The Construction and Application of a Multipoint Sampling System for Vehicle Exhaust Plumes

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ABSTRACT

To study the formation process of secondary organic aerosols (SOA) in a vehicle exhaust plume near the exhaust gas discharge outlet, a new multipoint sampling system was established. The system has five sampling heads and includes a particulate matter multi-channel film sampling system, a CO\textsubscript{2}/CO analyzer system, a volatile organic compound (VOC) sampling system, a particulate matter real-time analyzer system, and sensor interfaces. The vehicle exhaust near the exhaust nozzle can be sampled at multiple locations simultaneously using the new multipoint sampling system. Additionally, the system can be used to measure and analyze variations in the fine particulate matter, including the carbonaceous and ionic components, and organic compounds in the plume near the exhaust nozzle. This paper introduces the construction and application of the multipoint sampling system. The motor vehicle exhaust multipoint sampling system is reliable and can accurately capture the characteristics of the exhaust plume near the discharge outlet area. Changes in the CO\textsubscript{2} concentration were used to determine whether exhaust was accurately collected at the sampling points. The relationship between the dilution rate and distance was calculated on the basis of on-road test results using the following equation: \( DR = 21.4X^{1.16} \). This equation can be used for modeling purposes, especially in comparisons of model results and observations and in the evaluation of dispersion models.

Keywords: Multipoint; Sampling system; Exhaust plume; PM\textsubscript{2.5} components.

INTRODUCTION

Particulate matter pollution is not only a popular research topic but also a societal focus due to the high frequency of hazy days in China. Atmospheric particulate matter negatively affects human health, visibility, acid deposition, precipitation, and climate change. Organic aerosols (OA) are an important part of atmospheric particulate matter (Kanakidou et al., 2005). The OA directly emitted from sources such as motor vehicles and forest fires are defined as primary organic aerosols (POA), and the OA formed in the atmosphere from the oxidation of gas phase precursors are defined as secondary organic aerosols (SOA) (Robinson et al., 2007). Field studies have found that SOA are the most important OA in the atmosphere (Zhang et al., 2007; Jimenez et al., 2009; Takami et al., 2016), especially during haze events (Huang et al., 2014; Rastogi et al., 2015; Sui et al., 2015).

Numerical simulations of OA are associated with considerable uncertainty because of the lack of understanding regarding the formation, evolution, and measurement of OA (Goldstein and Galbally, 2007). Traditional SOA models can underestimate concentrations by a factor of 2 to 10 compared to the results of field measurements in contaminated areas (Heald et al., 2005; Volkamer et al., 2006). The underestimation of SOA has been studied by many researchers. The existing models do not include certain precursors, such as semi-volatile organic compounds (SVOCs) and intermediate-volatility organic compounds (IVOCs) (Goldstein and Galbally, 2007; Robinson et al., 2007; de Gouw et al., 2011). Additionally, the existing precursors used in these models may lead to the underestimation of SOA (Tsimpidi et al., 2010), and the definitions of SOA and POA can vary (Cheng et al., 2011). Moreover, POA emission inventories and SOA precursors often include considerable uncertainty (Kanakidou et al.,...
Motor vehicles have become the main source of urban pollution (Lang et al., 2017), especially in a busy street canyon (Krecl et al., 2015). The carbonaceous component represents the main fraction of PM$_{2.5}$ emitted from diesel vehicle (Jin et al., 2017), and research results have indicated that diesel exhaust oxidation reactions quickly generate a large number of SOA, but simulations of the concentrations of SOA yield less than 10% of the observed values according to known precursor gas contents and reaction pathways (Robinson et al., 2007).

Between the source and a receptor, motor vehicle pollutants undergo atmospheric processes. In these processes, the directly emitted pollutants experience complex physical and chemical changes and generate secondary pollution (Ning and Sioutas, 2010). Eventually, a complex mixture of pollutant discharge is obtained by the receptor. Atmospheric processes can be divided into a plume process and an ambient environmental process. The plume process and environmental process differ both in time and space (Zhang and Wexler, 2004). An environmental process can last a few hours or days at the city scale or regional scale. Generally, a plume process extends from the emission source to within a few hundred meters of the source and has a duration measured in minutes. Additionally, plume processes can be divided into tailpipe to road and road to ambient air processes. The plume processes analyzed in this study are mainly tailpipe to road processes.

