Southern Nevada Air Quality Study – Final Report

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13. ABSTRACT (Maximum 200 words) The Southern Nevada Air Quality Study (SNAQS) created cross-plume and in-plume measurement systems to quantify emissions distributions and source profiles from transportation emissions, specifically gasoline and diesel powered vehicles. The cross-plume system measures backscattered ultraviolet radiation to estimate particulate emissions and infrared and ultraviolet absorption to measure gas concentrations in exhaust plumes. The in-plume system draws a portion of air from the plume and directs it to continuous monitors and filter samples that are analyzed in the laboratory. Both systems were applied to on-road measurements in Las Vegas, Nevada. Results from both methods found that most of the particulate and gas pollutant emissions came from a small fraction of the vehicles. High carbon monoxide emitters were not always high particulate matter and oxide of nitrogen emitters, implying that smog checks must measure all of these pollutants to be effective. Receptor models were applied to ambient particulate samples taken in Las Vegas using source profiles obtained with the in-plume system. Gasoline engine exhaust was the largest contributor to the carbon component at all sites, and diesel exhaust was only a large contributor at commercial sites near major highways. Residential wood combustion was also an important contributor in residential areas, but not in the commercial areas.

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GLOSSARY/DEFINITION OF TERMS

$(NH_4)_2SO_4$ ..... Ammonium Sulfate
$[NH_4]\cdot HSO_4$ ..... Ammonium Bisulfate
°C ..... Degrees Celsius
°K ..... Degrees Kelvin
µm ..... Micrometers
µs ..... Microsecond
CC ..... City Center Site
CE-CERT ..... College of Engineering-Center for Environmental Research and Technology
CI ..... Compression Ignition
CLS ..... Classical Least Squares
CMB ..... Chemical Mass Balance
CO ..... Carbon Monoxide
CO_2 ..... Carbon Dioxide
CVS ..... Constant Volume Sampling
DOD ..... Department of Defense
EC ..... Elemental Carbon
EF ..... Emission Factors
ELPI ..... Electrical Low Pressure Impactor
EPA ..... U.S. Environmental Protection Agency
FTA ..... Federal Transit Administration
FTIR ..... Fourier Transform Infrared spectrometer
FTP ..... Federal Test Procedure
g/kg ..... Grams per Kilogram
g/mile ..... Grams per Mile
H_2O ..... Water/Water Vapor
HC ..... Hydrocarbon
HDDML ..... Heavy Duty Diesel Mobile Laboratory
HDDV ..... Heavy Duty Diesel Vehicles
HDGV ..... Heavy Duty Gasoline Vehicles
IPETS ..... In-Plume Emissions Test Stand
IR ..... Infrared
JD ..... J.D. Smith Elementary School Site
kHz ..... Kilohertz
kW ..... Kilowatt
L/min ..... Liters per Minute
LDDV ..... Light Duty Diesel Vehicles
LDGV ..... Light Duty Gasoline Vehicles
LIDAR ..... Light Detection and Ranging
MOBILE6 ..... EPA emissions model
MS ..... East Charleston Site
N_2O ..... Nitrous Oxide
NDIR ..... Non-Dispersive Infrared
NH_3 ..... Ammonia

NH_4NO_3 ..... Ammonium Nitrate
NO ..... Nitrogen Oxide
NO_2 ..... Nitrogen Dioxide
NO_3^- ..... Nitrate
NO_x ..... Oxides of Nitrogen (Nitrogen Oxides)
ns ..... Nanosecond
O_3 ..... Ozone
OC ..... Organic Carbon
OMC ..... Organic Compounds
OR ..... Orr Middle School Site
PART5 ..... EPA emissions model
PM ..... Particulate Matter
PM_{10} ..... Particles with aerodynamic diameters < 10 µm
$PM_{2.5}$ ..... Particles with aerodynamic diameters < 2.5 µm (also fine PM)
RH ..... Relative Humidity
SERDP ..... Strategic Environmental Development Plan
SNAQS ..... Southern Nevada Air Quality Study
SO_2 ..... Sulfur Dioxide
$SO_4^=$ ..... Sulfate
Stdev ..... Standard Deviation
TAZ ..... Traffic Analysis Zone
Ultrafine Particles ..... Particles with aerodynamic diameters < 0.1 µm
VERSS ..... Vehicle Emissions Remote Sensing System
VMT ..... Vehicle Miles Traveled
VOC ..... Volatile Organic Compound
VSP ..... Vehicle Specific Power

FOREWORD

This document is published to inform the public about the Southern Nevada Air Quality Study (SNAQS). The information provided here is useful for local environmental planners in Clark County Nevada to assess the relative contribution of various emission sources to local air quality. The methods developed under this project provide useful tools to all air quality planners and can be used to prioritize emission control efforts in their own airsheds.

The purpose of this air quality study was to develop and evaluate nonintrusive methods to measure air pollution emissions from vehicles operating on public roadways. The solutions that were developed included advanced measurement methods used to quantify real-world emissions of gases and particles from over 100,000 vehicles in Las Vegas, Nevada. Analysis of ambient air quality concentrations in the Las Vegas basin was examined to attribute pollutants to diesel exhaust, gasoline exhaust, and wood smoke. The instrumentation and analytical tools developed under this project have subsequently been used by other local air quality planning agencies and the Department of Defense to address their own air quality issues.

The results of this project are summarized in the executive summary and described in detail in the body of the report.

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EXECUTIVE SUMMARY

Transportation emissions are large contributors to excessive concentrations of $PM_{2.5}$ (particles with aerodynamic diameters less then 2.5 μm), ozone (O_3), and carbon monoxide (CO). A portion of $PM_{2.5}$ is directly emitted from exhaust pipes and roadway surfaces, as well as industrial, residential heating, cooking, and other fugitive dust sources. Another portion of $PM_{2.5}$ and all of the atmospheric ozone forms from oxides of nitrogen (NO_x) and volatile organic compound (VOC) emissions that are often, but not always, dominated by transportation sources. $PM_{2.5}$, VOC, and CO exhaust emissions vary substantially from vehicle to vehicle and are not adequately represented by emissions inventories. These deviations occur because actual driving procedures do not correspond to those applied for engine certification. On-road tests show that a small fraction of poorly maintained vehicles can often constitute a large fraction of total vehicle emissions. High $PM_{2.5}$ emitters are not necessarily high VOC or CO emitters.

The Southern Nevada Air Quality Study (SNAQS) intended to quantify contributions of transportation emissions to pollutants in the Las Vegas metropolitan planning area. Specific SNAQS objectives were to: 1) develop, test, and evaluate advanced measurement methods to determine real-world vehicle emissions; 2) quantify on-road motor vehicle exhaust emissions for directly emitted $PM_{2.5}$, VOC, and CO and establish methods for identifying high emitters: 3) determine relative contributions of transportation and other sources to ambient pollutant concentrations for the Las Vegas metropolitan area; and 4) expand the application of technology developed during this air quality study to other areas with air quality problems. SNAQS accomplished these objectives in three phases that were carried out between 1999 and 2005.

- **Develop, test, and evaluate advanced measurement methods to determine real-world vehicle emissions.** Cross-plume and in-plume measurements systems were designed, built, tested and applied to real-world traffic emissions. Emission factors from the cross-plume system compared favorably with those from the U.S. Environmental Protection Agency (EPA) emissions models. The in-plume system demonstrated that it is possible to obtain emissions factors for other species of interest, such as ammonia, sulfur dioxide and ultrafine particles, in addition to the emission factors for standard components such as carbon monoxide, nitrogen oxide and volatile organic compounds. Emission factors for the in-plume and cross-plume systems compared favorably when applied to the same school bus emissions. They also compared favorably when applied at different times and places to real-world emissions in Las Vegas, Nevada. The in-plume system showed highly correlated results with a mobile laboratory certification system, but there were systematic biases for NO and $PM_{2.5}$ emission factors. The reasons for these discrepancies are still being investigated.

- **Quantify on-road motor vehicle exhaust emissions for directly emitted $PM_{2.5}$, VOC, and CO and establish methods for identifying high emitters.** Tests were conducted in Las Vegas, Nevada, using both the cross-plume and in-plume systems. Although these tests occurred at different times and places, and used different measurement methods, similar results were found for average emission factors. Emission distributions found that emissions distributions were highly skewed for high emitters. The tests added value to the emissions

models by demonstrating that the distribution of emissions is highly skewed toward higher emitting vehicles. Although this was known for gas emissions, this air quality study provided the first evidence that this is also true of $PM_{2.5}$ emissions. The simultaneous measurements of $PM_{2.5}$, CO, and NO demonstrated that most of the high CO emitters did not correspond with the high $PM_{2.5}$ and NO emitters. This indicates that periodic smog tests measuring only CO and VOC will not identify high $PM_{2.5}$ and NO emitters.

- **Determine relative contributions of transportation and other sources to ambient pollutant concentrations for the Las Vegas metropolitan area.** Chemical source profiles were measured with the in-plume system and applied to a Chemical Mass Balance source apportionment of ambient samples in Las Vegas during January, 2003. This modeling showed that gasoline vehicle exhaust was the largest contributor to carbon in $PM_{2.5}$ at most of the monitoring sites. Residential wood combustion was an important contributor at residential sites, but not at the commercial sites near highways. Diesel exhaust was only a large contributor at sites near major highways. The zone of influence for these emissions sources was found to be relatively small and appeared to decrease with distance from the major roadways.

- **Expand the application of technology developed during this air quality study to other areas with air quality problems.** The in-plume and cross-plume systems were applied to source characterization at Lake Tahoe to determine source profiles for wood smoke, cooking, and vehicle exhaust. It was also used to determine the differences in emissions from diesel school buses using regular diesel and biodiesel. In this study, it was found that real-world emissions from biodiesel were higher, probably due to contamination of the fuel during transport and distribution. Continued sponsorship was achieved from the Department of Defense (DOD) to characterize emissions from non-road stationary and mobile diesel sources used on military bases. The program is now self-sustaining, and Federal Transit Administration (FTA) resources are still being leveraged to provide a more advanced understanding of transportation contributions to urban and regional pollution levels.

