliminates particles larger than 10 microns. The
flow exiting the cyclone is divided into two branches. In the first branch, the diluted exhaust is
drawn through the PM sample filter and the mass flow controller MFC2 by Pump1. The mass
flow controller MFC2 ensures that the mass flow rate of diluted exhaust drawn through the
filter(s) is proportional to the tail pipe exhaust mass flow rate. The particulate matter is trapped

by the filter(s) which are weighed after the test is completed to determine the PM emission. The output from Pump 1 may be used to fill a bag and the bag concentrations of gaseous pollutants can be measured to cross-correlate the results obtained from the gaseous emissions measuring system. The mass flow controller MFC4 diverts only a fraction of the flow into the bag in order to limit the size of the sample bag. In the second branch, Pump 2 draws a fraction of the dilute sample from the cyclone, and MFC3 ensures that the total volume flow rate of diluted exhaust through the cyclone is constant. This system will insure that the mass flow rate of the exhaust gas drawn through the sample filter and the mass flow rate of the exhaust gas that fills the bag are representative of the mass flow rate of bus exhaust, while maintaining a constant volume flow rate through the cyclone.

### 4.2 Carbon dioxide and Carbon monoxide

Carbon dioxide ($CO_2$) and carbon monoxide (CO) concentrations are typically measured using non-dispersive infrared detection (NDIR), using the principle of infrared light absorption. The detector has a narrow band-pass optical filter which isolates a spectral region specific to the gas being measured (CO or $CO_2$). The infrared beam also passes into a reference cell. When a non-absorbing gas flows through the sample cell, the reference detector and sample detector receive the same amount of infrared light energy. When an absorbing gas flows through the sample cell, less infrared energy reaches the sample detector than the reference detector. The difference between the sample and reference signals is mathematically converted to yield the concentration of the constituent gas being measured.

The primary components of the $CO_2$/CO sampling system are illustrated schematically in Figure 5. Sample is withdrawn from the undiluted vehicle exhaust using a sampling probe and conveyed through a heated sample line and heated filter housing by a heated head diaphragm pump. Sample probes are generally constructed of stainless steel and heated sampling lines can be lined with either stainless steel or Teflon. The heated filter housing contains a filter cartridge that removes particles greater than 0.1 micron with a filtration efficiency of greater than 95%. Down stream of the heated pump, the sample passes through a refrigerated chiller/drier to remove water vapor from the sample gas stream. The sample stream is chilled to achieve a dew point temperature of approximately 5° C, which is equivalent to 0.86% water by volume. All components upstream of the chiller/drier are maintained between 110-120° C (235-250 °F) to prevent uncontrolled condensation. Downstream of the chiller/drier, heating of the sampling system components is not required. A pressure regulator, flow meters and a bypass line downstream of the sample pump will allow for varying flow rates and hence residence times of the sample gas within the sampling system while maintaining a constant flow rate and sample pressure through the NDIR analyzers.