Nucleation and condensation processes may occur in motor vehicle exhaust during the release of emissions from the exhaust pipe to the road (Wang and Zhang, 2012). The temperature of the exhaust gas rapidly decreases due to dilution with the ambient air, which can cause precursor gas supersaturation (Yang et al., 2015). The supersaturated gaseous compounds form new particles via nucleation. The supersaturated gaseous compounds generally condense onto any particle surface, including existing particle surfaces (Keskinen and Rönkkö, 2010). Some researchers (Tobias et al., 2001; Sakurai et al., 2003a, b) have studied the condensation of gaseous compounds in exhaust gas on the surface of black carbon particles. The mass or volume of hydrocarbons that have condensed on the surfaces of black carbon particles can reach 20–80% of that of the particles (Sakurai et al., 2003b; Ristimaki et al., 2007). Due to the pore structure of black carbon particles, the condensation process does not change the quantity or particle size distribution of the particulate matter (Ristimaki et al., 2007). Therefore, if no new particles are generated, dilution does not influence the particle size distribution.

Chasing tests have been used to measure the particulate matter emission characteristics in vehicle plumes using mobile laboratories (Vogt et al., 2003; Pirjola et al., 2004; Giechaskiel et al., 2005; Kittelson et al., 2006; Rönkkö et al., 2006; Casati et al., 2007; Rönkkö et al., 2007; Lemmetty et al., 2008). However, researchers have only focused on particulate matter concentration, particle size distribution, and instantaneous mass concentration measurements in smoke plumes. Additionally, these studies used commonly used instruments such as condensation particle counters (CPCs), electrical low-pressure impactors (ELPIs), and engine exhaust particle sizers (EEPSs), but the components of the particulate matter in the plumes cannot be measured by these instruments. However, Schneider et al. (2005) studied the size and components of particulate matter in vehicle exhaust.

When real world, on-road vehicles are chased by mobile laboratories, the mobile laboratories must maintain a certain distance from the vehicles due to safety considerations. Thus, the distance between the sample point and the exhaust nozzle is generally more than 5 m (Giechaskiel et al., 2005; Kittelson et al., 2006; Rönkkö et al., 2007; Kittelson et al., 2008; Bergmann et al., 2009) and can reach as high as 100 m (Vogt et al., 2003; Casati et al., 2007). However, German researchers (Uhrner et al., 2007; Wehner et al., 2009; Uhrner et al., 2011) designed a new device that can be installed on the back of a car, and the sampling point can be adjusted within the range of 45–90 cm. This new system can measure the emission characteristics of the particulate matter in the plume at a distance of less than 1 m from the exhaust nozzle. However, only a scanning mobility particle sizers (SMPS) is used in this system; therefore, the particulate matter components in the plume cannot be measured. Additionally, diesel trucks have not been tested.

A new multipoint sampling system for vehicle exhaust plumes was constructed in this study. Using this system, the vehicle exhaust near the exhaust nozzle can be sampled at multiple locations simultaneously. Additionally, the system can determine the levels and variations in the fine particulate matter, including the carbonaceous and ionic components, and the organic compounds in the plume near the exhaust nozzle.

**DESIGN OF THE MULTIPOINT SAMPLING SYSTEM**

**Structure of the Multipoint Sampling System**

The multipoint sampling system was developed to measure and analyze the variations in vehicle exhaust emissions. As shown in Fig. 1, the #1 to #4 are sampling heads located at different distances from the exhaust pipe. At these locations, tailpipe emission samples that are directly diluted by the atmosphere are collected. The #5 sampling head is positioned opposite the emission direction and away from the eliminator to collect air samples as background values. The vehicle exhaust or air collected at the sampling heads is divided into five parallel branches. Then, the vehicle exhaust or air in each parallel branch is transported to an independent sampling and analyzer system via the gas distribution box. The independent sampling and analyzer systems include a particulate matter multi-channel film sampling system, a CO$_2$/CO analyzer system, a volatile organic compound (VOC) sampling system, a particulate matter real-time analyzer system (DustTrak 8530, DMM230, SMPS), and sensor interfaces (SEMTECH-DS and other instruments).