1. INTRODUCTION

1.1 Background

Transportation affects air quality via vehicle exhaust emissions, suspended road dust, and road construction and repair. These emissions are large contributors to excessive concentrations of $PM_{2.5}$ (particles with aerodynamic diameters less then 2.5 μm), ozone (O_3), and carbon monoxide (CO). A portion of $PM_{2.5}$ is directly emitted from exhaust pipes and roadway surfaces, as well as industrial, residential heating, cooking, and other fugitive dust sources. Another portion of $PM_{2.5}$ and all of the atmospheric O_3 forms from oxides of nitrogen (NO_x) and volatile organic compound (VOC) emissions that are often, but not always, dominated by transportation sources.

Recent tests of on-road vehicles have demonstrated that $PM_{2.5}$, VOC, and CO exhaust emissions vary substantially from vehicle to vehicle and are not adequately represented by emissions inventories. These deviations occur because actual driving procedures do not correspond to those applied in the Federal Test Procedure (FTP) or Inspection and Maintenance tests. These tests show that a small fraction of poorly maintained vehicles can often constitute a large fraction of total vehicle emissions. High $PM_{2.5}$ emitters are not necessarily high VOC or CO emitters. On-road NO_x emissions tend to be in better agreement with emissions estimates derived from FTP tests.

Since $PM_{2.5}$ and O_3 have in common some of the same precursors, the effectiveness of VOC and NO_x emissions reductions on the concentrations of both pollutants must be understood. Owing to the non-linearity of atmospheric chemical transformations, an emissions reduction that ameliorates excessive O_3 may increase $PM_{2.5}$ and vice versa. On the other hand, the concentrations of both pollutants might be reduced by the same control strategy.

$PM_{2.5}$ and O_3 generated within an urban area are superimposed on concentrations transported from other urban areas. An area of violation for a national air quality standard does not necessarily correspond to an area of influence of source emissions that may be hundreds of miles larger. Direct and precursor emissions with a metropolitan planning area must be coupled with knowledge of the $PM_{2.5}$ and O_3 transported into that area from other planning areas in order to develop least cost and highly effective emissions reduction strategies.

1.2 Goals and Objectives

The Southern Nevada Air Quality Study intended to quantify contributions of transportation emissions to pollutants in the Las Vegas metropolitan planning area. A secondary goal was to develop measurement and modeling tools that can be applied to Las Vegas transportation networks and that can be adapted to other urban areas with similar air quality problems. Specific objectives of this air quality study were to:

- Develop, test, and evaluate advanced measurement methods to determine real-world vehicle emissions.

- Quantify on-road motor vehicle exhaust emissions for directly emitted $PM_{2.5}$, VOC, and CO and establish methods for identifying high emitters.

- Determine relative contributions of transportation and other sources to ambient pollutant concentrations for the Las Vegas metropolitan area.

- Expand the application of technology developed during this air quality study to other areas with air quality problems.

1.3 Methodology and Scope

These objectives were accomplished by a combination of instrument development and testing, field measurements, data analysis, and modeling. Much of the work involved the development, testing, and application of two novel measurements systems for quantifying real-world emissions from individual vehicles as they pass the sensors. The first is a cross-plume remote sensing system that permits the detection of $PM_{2.5,}$ NO_x, CO, and VOC in the exhaust plumes of passing vehicles. This system uses a combination of ultraviolet backscattered radiation to quantify particles and infrared absorption to quantify gases. The second device is an in-plume extractive system that draws a portion of the exhaust from each vehicle through a series of analyzers with fast time response (~1 second). This allows for measurement of $PM_{2.5}$, NO_x, CO, and specific VOC compounds, as well as other pollutants of interest such as sulfur dioxide (SO_2), ammonia (NH_3), and ultrafine particles (those with aerodynamic diameters less than 0.1 µm). The in-plume system also collects $PM_{2.5}$ from many vehicles onto filters for subsequent chemical analyses. These laboratory analyses are used to create source profiles, the abundances of chemical marker species that can be used to quantify vehicle contributions to ambient $PM_{2.5}$ concentrations.

Excess carbon dioxide (CO_2) above ambient levels is measured with the other pollutants, which allows fuel-based emission factors to be estimated for application to emission inventories. The excess CO_2 is related to the carbon content of the fuel combusted by the vehicle fleet, thereby yielding emission factors in terms of g/kg fuel rather than g/mile traveled. Since fuel sale data is very accurate for a region, and since a large fraction of emissions are believed to derive from traffic congestion, this type of emission factor allows for more accurate urban emission inventories. The fuel-based emission factor can be related to the mileage factor using reasonable estimates of fleet-averaged fuel economy.

Obtaining emission factors for individual vehicles using the cross-plume and in-plume methods allows distributions of emission factors to be created. These distributions are not normal bell-shaped curves, but are highly skewed toward the high emitters. Previous studies for CO have shown that ~20% of the vehicles account for more than 80% of the emissions. The cross-plume and in-plume technologies allow these distributions to be examined for a broader range of vehicle-related pollutants.

The filter samples obtained from the in-plume system were analyzed in the laboratory for mass, elements, ions, organic and elemental carbon, and specific organic marker compounds. The chemical concentrations were normalized to the mass to create source profiles. Profiles were also measured for other pollution sources, specifically cooking and wood burning which are believed to be large emitters of $PM_{2.5}$ carbon in Las Vegas. $PM_{2.5}$ samples were also acquired at ambient sampling sites and submitted to the same chemical analyses. The Chemical Mass Balance (CMB) receptor model (Watson and Chow, 2004) used these data to determine the contributions from different source types.

The development of the in-plume and cross-plume systems as part of Federal Transit Administration (FTA) sponsorship allowed other resources to be acquired. Additional source and ambient characterization was performed using the cross-plume and in-plume systems for the California Air Resources Board, the Clark County Department of Air Quality Management, the Community Planning Association of southwest Idaho, and the U.S. Department of Defense's Strategic Environmental Development Program (SERDP). These leveraging opportunities shared the cost of instrument development and testing as well as allowing for data acquisition for a wide range of transportation-related sources.

1.4 Report Organization

Detailed technical reports and publications were produced at different stages of the air quality study, and these will be cited where appropriate in the following report sections. This introduction has provided the motivation for the study, stated its objectives, and described the methodology. Section 2 describes the cross-plume sampling system, its development and testing, and the results for different studies in which it was applied. Section 3 describes the in-plume sampling system, its evaluation activities, and example results. Section 4 summarizes the ambient source apportionment study and its results. Section 5 summarizes the results of the study and identifies knowledge gaps that can be filled by further application of the methods developed as part of this air quality study. Section 6 presents the reference citations, including reports and peer-reviewed journal publications produced as part of this project.

2. CROSS-PLUME MEASUREMENTS

2.1 Cross-Plume Configuration

The cross-plume Vehicle Emissions Remote Sensing System (VERSS) $PM_{2.5}$ detection uses Light Detection and Ranging (LIDAR) to measure the backward scattered light in a column defined by the laser beam through an exhaust plume (Barber et al., 2004, Moosmuller et al., 2003). Simultaneously, an infrared source is used to detect the CO_2 in a similar column through the exhaust plume. The ratio of $PM_{2.5}$ to CO_2 gives a relative measure of the pollution being generated by the vehicle in grams of $PM_{2.5}$ per unit of fuel carbon consumed.

When light illuminates a small pollution particle in an exhaust plume, the light is both scattered in all directions and absorbed by the particle (Watson, 2002). For a particular incident light beam, the nature of the scattering and absorption interaction is determined by the physical characteristics of the particle – its size, shape, and material characteristics as well as by the size and shape distribution of a suspension of particles. If the characteristics of the incident light are known, specifically its direction of propagation, polarization, wavelength, and intensity, then this knowledge, coupled with the nature of the scattered light and a laboratory calibration, can be used to determine some features of an unknown small particle or size distribution of particles.

The light scattered by a particle or suspension of particles back in the direction of the incident light is particularly sensitive to the physical characteristics of the particle. Analysis of this "backscattered" light to determine particle characteristics is analogous to what is done with radar, whereby microwave radiation is "bounced" back from an unknown airborne target to determine its location. The sensitivity of detection of the backscattered light can be maximized by choosing a light source at a wavelength that is comparable to the size of the particles being measured. Soot in vehicle exhaust generally falls in the size range of 0.05 to 0.5 μm.

Figure 2-1 shows the configuration for the patented (Moosmuller and Keisler, 2003) in-plume system developed as part of this air quality study. A short-duration pulse (nominally 1 ns in duration) at an ultraviolet wavelength of 0.266 μm leaves the transmitting laser at one side of the road and is partially scattered back toward the transmitter by particles in the exhaust plume. The received signal is the output of a photo-multiplier tube (a voltage) vs time. The dimensions of the typical roadside configuration are such that the 1 ns pulse (traveling at the speed of light) interacts with the exhaust plume and the beam termination and is returned in less than 100 ns. For the given pulse repetition frequency of 6.8 kHz, a pulse is transmitted approximately every 150 μs, ensuring that only a single 1 ns transmitted pulse interacts with the exhaust plume at a time.

In general, three species are of interest: 1) $PM_{2.5}$ in the exhaust plume of the vehicle being measured, 2) background molecular gases in the atmosphere, and 3) the ambient $PM_{2.5}$. This latter quantity may include multiple components, such as the background PM from regional sources, PM from vehicles that immediately preceded the vehicle being measured, and dust particles suspended from the road surface by vehicle motion and roadway tire contact.