### 4.3 Oxides of Nitrogen

Nitric oxide (NO) and nitrogen dioxide ($NO_2$) taken together are referred to as $NO_x$ for engine emissions testing purposes. A chemiluminescent $NO_x$ analyzer is proposed for dry measurement of $NO_x$ in raw or dilute diesel engine emissions. The sample must be properly conditioned with an external $NO_x$ converter positioned upstream of a chiller/dryer (Figure 6). The $NO_x$ converter converts $NO_2$ to NO to prevent the loss of soluble $NO_2$ with the condensed water. With the exception of the $NO_x$ converter, the $NO_x$ sample system is identical to the CO/$CO_2$ sample system.
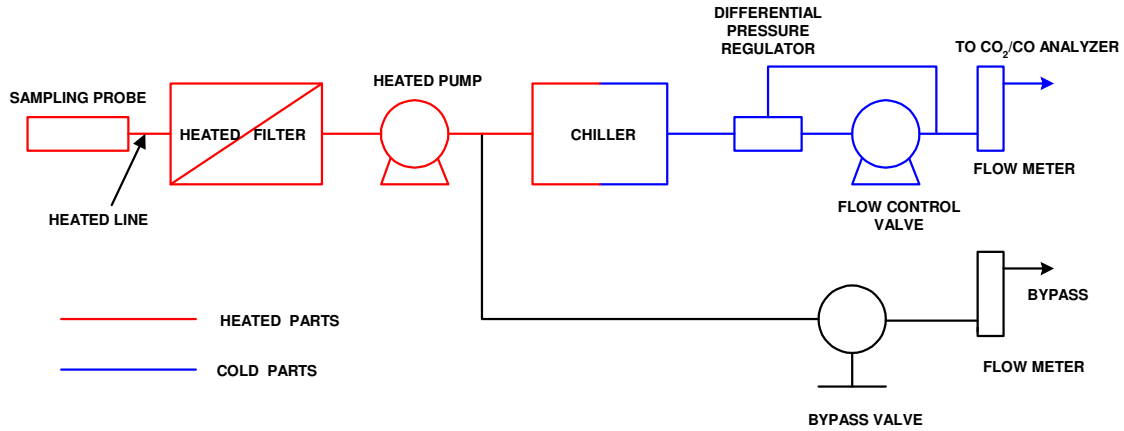
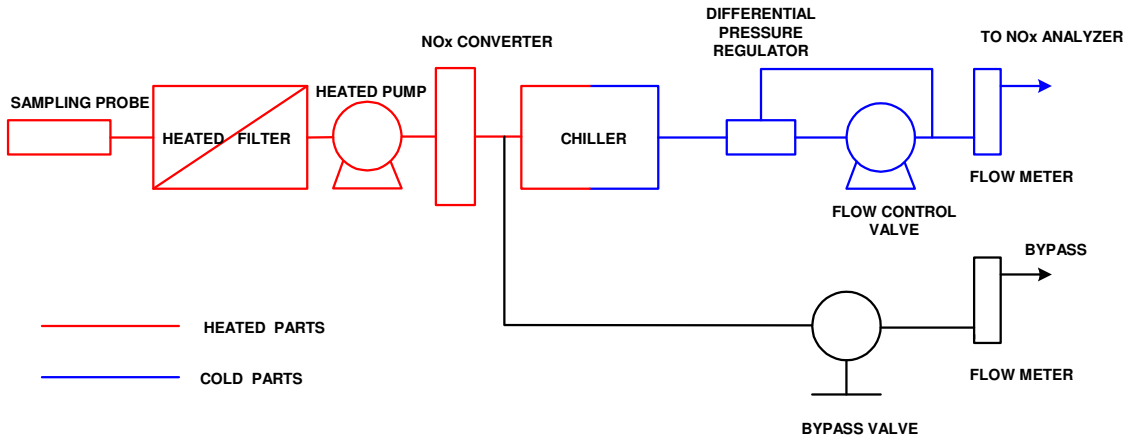**Figure 5. General Schematic of a $CO_2$/CO sampling system**



**Figure 6. General Schematic of a $NO_x$ sampling system**

 4.4 <u>Hydrocarbons</u>

A heated flame ionization detector (HFID) is required for measuring diesel hydrocarbons in order to prevent condensation of the heavier hydrocarbons constituents found in diesel engine exhaust. The sample line, sample path components and HC analyzer for should be maintained at a minimum temperature 190 °C to prevent condensation.

**5 SUMMARY AND FUTURE WORK**

The increasingly stringent emissions standards being mandated by the EPA necessitate the development of new measurement technologies and methodologies.  Standard measurement techniques such as full-scale dilution of tailpipe exhaust may prove to be less practical and less effective when compared to the other methods proposed.  Based on performance and cost considerations, test results at PTI indicate that a partial dilution sampling system with the use of

a constant dilution ratio is an attractive and practical alternative for PM measurements, while raw exhaust sampling is the optimum method for gaseous emissions measurements.

Due to the limitations of in-vehicle sampling, PTI proposes using a chassis dynamometer based emissions test that includes a series of different simulated transit operating cycles. A chassis dynamometer based test with partial sampling for PM measurement combined with raw exhaust sampling for gaseous emissions measurement, provides a practical alternative to full-scale dilution testing. The benefits of this approach demonstrate the potential of being more effective in evaluating vehicles designed to comply with the increasingly tighter EPA emission standards.

## ACKNOWLEDGEMENTS

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