**Single Channel Sampling System**

The single channel sampling system is shown in Fig. 2. The air, non-diluted vehicle exhaust, and diluted vehicle exhaust...
exhaust in air were collected via sampling heads and transported to different systems for analysis. The particulate matter multi-channel film sampling system measured the mass of PM$_{2.5}$, the carbonaceous components of PM$_{2.5}$, the ionic components of PM$_{2.5}$, and the other components of PM$_{2.5}$. The CO$_2$/CO analyzer system measured the instantaneous concentrations of CO$_2$ and CO in the motor vehicle exhaust and air. The VOC sampling system measured the VOC species using Tedlar bag sampling and 2, 4-dinitrophenyhydrazine (DNPH) cartridge sampling. The particulate matter on-line analyzer system (DustTrak 8530, DMM230, SMPS) measured the instantaneous mass concentration and size distribution of PM$_{2.5}$.

**CO$_2$/CO Analyzer System**

The CO$_2$/CO analyzer system comprised five CO$_2$/CO
Multi-Channel Particulate Matter Film Sampling System

The multi-channel particulate matter film sampling system includes five single channel filter sampling systems. Each single channel filter sampling system was composed of a PM$_{2.5}$ cyclone, filters, a flow regulator, and a pump, as shown in Fig. 2. The PM$_{2.5}$ cyclone (URG 2000-30ED – 3 L min$^{-1}$, URG 2000-30EN - 10 L min$^{-1}$, URG Corp, USA) collects particles with an aerodynamic diameter of 2.5 µm or less. Samples that passed through the PM$_{2.5}$ cyclone were divided into two parallel channels. Channel A consisted of bare Quartz (Q) and Quartz-backup-Quartz (QBQ) filters, and channel B consisted of front Teflon (T) and Quartz-behind-Teflon (QBT) filters. A flow regulator was connected to each channel. The flow rates in the channels of the #1 and #2 sampling heads were controlled at 1.5 L min$^{-1}$, and flow rates in the channels of the #3 and #4 sampling heads were controlled at 5 L min$^{-1}$. Additionally, the flow rate in the channel of the #5 sampling head was controlled at 100 L min$^{-1}$ because the concentration of PM$_{2.5}$ in air is lower than that in the vehicle exhaust. Each exit was equipped with a pump (Quick Take®30, SKC, USA; URG-3000-02BBM, URG Corp, USA) to provide dynamic sampling.

Volatile Organic Compound Sampling System

The VOC sampling system includes five single channels. As shown in Fig. 2, each single channel includes two parts: one for DNPH cartridge sampling and one for Tedlar bag sampling. Carbonyls, including aldehydes and ketones, were trapped on two DNPH - coated silica gel cartridges (Bonna-Agela Technologies Inc., China) powered by an oil-less pump (Gast Manufacturing Inc., USA) at a flow rate of 1 L min$^{-1}$ and controlled by a rotary flow meter. The cartridges were downstream of a KI oxidant scrubber (Bonna-Agela Technologies Inc., China) powered by an oil-less pump (Bonna-Agela Technologies Inc., China). The material was often used when assessing the OC and EC contents of diesel-laden aerosols (Birch and Cary, 1996). The material on the remaining quartz filters was ultrasonically extracted using distilled de-ionized water to determine the Water Soluble Ions (WSIs) via ion chromatography (IC; ICS2100, Thermo, USA). After weighing, the entire Teflon filter was used to analyze the elements. The PM$_{2.5}$ was digested in closed Teflon digestion vessels using a programmable microwave digestion unit (MARS55, CEM Corp., USA). The digested acid mixture was then analyzed via inductively coupled plasma mass spectroscopy (ICP-MS; X SERISIII, Thermo-Fisher, USA).

### Table 1. The ranges, resolutions, and accuracies of the five CO$_2$/CO analyzers.

<table>
<thead>
<tr>
<th>Sampling head</th>
<th>Range</th>
<th>Resolution</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>CO$_2$ (%)</td>
<td>0–20</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>CO (%)</td>
<td>0–4</td>
<td>0.001</td>
</tr>
<tr>
<td>#2</td>
<td>CO$_2$ (ppm)</td>
<td>0–10</td>
<td>0.01</td>
</tr>
<tr>
<td>#3</td>
<td>CO (ppm)</td>
<td>0–2000</td>
<td>1</td>
</tr>
<tr>
<td>#4</td>
<td>CO (ppm)</td>
<td>0–8000</td>
<td>1</td>
</tr>
<tr>
<td>#5</td>
<td>CO$_2$ (ppm)</td>
<td>0–1000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CO (ppm)</td>
<td>0–5000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ (ppm)</td>
<td>0–500</td>
<td>1</td>
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<td></td>
<td>CO (ppm)</td>
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canisters (Entech Instruments Inc., USA) using a Teflon connector. These canisters were cleaned in the laboratory following U.S. EPA method TO-14 through repeated evacuation and pressurization with high-purity nitrogen before sampling (U.S. EPA, 1997).