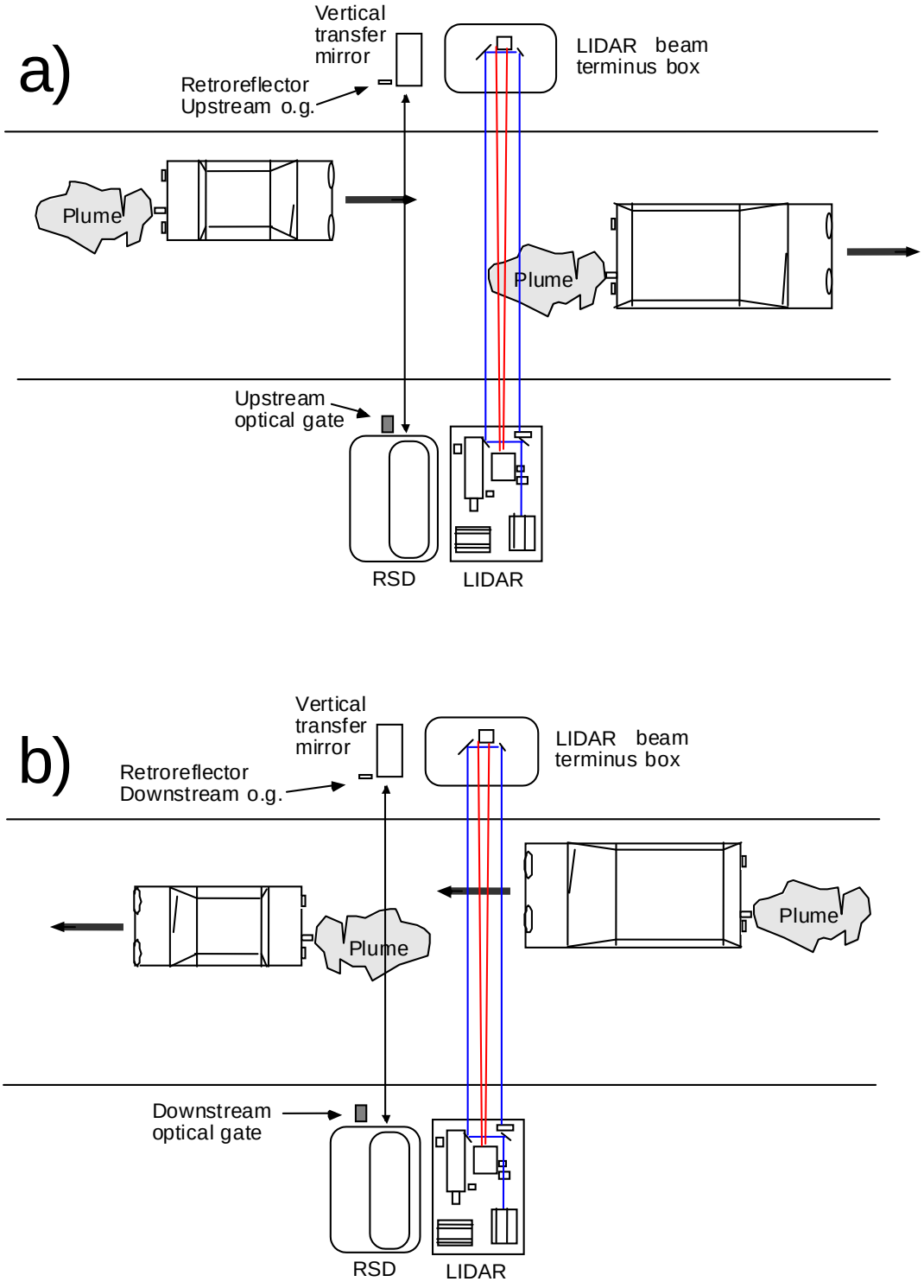


Figure 2-1. Top view of the cross-plume sampling system. The LIDAR measures backscattered laser light from $PM_{2.5}$ in the exhaust plume. The RSD3000 is a commercial instrument that measures infrared radiation absorbed by gases in the exhaust plume. Panel a) shows the setup for the right side of a traffic lane and panel b) shows it for the left side of the traffic lane.

A detailed schematic of the LIDAR system is shown in Figure 2-2. The ultraviolet laser is pulsed at a high rate and directed out of the enclosure toward the exhaust plume. The shutter imparts a modulation frequency that allows the return signal to be separated from stray light. Part of the laser light is scattered back toward its origin by the particles in the plume. The higher the density of these particles, the more light is backscattered. All of the returned light is focused on a rapid response detector. Another part is reflected back by the retro-reflector on the opposite side of the road. This is a reference beam that accounts for dispersion and scattering by air molecules. The laser pulse rate is so fast that the longer distance that the reference signal travels results in a delay in its detection. This delay allows it to be separated from the return signal from particles in the plume.

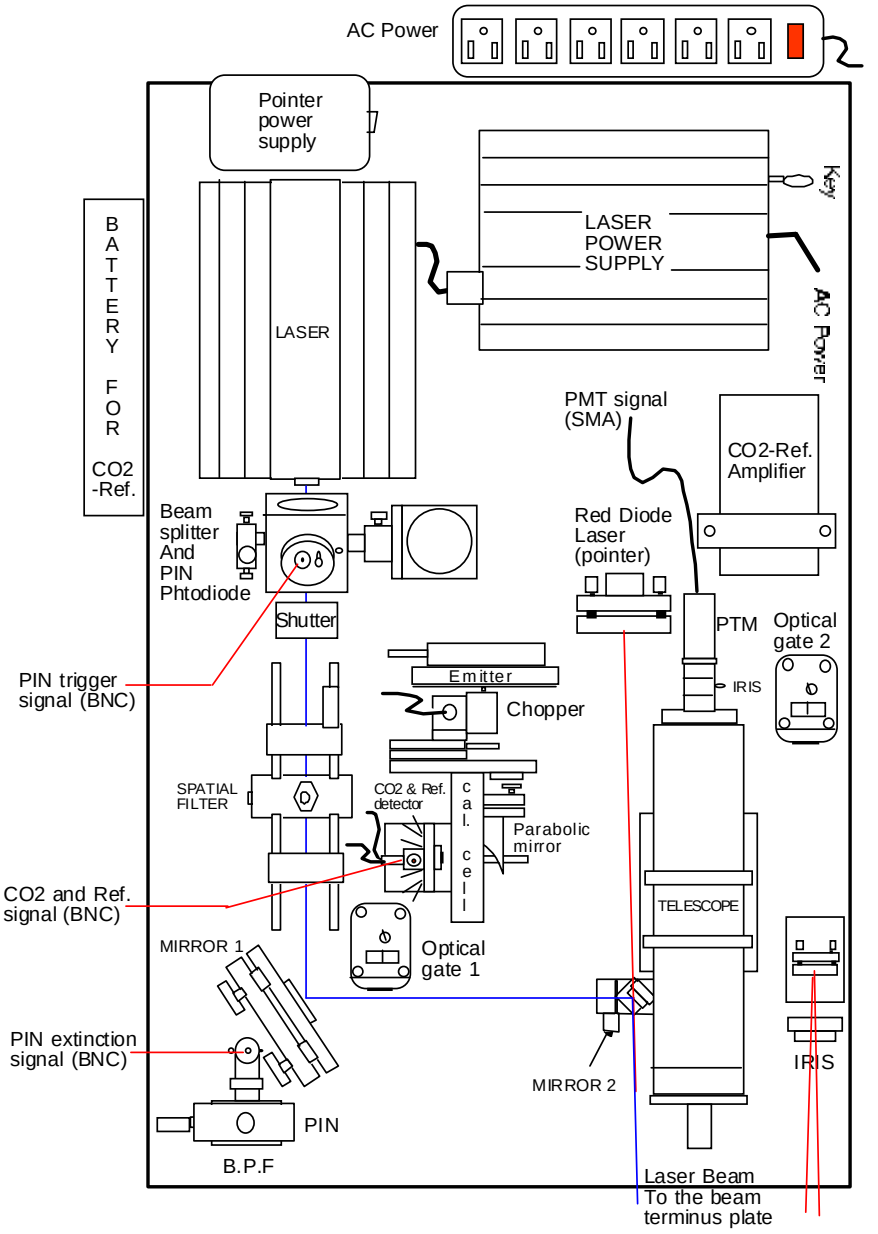


Figure 2-2. Physical configuration of the cross-plume LIDAR projection and detection system.

Light scattering is related to mass concentrations through a mass scattering efficiency that can be calculated for different particle characteristics. Barber et al. (2004) evaluate these efficiencies for different size distributions, compositions, and densities of small particles originating in vehicle exhaust. Even with expected deviations from the ideal case, the efficiency is constant within ±25% for most conditions. This is adequate precision for determining on-road $PM_{2.5}$ emission factors which vary over several orders of magnitude for different emitters.

During SNAQS the LIDAR unit was operated alongside a commercially available remote sensing system, the RSD3000, to measure CO, VOC, NO, and CO_2. The RSD3000 projects broad-band radiation in the infrared and ultraviolet regions of the electromagnetic spectrum, and reflects it back to the detectors. Interference filters in front of the detectors select the wavelengths that are absorbed by the gases in the exhaust plume. Reduction in the detector's voltage output is caused by absorption of light by the molecules of interest. Because the effective plume path length and amount of plume seen depend on turbulence and wind, ratios of CO, hydrocarbons (HC), and nitrogen monoxide (NO) to CO_2 are recorded instead of absolute values. This is sufficient to derive a fuel-based emission factor.

The ratios of different pollutants to CO_2 are also useful for understanding the combustion system. With the aid of a fundamental knowledge of combustion chemistry, many parameters of the vehicle's operating characteristics can be determined including: 1) the instantaneous air/fuel ratio, 2) the %CO, %HC, or %NO which would be read by a tailpipe probe, and 3) the grams CO, VOC, or NO emitted per gallon of gasoline. Since most new gasoline powered vehicles emit little CO or VOC, they show low emission rates. Larger emission rates imply that the engine has a fuel-rich air/fuel ratio and that the emission control system, if present, is not fully operational. A lean air/fuel ratio, while impairing vehicle performance, produces very little CO. If the air/fuel ratio is lean enough to induce misfire then a large amount of unburned fuel, as manifested by a high VOC/CO_2 ratio, will be found.

The height of the sensing beam is typically set at 20-30 cm above the road surface to observe exhaust plumes from light duty vehicles, provided the exhaust plume exits the vehicle within a few feet of the ground. The remote sensor is accompanied by a video system for vehicle identification information. The video camera is coupled directly into the data analysis computer so that the image of each passing vehicle is displayed on the video screen.