To improve the convenience of installation and disassembly during the experiment, the five single channel particulate matter film sampling systems, including five single channel VOC sampling systems, were integrated into one system, as shown in Fig. 4.

### System Calibration/Verification
The different test instruments in the system require different preheating times to ensure the accuracy of the measurement results. The SEMTECH-DS requires 60 mins, the DMM-230 requires 30 mins, and the CO₂/CO analyzer system requires 30 mins.

The SEMTECH-DS was zeroed with high-purity nitrogen (higher than 99.999%) before each test and was calibrated with standard gases (CO₂, CO, NO, and C₃H₈) before the first test of the day. The DustTrak II 8530 was adjusted using the gravimetric filter method prior to each experiment and was zeroed with filtered air before every test. The CO₂/CO analyzer system was zeroed with high-purity nitrogen and calibrated with standard gases.

The flow in each channel was calibrated with the Defender530 calibrator (BIOS, USA) both before and after each experiment. Additionally, the air tightness of the system was tested before each experiment.

Anti-static tubing (TSI, USA) with a Teflon inner coating was used for all the pipelines to reduce the measurement error. A Teflon tube was used in the VOC sampling system.

We set up the multi-channel particulate matter film sampling system. The system was used to research the variations in PM₂.₅ in vehicle plumes. Because the accuracy of parallel tests in each channel influences the test results, parallel tests of the multi-channel particulate matter film sampling system were conducted in the laboratory before the on-road measurements, and the results are shown in Fig. 5. The concentrations of OC, EC, TC, NH₄⁺, NO₃⁻, SO₄²⁻, and OC/EC in the four channels were similar, with relative standard deviations of less than 7.6%. The standard deviation is the comprehensive deviation associated with the sampling system and the analysis process. The standard deviation values suggest that the multi-channel particulate matter film sampling system is reliable and can be used in actual analyses in the future.
EXPERIMENTAL APPLICATION AND DISCUSSION

It is difficult to install the sample heads in a manner that accurately captures the exhaust plume during an experiment. The installation method and locations of sampling points were confirmed after repeated experimentation and adjustment, and these locations must be adjusted for different vehicles. The first sampling point is located 10–20 cm inside the exhaust pipe to reduce the interference of air. The second, third, and fourth sampling points are distributed in the direction of exhaust emissions along the exhaust plume centerline to accurately acquire exhaust plume measurements. The changes in CO₂ concentrations are used to evaluate the accuracy of plume acquisition. The distances between the second, third, and fourth sampling points and the exhaust nozzle will change based on the test vehicle to ensure accurate plume collection and convenient installation. The fifth sampling point (background point) is located in the direction opposite the exhaust emissions and away from the exhaust pipe to reduce the influence of the test vehicle.

Data Synchronization

The SEMTECH-DS is an important part of the PEMS, as explained in detail in our previous studies (Yao et al., 2011; Shen et al., 2014; Yao et al., 2015). The SEMTECH-DS can test the speed, latitude, longitude, elevation, air temperature, air humidity, exhaust temperature, and concentrations of CO, CO₂, HC, and NOₓ in the exhaust. Thus, the sampling system can test these parameters, as well as the humidity of the exhaust, the concentrations of CO₂ and PM₂.₅ along the exhaust plume, the concentrations of CO₂ and PM₂.₅ in the air, and the carbon component and ion component concentrations of particulate matter measured in the laboratory. The temporal resolutions of these results vary because they are tested using different instruments; thus, temporal synchronization must be performed before calculations can be made. First, the data collected by the SEMTECH-DS should be temporally synchronized. The CO₂ concentration in the exhaust vent was measured using both the SEMTECH-DS and Infralyt50 at sampling point #1. Certain parameters collected by the SEMTECH-DS, such as speed and air temperature, and the CO₂ concentration in the exhaust plume were temporally synchronized based on the temporal resolution of the CO₂ concentration, as shown in Fig. 6. The dilution rate (DR) is calculated based on the difference in the CO₂ concentration between a sampling point and the exhaust vent. Detailed information regarding these calculations is provided in the section of dilution rate. The CO₂ concentration in the exhaust plume measured by the Infralyt50 had the same temporal resolution as the DR. Therefore, parameters such as speed and air temperature collected by the SEMTECH-DS were temporally synchronized with the DRs at different sampling points in the exhaust plume. Anomalous data obtained by some instruments were deleted, and the results obtained using different types of test equipment remained the same throughout the temporal synchronization process.

The switching and data recording times of different instruments were different, but the temporal synchronization process reduced the associated error. Thus, through temporal synchronization, all parameters measured by the plume multipoint sampling system were temporally uniform, thereby eliminating anomalous data and reducing the system error.

Judgment Criterion of Accurate Exhaust Collection

Accurate exhaust collection is the basis of this study. Chemically, CO₂ is stable and does not readily react with other matter in the atmosphere. Changes in the CO₂ concentration...
were used to determine whether exhaust was accurately collected at the sampling points. The CO$_2$ in vehicle exhaust is gradually diluted after being discharged into the air. The CO$_2$ concentration in the exhaust plume should decrease as distance from the exhaust nozzle increases, and the distributions at different distances should exhibit similar variations. If the variations in the CO$_2$ concentrations at different sampling points are identical and the concentrations are higher than the CO$_2$ concentration in the air, we assume that the different sampling points effectively collected the exhaust plume from the vehicle. The sampling points were assumed to have failed to effectively collect the exhaust plume from the vehicle in two situations. First, if the CO$_2$ concentrations at sampling points in the exhaust plume were the same as that in the ambient air, the exhaust plume was not effectively captured at the sampling points. Second, if the CO$_2$ concentrations at sampling points in the exhaust plume were higher than those in ambient air but exhibited different trends compared to those at other sampling points, the vehicle exhaust was not accurately collected at a sampling point or sampling points. Generally, the sampling point that least effectively collected the smoke plume was the one located farthest from the exhaust pipe.

The CO$_2$/CO analyzer system can display the numerical values and plots of the five channels of CO$_2$/CO data in real time and can store, query, and export data. We can determine whether each sample point accurately sampled the smoke plume by monitoring changes in the CO$_2$ concentration during the experiment. If the samples are not being accurately collected, the experiment should be immediately stopped to address the problem.

The proposed sampling system was used to conduct an on-road test, and the variations in the CO$_2$ concentrations in the ambient air and at different sampling points in the plume are shown in Fig. 7. As illustrated in Fig. 7, the CO$_2$ concentrations at different sampling points in the plume exhibit the same variations and are higher than that in the background air. Thus, the exhaust plume from the measured vehicle was accurately collected at all the sampling points.

The instantaneous PM$_{2.5}$ concentrations were also measured during the experiment. The instantaneous PM$_{2.5}$ data can be used to correct the results when the sampling points failed to accurately sample the exhaust plume. The instantaneous PM$_{2.5}$ and CO$_2$ concentrations of the background air were also measured.

**Dilution Rate**

In previous studies, the variations in the concentrations of NO$_x$ (Vogt et al., 2003; Morawska et al., 2007; Kwak et al., 2014), CO$_2$ (Giechaskiel et al., 2005; Lipsky and Robinson, 2006; Casati et al., 2007; Rönkkö et al., 2007; Uhrner et al., 2007; Kittelson et al., 2008), and soot particles (Rönkkö et al., 2006) in exhaust plume were used to calculate the DRs at different distances from the exhaust vent. The NO$_x$, CO$_2$, and soot particle concentrations in the exhaust nozzle and in the exhaust plume were not measured simultaneously in some studies (Vogt et al., 2003; Giechaskiel et al., 2005; Rönkkö et al., 2006; Casati et al., 2007; Rönkkö et al., 2007). In these studies, the NO$_x$, CO$_2$, and soot particle concentrations in the exhaust nozzle were tested using a chassis dynamometer in the laboratory, and an exhaust plume was tested during the on-road tests. These concentrations were influenced by the driving cycle, air temperature, air humidity, etc. Additionally, calculating the DR using asynchronous data generally increases the calculation error.