Aside from the difficulty in moving and situating the LIDAR and RSD3000 systems for each test, the light beams from the two systems are not exactly aligned and their timing is not precisely coordinated. This introduces some uncertainty into the measurements that could be resolved with a more integrated system. The final effort in this air quality study, continued with Department of Defense (DoD) sponsorship (Watson et al., 2003, 2004, 2005), is the integration of remote gas detection with the LIDAR. The integrated system is based on a miniature broadband blackbody infrared (IR) emitter operating at a temperature of 1170 °K, as illustrated in Figure 2-3.

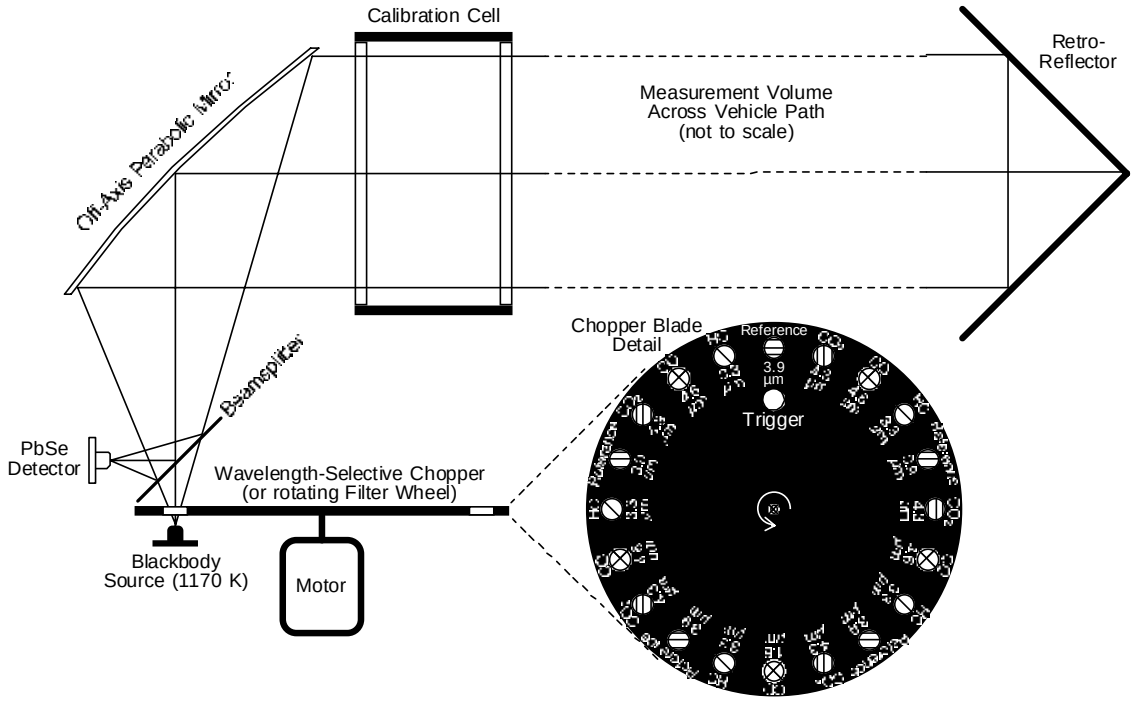


Figure 2-3. Schematic diagram of cross-plume infrared gas sensor to be integrated with the LIDAR $PM_{2.5}$ sensor.

The black body source is modulated by a chopper wheel, as shown in the figure, to allow its signal to be separated from stray light. The source radiation is monitored with a lead-selenium (PbSe) detector, then directed toward the retro-reflector by a mirror. The vehicle plume is measured as it passes through the measurement volume. The attenuated return signal is transmitted to detectors through the partially reflecting mirror. A calibration cell containing known concentrations of the gases being monitored is periodically placed in the measurement volume to relate the infrared attenuation to integrated plume concentrations.

Speed and acceleration strips consist of two bars approximately 2 meters in length, placed at intervals along the roadside. One is equipped with two diode lasers at either end and the other is equipped with two photodetectors at either end. These are aligned such that each diode laser hits the corresponding photodetector. As the front and back tires sequentially break the upstream and downstream beams, the speed and acceleration can be computed for the vehicle. License plates are photographed and digitized for an experiment. These can then be related to vehicle make, model, year, and general location of the registered owner by relating them to vehicle registration data from the Department of Motor Vehicles.

2.2 Cross-Plume Results from the Las Vegas Field Study

During the spring and summer of 2000, 2001, and 2002, gaseous and particulate matter (PM) fuel-based emission factors for about 150,000 individual vehicles in the Las Vegas, NV area were measured with the cross-plume sensor (Kuhns et al., 2002, 2004a, Mazzolini et al., 2004a, 2004b). Figure 2-4 shows the locations where measurements were acquired. These were selected based on the ability to locate the equipment, direct traffic within the sample volume, and

to represent a variety of different vehicles and driving conditions. Figure 2-5 shows a typical setup for the cross-plume monitoring.

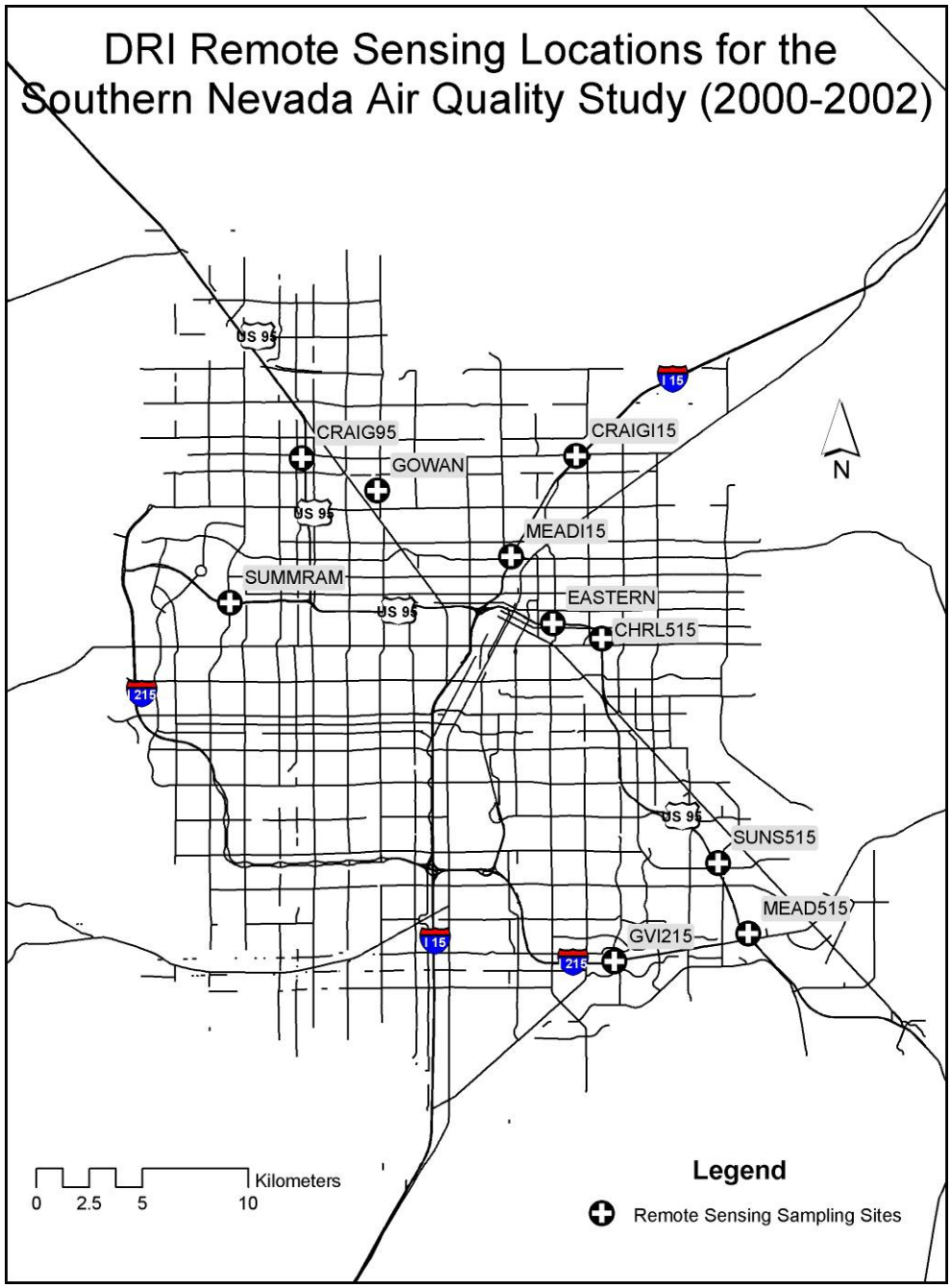


Figure 2-4. Measurement locations for on-road emissions measurements taken in Las Vegas with the cross-plume sampling system.