The CO$_2$ is not easy to react with other substances in the air because of its low chemical activity and the test instrument of CO$_2$ is more reliable and cheaper than NO$_x$.
and soot particles, so the CO₂ concentrations were used to calculate the DRs in this study; The CO₂ concentrations at different sampling points were tested using the same instruments at the same time, and the results show the same variations. A good linear relationship was observed between the CO₂ concentrations corrected based on the background CO₂ concentrations at two different sampling points, as shown in Fig. 8. The results show that the DR is relatively constant at a constant distance from the exhaust vent. Additionally, the DR is affected by the driving cycle far less when the distance between a sampling point and the exhaust vent is constant. Morawska et al. (2007) reached a similar conclusion in their study. Thus, Eq. (1) was used to calculate the DRs at different sampling points in this study:

$$ DR = \frac{(C_0 - C_{\text{air}})}{(C_X - C_{\text{air}})} $$

(1)

where DR is the dilution rate, $C_X$ is the CO₂ concentration in the exhaust plume at distance X m from the exhaust vent, $C_0$ is the CO₂ concentration in the exhaust vent, and $C_{\text{air}}$ is the CO₂ concentration in the background air.

Although the CO₂ concentration was also used to calculate the DRs in previous studies (Giechaskiel et al., 2005; Casati et al., 2007; Rönkkö et al., 2007; Uhrner et al., 2007; Kittelson et al., 2008), the CO₂ concentration in the exhaust vent was measured using a chassis dynamometer in the laboratory, and the speed was the same as that in the chasing test. Kittelson et al. (2008) and Uhrner et al. (2007) measured the CO₂ concentrations in the exhaust vent and exhaust plume simultaneously, but they had only two sampling points. In this study, five different sampling points were used in the system, and the variations in the DRs of the exhaust plume at four locations were analyzed simultaneously. Additionally, we validated that the exhaust plume was accurately collected at all the sampling points, and the CO₂ concentration was instantaneously measured using five
Fig. 8. The relationship between the CO2 concentration and the corrected CO2 concentration based on the background levels at two different tests (A and B). Note: the error bars are the standard deviation.

versions of the same instrument at different ranges and resolutions to ensure the accuracy of the CO2 concentration and DR measurements.

The DRs at the different sampling points were calculated based on the CO2 concentration results. The relationship between the DR and distance is shown in Fig. 9. Fig. 9 illustrates that the DR and distance are highly correlated ($R^2 = 0.85$), and the relationship between these parameters was fitted, as shown in Eq. (2):

$$DR = 21.4X^{1.16}$$

where DR is the dilution rate and X is the distance from the exhaust vent (m).

Kim et al. (2001) calculated the relationship between the DR and distance as $D = 17.6X^{1.3}$, and the results were used in the model established by Zhang and Mexler (2004). Morawska et al. (2007) obtained a similar relationship using the NOx concentration. The results in this study were similar to the results of previous studies and showed that the entire exhaust plume was accurately sampled at all the sampling points. Additionally, our results provide experimental data for numerical simulations of particulate matter variations in an exhaust plume.

CONCLUSIONS

The multipoint sampling system for vehicle exhaust plumes designed and built in this study performed very well during the on-road tests. It proved to be a useful tool for measuring vehicle exhaust plumes near the discharge outlet of the exhaust gas. The multipoint sampling system includes a particulate matter multi-channel film sampling system, CO2/CO analyzer system, VOC sampling system, particulate matter real-time analyzer system, and sensor interfaces (SEMTECH-DS and other instruments). The vehicle exhaust can be sampled at multiple locations near the exhaust nozzle simultaneously using the multipoint sampling system, and the resulting data include the variations in fine particulate matter, including the carbonaceous and ionic components, and the organic compounds in the plume near the exhaust nozzle.

A parallel test of the multi-channel particulate matter film sampling system was conducted in the laboratory before the on-road measurements, and the results show that the system is reliable and can be used for actual analyses in the future. In summary, through temporally synchronous processing, all parameters measured by the plume multipoint sampling system were temporally uniform, thereby eliminating anomalous test data points and reducing the system error.

Changes in the CO2 concentration were used to determine whether exhaust was being accurately collected at the sampling points. If the changes in CO2 concentrations at different sampling points were identical and the CO2 concentrations at these points were higher than that of the air, we assumed that the exhaust plume from the vehicle was being accurately collected at the sampling points. The exhaust plume of the measured vehicle was accurately collected at all the sampling points in our on-road tests.

The DRs at the sampling points at different distances were calculated based on the CO2 concentration results. The relationship between the dilution rate and distance was calculated based on the on-road test results, and this relationship is as follows: $DR = 21.4X^{1.16}$. The equation can be used for modeling purposes, especially in comparisons of model results and observations and in the evaluation of dispersion models.

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