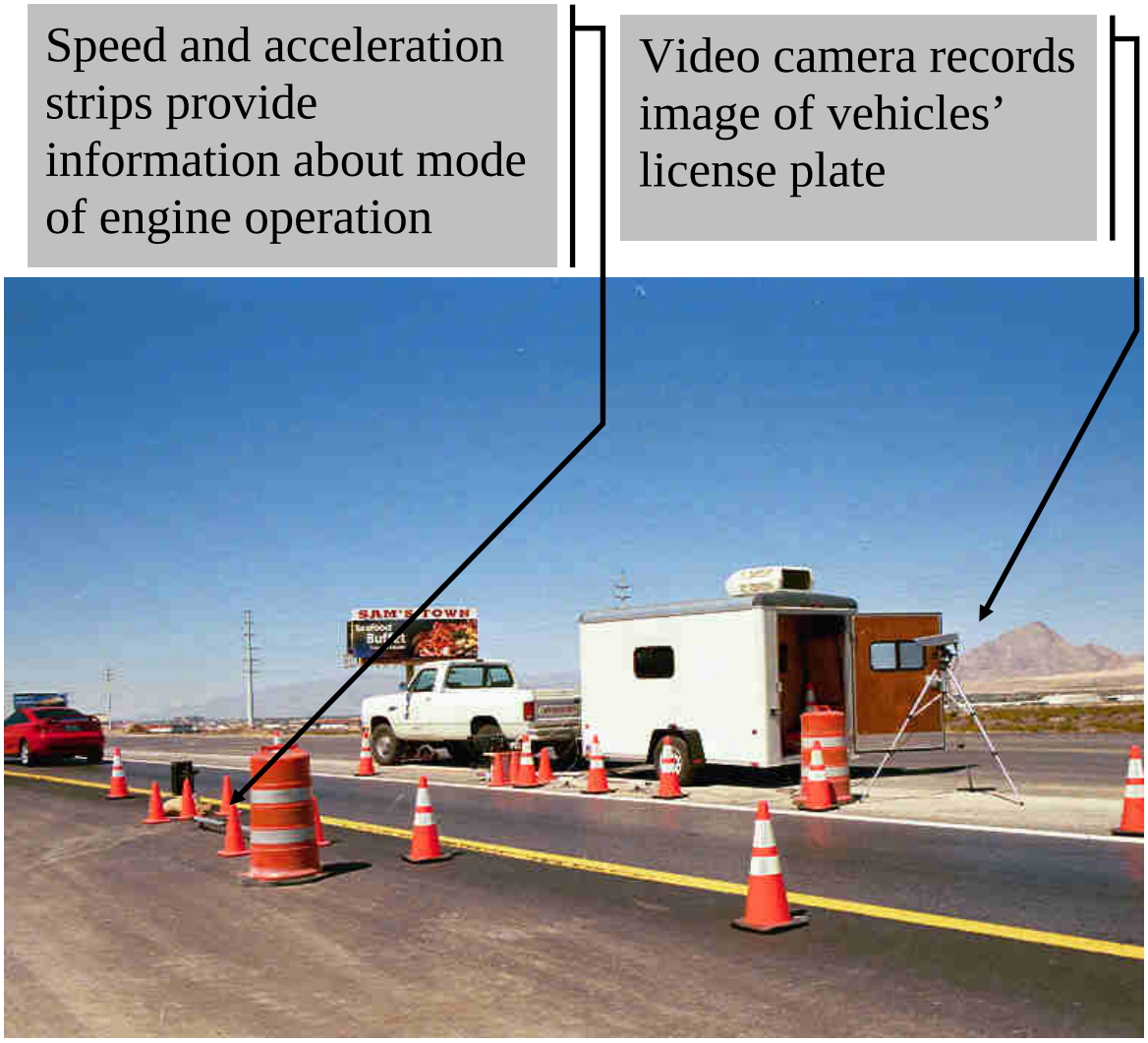


Figure 2-5. Typical setup of the LIDAR and RSD300 cross-plume monitor in Las Vegas, Nevada.

The $PM_{2.5}$, CO, NO, and VOC data were processed for each of these vehicles and related to the vehicle make and model through records from the Nevada Department of Motor Vehicles. Figure 2-6 shows an example of emissions distributions for $PM_{2.5}$ and CO. Skewness is evident with 78% of the overall CO emissions deriving from just 10% of the entire fleet. The higher CO emitters contributed about 35% of the overall $PM_{2.5}$ emissions, implying that the elimination from the fleet of all the vehicles belonging to the highest CO emission decile would reduce 78% ± 9% of CO and 35% ± 20% of $PM_{2.5}$ emissions. Similarly, the 10% higher CO emitters contributed 29% ± 4 % of the overall VOC emissions, and 15% ± 2% to the overall NO emissions. These results suggest that annual smog checks that test for only CO and VOC emissions will probably have only a minor effect on high NO and VOC emitters.

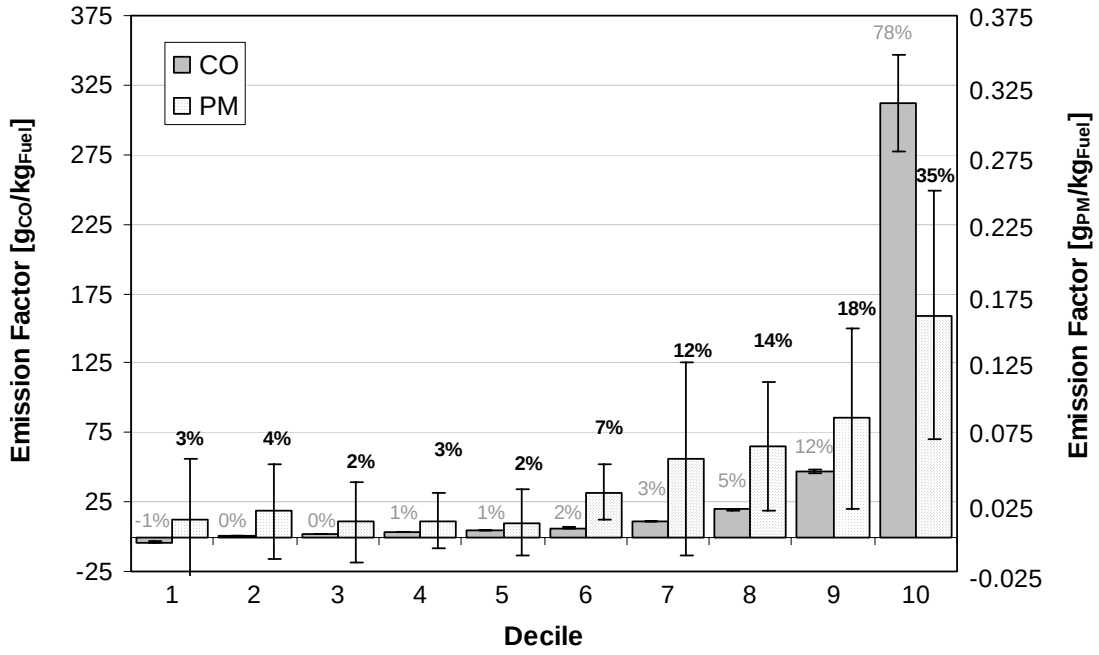


Figure 2-6. Contribution of lowest to higher CO emitters to the CO and PM emission factors for the spark ignition vehicles measured in Las Vegas in 2002. The error bars represent the standard error of the single decile average, calculated as the standard deviations of averages of arbitrarily chosen bins for each decile (the central limit theorem). The percent above each column indicates the contribution of the respective decile to the overall emission factor of CO or $PM_{2.5}$.

Average emission factors from the experiments in Las Vegas are compared with those from the U.S. Environmental Protection Agency (EPA) emissions models MOBILE6 and PART5 in Table 2-1 for four vehicle classes. Vehicle classes were determined by matching the license numbers to the registration data. For CO, MOBILE6 gasoline vehicle emissions exceeded the on-road measurements by 102% and 78% for light duty gasoline vehicles (LDGV) and heavy duty gasoline vehicles (HDGV), respectively. In contrast, MOBILE6 CO emissions were 26% to 54% lower than on-road measurements for diesel vehicles. With the exception of light duty diesel vehicle emissions, MOBILE6 freeway VOC emissions were 19% and 43% higher than the on-road emissions. MOBILE6 light duty diesel vehicle (LDDV) VOC emissions were 180% higher than VERSS values. MOBILE6 NO emissions for LDGV were similar to the on-road measurements, but they were higher for the other vehicle categories, with heavy-duty vehicles between 78% and 84% larger than the on-road measurements.

PART5 emission factors are based on dynamometer tests with PM being quantified on filters that are weighed prior to and after sampling. The cross-plume PM emission measurements are based on optical measurements that only approximately correspond to the gravimetric mass (Barber et al., 2003). PART5 estimates 27% percent more PM emissions from light duty gasoline vehicles compared to the on-road averages. LDDV and heavy-duty diesel vehicle (HDDV) emission factors from the cross-plume measurements were similar at 2.6 g/kg fuel. However, PART5 HDDV PM emissions were 45% lower than the PART5 LDDV emission estimates. The largest discrepancy between cross-plume PM and PART5 emission factors was

found for HDGV emissions, with PART5 estimating PM emission more than 2.5 times those measured by the VERSS.

The influence of cold start emissions has been excluded from this comparison since it is assumed that the exhaust measured on the freeway onramp is from hot stabilized engines. The discrepancies between the running emissions rates from the MOBILE6 and PART5 model versus the cross-plume measurements are substantially larger than the emission factors differences associated with the choice of driving cycle or mode.

Table 2-1. Comparison of fleet averaged emission factors measured by the RSD and LIDAR cross-plume sensors with modeled MOBILE6 and PART5 output for light duty gasoline vehicles (LDGV), light duty diesel vehicles (LDDV), heavy duty gasoline vehicles (HDGV) and heavy duty diesel vehicles (HDDV).

	CO (g/kg fuel)			*VOC (g/kg fuel)*			*NO (g/kg fuel)*			*PM (g/kg fuel)*		
Vehicle Type	**RSD**	**MOBILE6**	**% diff**	**RSD**	**MOBILE6**	**% diff**	**RSD**	**MOBILE6**	**% diff**	**Lidar**	**PART5**	**% diff**
LDGV	49	99	***+102***	2.8	4.0	***+43***	8.8	8.8	***0***	0.10	0.13	***+30***
LDDV	19	8.7	***-54***	2.3	6.5	***+183***	15.2	19	***+25***	2.6	1.9	***-27***
HDGV	56	100	***+78***	2.6	3.6	***+38***	10.3	19	***+84***	0.07	0.25	***+257***
HDDV	10	7.4	***-26***	1.6	1.9	***+19***	19.9	35.5	***+78***	2.6	1.0	***-61***

Figure 2-7 compares average emission factors as a function of age for the light duty gasoline vehicles for the cross-plume measurements and those derived from EPA's MOBILE6 and PART5 emission models. Each cross-plume data point represents the average of at least 100 vehicles. Cross-plume CO emission factors are similar to the MOBILE6 factors for the newest vehicles. For vehicles 1 to 14 years old, MOBILE6 CO emissions are higher than the on-road measurements by up to a factor of 3. MOBILE6 and cross-plume CO emission factors converge for vehicles 15 years and older. VOC and NO emissions are more consistent between MOBILE6 estimates and cross-plume measurements. For VOC emissions, measured and modeled freeway emissions are in good agreement for vehicles less than 14 years old. For older vehicles, MOBILE6 estimates VOC emissions higher than those measured. Similarly, NO emissions from MOBILE6 are in good agreement with measurements for vehicles less than five years old. For older vehicles, the MOBILE6 NO emissions are lower than the on-road measurements. EPA's PART5 PM emissions model does not stratify its output by vehicle age; the PM emission factor for all model year 1987 and newer vehicles is a constant. The cross-plume show that later model vehicles emit less PM mass per fuel consumed than older vehicles.

Up to half of the trips in an urban area originate at a vehicle owner's registered address. For a typical weekday, these trips begin in the morning after the vehicle has been unused over the previous 12 hours. Although vehicles emit pollutants over the entire length of a trip, the registration address provides useful information for spatially allocating emissions in an airshed. Cold start emissions typically occur within 1 mile of the registration address. In addition, short trips (i.e., residence to school, residence to grocery, etc.) occur within close proximity to the registration address.

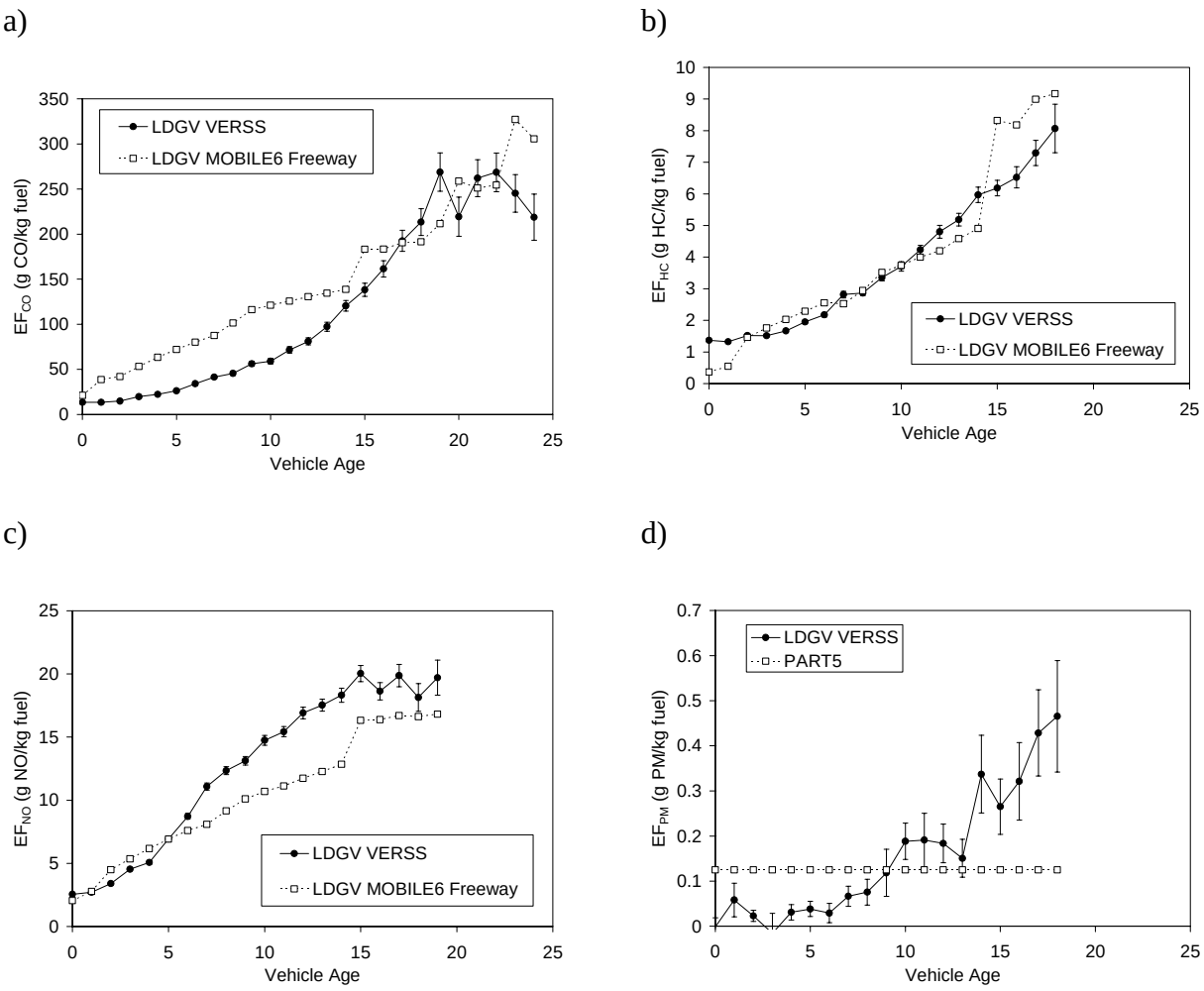


Figure 2-7. Comparison of cross-plume VERSS measurement results with emission factor models MOBILE6 and PART5. Panels a, b, c, and d show the relationships between light duty gasoline vehicle (LDGV) age and CO, VOC, NO, and PM emission factors, respectively.

General registration locations were linked to 60,000 of the light duty gasoline vehicles detected by the cross-plume system through the license numbers and registration records. Using the Geographic Information Systems program ARCGIS, the geographic coordinates of the registration address were spatially joined to one of the 800+ traffic analysis zone (TAZ) polygons used for traffic demand and forecast modeling. For TAZs with more than 20 registered vehicles, the average emission factors for CO, VOC, NO, and PM were calculated.

Figure 2-8 shows number of vehicles registered in each TAZ for different CO emissions groupings. White TAZs have insufficient numbers of registered vehicles to calculate an average. The lightest gray shade represents TAZ with average CO emissions from 0 to 30 g/kg fuel, which typifies most of the vehicle origin areas. There are few black TAZ (90 – 120 g/kg fuel), but there are many dark gray areas with average CO emissions three times higher than those of the lightest gray areas.

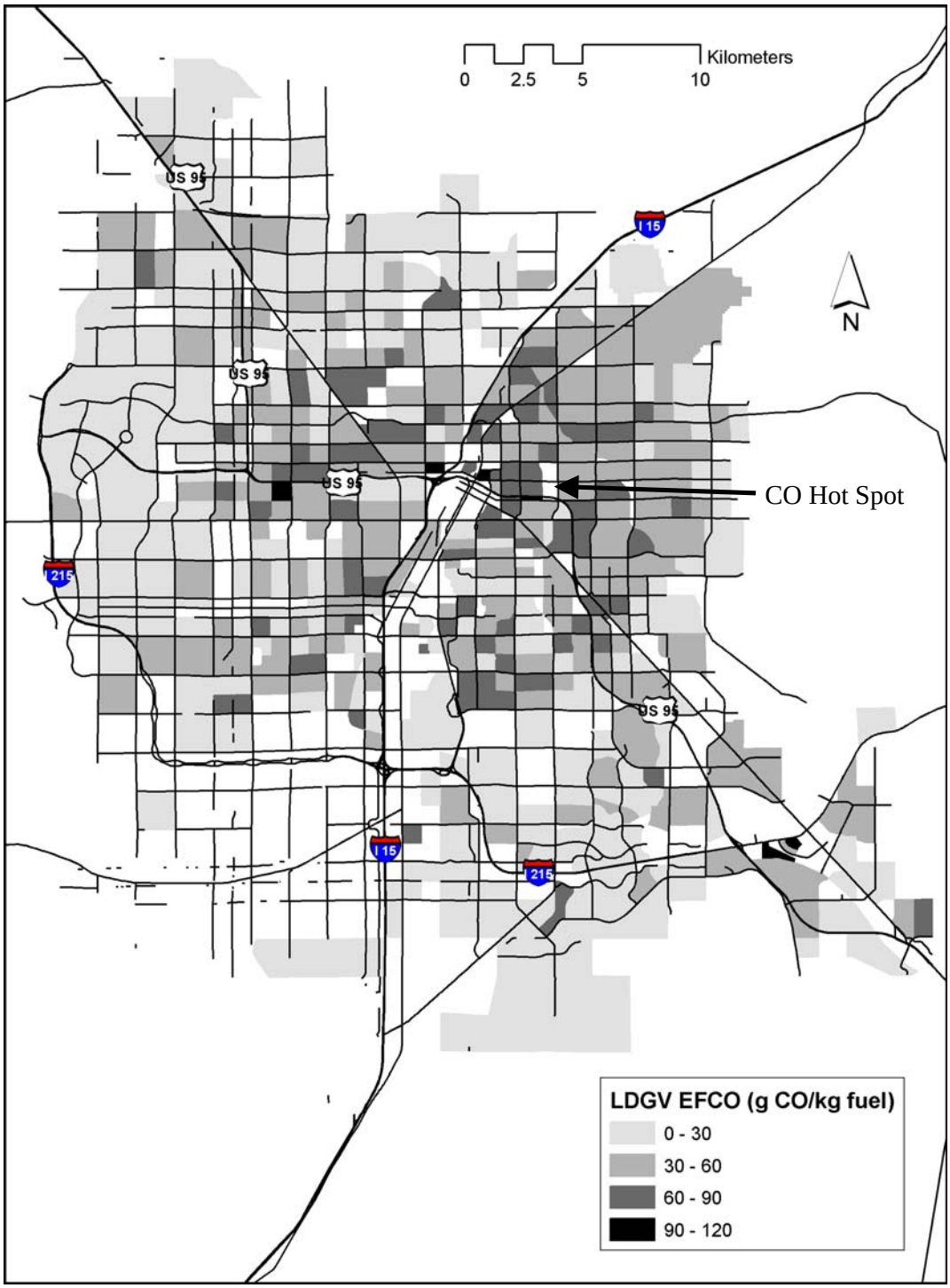


Figure 2-8. Map of average CO emission factors for each traffic analysis zone containing more than 20 remotely sensed registered vehicles.

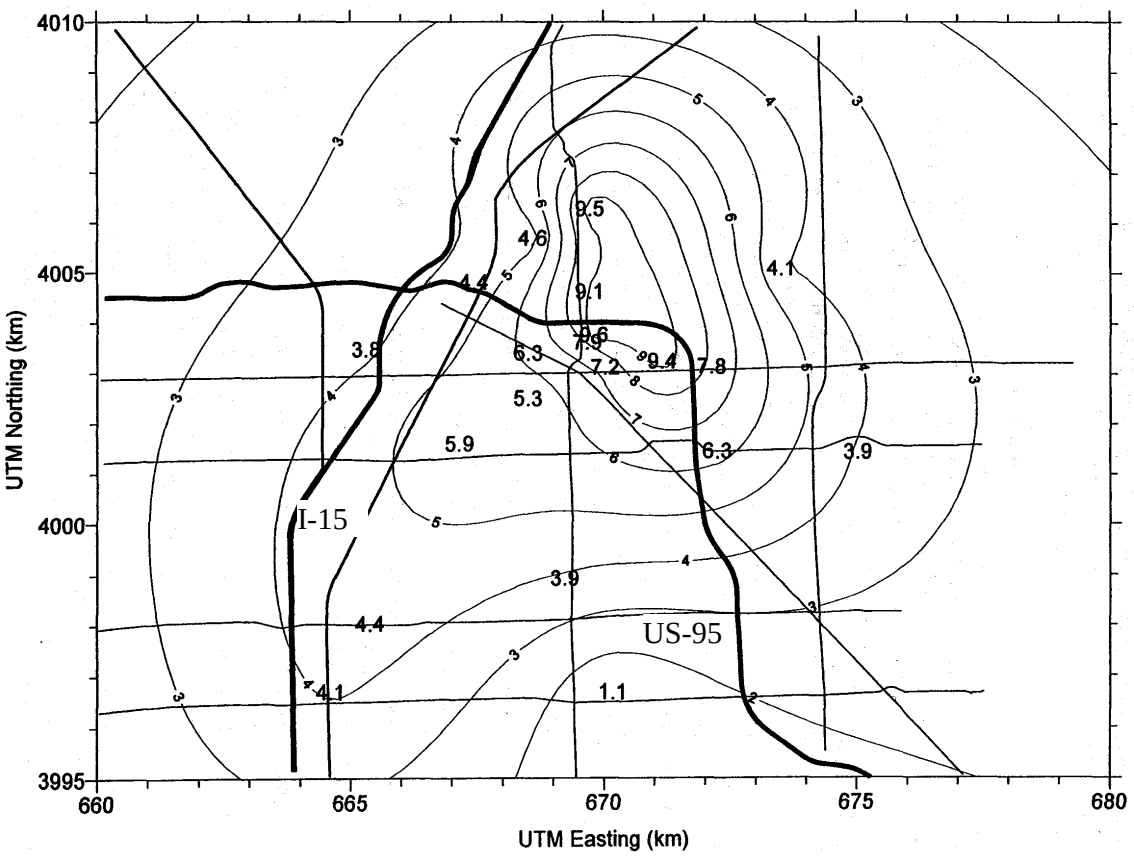


Figure 2-9. Map of 8-hour average CO for December 8-9, 1996.

The map shows that vehicles with low emissions are based near the perimeter of the Las Vegas Valley (i.e., Summerlin and Green Valley) and vehicles with higher emissions are based in areas near the center of the Valley (i.e., East Charleston area). Figure 2-9 shows the location of the highest CO concentrations measured in the Las Vegas Valley during 1996. There is an approximate correspondence between the locations of high CO concentrations and the registered location of vehicles with CO emission of 60 to 90 g/kg fuel in Figure 2-8. The current Clark County CO emissions inventory spatially apportions MOBILE6 CO emission factors by vehicle miles traveled (VMT) in a TAZ as estimated by a traffic demand model. The emission model does not consider areas that may have a higher fraction of high emitting vehicles or a larger number of morning cold starts.

Although Figure 2-8 shows a correspondence between the locations of high ambient CO and registered locations of high CO emitting vehicles in the East Charleston area, several other areas in the city contain high CO emitting vehicles that do not correspond to excessive CO concentrations. Meteorology and topography influence the ambient concentrations, as well as movement of high emitting vehicles from their home TAZ to other areas throughout the city. Maps are similar for light duty gasoline vehicle VOC and NO emissions that are precursors for O_3 and secondary PM (typically nitrates, sulfate, and some organic particles). Vehicle registration locations for average PM emissions in Figure 2-10 are mostly less than 0.2 g/kg fuel for each TAZ. There are only a few TAZ contain home locations higher than 0.2 g/kg fuel.

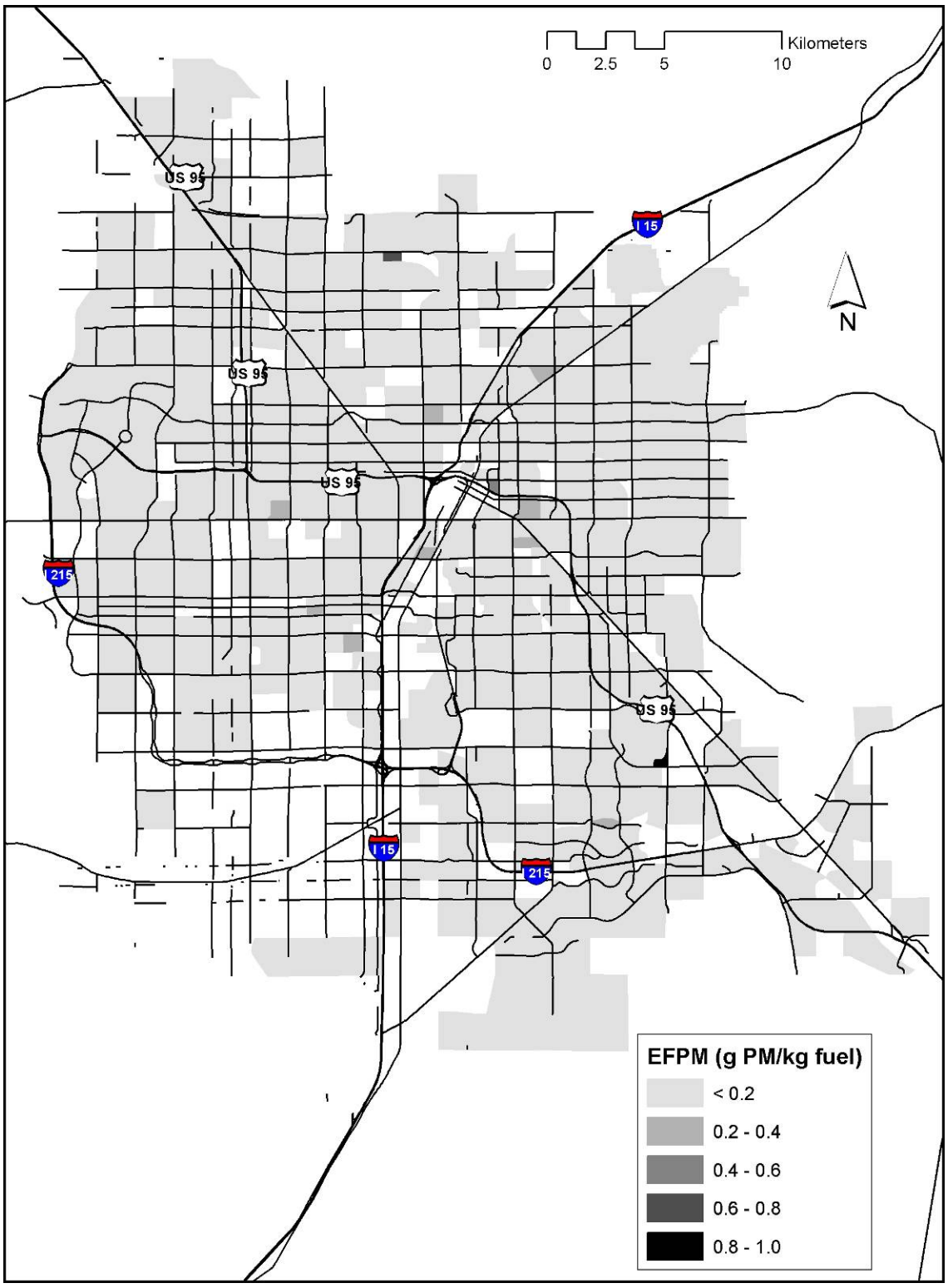


Figure 2-10. Map of average PM emission factors for each traffic analysis zone containing more than 20 remotely sensed registered vehicles.

Major findings from the cross-plume field experiments, which are described in more detail by Kuhns et al. (2002, 2004a) and Mazzoleni et al. (2004a, 2004b), are:

- Only small differences in average running emission factors (< 6%) would be observed if the population of vehicles had a vehicle specific power (VSP) distribution identical to that of the FTP used on dynamometers for vehicle certification. VSP is an indicator of the load on the engine, and it increases when the vehicle accelerates. This result suggests that the variability of the emissions based on driving mode is small compared to other sources of variability that influence fleet wide emissions.

- The consistency of emission factors with small changes in VSP suggests that cross-plume emission factors complement the limited chassis dynamometer data used to calibrate the MOBILE6 and PART5 models.

- The CO, VOC, NO, and PM fuel-based emission factors for light duty gasoline vehicles, the most common on-road emitters, stratified by vehicle age deviated from the EPA MOBILE6 and PART5 emission model factors. For each pollutant species, the measured and modeled emission factors were in agreement for at least a few model years. The best agreement was observed for NO emissions for vehicles 3 to 11 years old and HC emissions for vehicles less than 5 years old. MOBILE6 CO emission factors were up to 3 times larger than measured values for LDGV between 1 and 13 years old. Emissions factors embedded in PART5 do not resolve PM emissions based on model year. Due to sparse PM emission factor data, emission factors are aggregated by groups of years for a variety of vehicle classifications.

- Cross-plume measurements permit the monitoring of a large number of vehicles at low cost and under real-world conditions For both gaseous and PM measurements, the emission factor distribution was skewed toward high emitters, indicating important implications for emission reduction policy and further evidencing the need of new techniques for large vehicle sample collection. The comparison with previous results suggests that local conditions strongly influence the emissions distribution shape and a local input to emission models, possibly achievable by a large scale use of gaseous and PM cross-plume studies, would increase the accuracy of motor vehicle emission inventories.

- Average CO, HC, NO and PM emission factors for Las Vegas for 200 to 2002 were 48.8 g_{CO}/kg-fuel for a total of 42,134 vehicles, 5.5 g_{HC}/kg-fuel for 42,134 vehicles, 9.0 g_{NO}/kg-fuel for 40,245 vehicles, and 0.08 g_{PM}/kg-fuel for 15,219 vehicles respectively. The 10% highest emitters contributed to more than 76% for CO, 42% for HC, 45% for NO, and 80% for PM. Detection limits, as one standard deviation, were determined by a statistical analysis of the emission factors distribution and were evaluated to be ~ 5 g/kg-fuel for CO, ~ 1 g/kg-fuel for HC, ~ 1 g/kg-fuel for NO and ~ 0.3 g/kg-fuel for PM.

3. IN-PLUME MEASUREMENTS

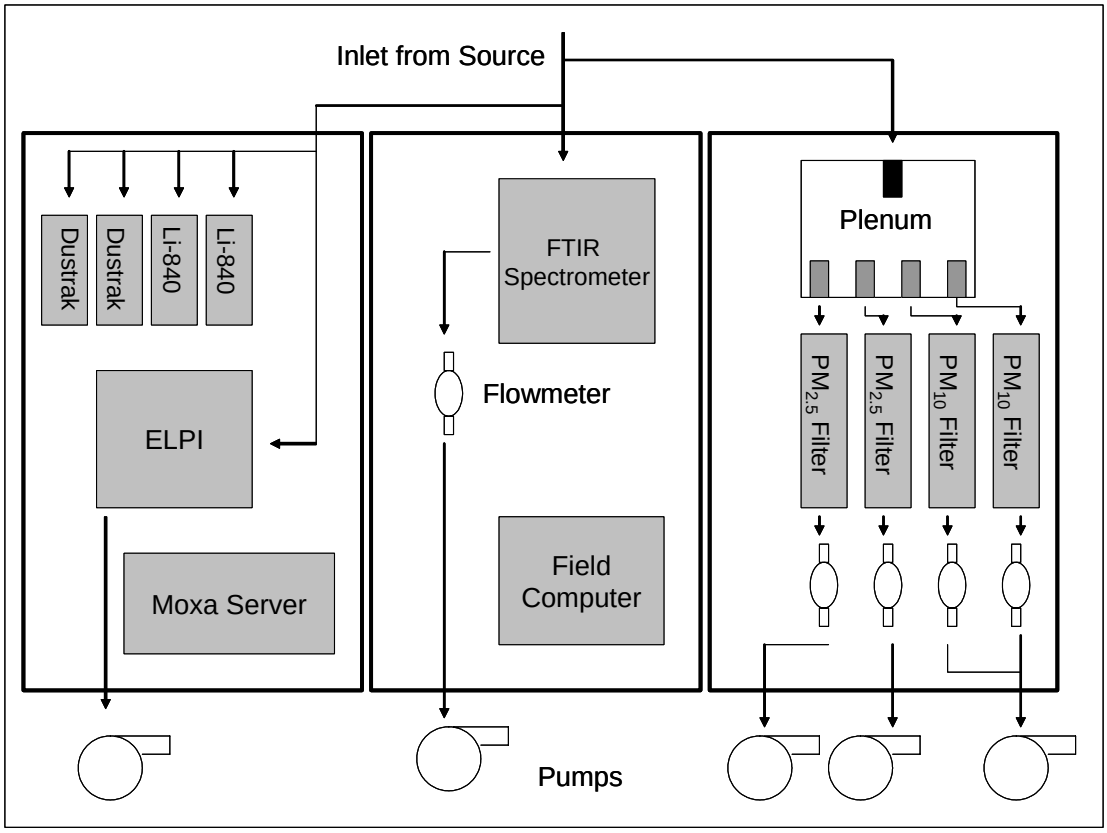
3.1 In-Plume Configuration

It was recognized early in the development of the cross-plume system that some linkage was needed to more conventional measurements used for engine certification and smog tests. Engine certification tests place light duty gasoline vehicles on dynamometers, run them according to pre-set driving cycles, dilute the exhaust, and draw samples from the diluted air stream. Gases are measured by conventional air quality monitors and $PM_{2.5}$ is collected on filters that are weighed before and after sampling to determine mass emissions. It was also recognized that the cross-plume system was limited in the pollutants and particle sizes that could be measured. The in-plume system described here offered the opportunity to provide this verification and to obtain more information about vehicle emissions that is important to human health, visibility, climate change, and apportioning ambient concentrations to their sources.

The In-Plume Emissions Test Stand (IPETS) is illustrated in Figure 3-1. The basic components are: 1) Fourier Transform Infrared spectrometer (FTIR, Illuminator series, Midac, Costa Mesa, CA) and two LI-840 CO_2/water vapor (H_2O) Gas Analyzers (Licor Biosciences, Lincoln, NE) for gaseous analysis, 2) an Electrical Low Pressure Impactor (ELPI, Dekati, Finland) and two DustTraks™ (Model 8520, TSI, Shoreline, MN) for particulate matter size distribution and mass concentrations, and 3) filter samples for PM chemical analysis, as described in Table 3-1. Other detectors can be added to the system to gain a larger variety of fuel-based emission factors. Sample air is drawn from an exhaust plume diluted with ambient air at ~220 liters per minute (L/min) into a manifold that distributes the sample to a variety of instruments. The inlet of the system can be supported to reach elevated sources such as high-stack diesel vehicles, or can be located in the road, protected by cable protectors, for sources like on-road vehicles. For easy transport and setup in the field these components are mounted on three handcarts and can be operated either in the van, or unloaded to be close to the source if access is limited.

The FTIR spectrometer measures infrared exhaust absorption spectra at 1.5 second intervals. Calibration spectra were prepared using EPA certified gases diluted with ultra pure nitrogen using an Environics 2020 computerized-gas-dilution-system (Environics, Tolland, CT) gas dilution system. Species concentrations are determined using a classical least squares (CLS) fitting technique as implemented in the software package. Prior to measurements the cell is purged with ultra pure nitrogen to reduce measurement interference from the background air.

The LI-840 CO_2/H_2O Gas Analyzer operates on the non-dispersive infrared (NDIR) absorption principle. The measurement of the CO_2 and H_2O concentrations is achieved by measuring the infrared absorption in the sample cell within the CO_2 and H_2O absorption bands at 4.26μm and 2.595μm, respectively. CO_2 is the most important measurement, because all other concentrations are normalized to this component to obtain the fuel-based emission factor. H_2O absorbs over a broad range of infrared wavelengths, and it must be measured accurately to perform the appropriate corrections for other gases.



(a)

(b)

Figure 3-1. (a) Schematic diagram of the in-plume sampling system. Solid arrows indicate sample flow streams. Dashed arrows indicate data connections. (b) Field operation of In-Plume Emissions Test Stand (IPETS) in a van.

Table 3-1. Instrumentation of the in-plume measurement system.

Instrument	Measurement	Method	Response Time (s)
Midac I-Series Fourier Transform Infrared Spect-rometer (FTIR)	Molecular gas species concentration	Dispersive infrared	1.5
LI-840 CO^2/H_2O gas monitors	CO_2 and H_2O concentrations	Non-dispersive infrared	1
Dekati Electric Low Pressure Impactor (ELPI)(10 L/min)	Aerodynamic number size distribution of particles	Current dissipation arising from deposition of charged particles to impactor substrates	1
TSI DustTrak	Particle mass	780 nm laser light scattering of particle stream at 90 degrees	1
Filter samples	Mass and chemical composition of particles and gases	Collection and analysis of exposed filters	>1000
TSI 4043 Mass Flow Meters	Mass flow through filter	Hot wire anemometer	<1

The ELPI measures the particle size distribution, which is needed to more accurately estimate the mass scattering efficiencies for the cross-plume system. Sampled particles are separated into 12 different size ranges in a cascade impactor based on their aerodynamic diameter. In this configuration, oiled sintered impaction substrates and a backup filter are used, resulting in size ranges of >0.007, 0.024, 0.03, 0.056, 0.1, 0.22, 0.32, 0.59, 0.91, 1.5, 2.5, 3.8, and 6.4 μm. The sintered oil impaction substrate reduces bounce of larger particles to lower stages and extends the loading capacity of the impaction substrates. The filter stage extends the measurement of ultrafine particles from 30 nm to 7 nm. The substrates are electrically isolated with Teflon supports and the accumulating charge on each of the substrates is measured by an array of electrometers. The measured current on each of the stages is proportional to the number of particles deposited on the stage, which can be converted to mass by assuming the particles to be singly charged, spherical, and bulk mass density of 1 g/cm^3.

The DustTrak™ measures the scattering of a laser diode beam by particles at a wavelength of 780 nm. PM_{10} and $PM_{2.5}$ aerodynamic size cut inlets are installed upstream of its analytical chamber to limit the size of measured aerosol particles. The DustTrak™ has a flow rate of 1.7 L/min and is factory calibrated to the respirable fraction of standard ISO 12103-1 A1 test dust (previous Arizona test dust). Diesel particles have similar mass scattering efficiency to the calibration material, despite their difference in size and index of refraction.

For PM_{10} and $PM_{2.5}$ speciation, the flow is drawn through size-selective inlets and distributed to several different filters that operate continuously during an experiment. The sample air passes through different configurations of filter pack samples using Teflon filters for the measurement of PM mass and 40 elements (Na to U) (Watson et al., 1999), and quartz fiber

filter for water-soluble cations and anions (Chow et al., 1999), organic and elemental carbon (Chow et al., 1993), and detailed organic characterization (Ho and Yu, 2004). Citric acid impregnated cellulous fiber filters for measurement of ammonia (NH_3) and potassium carbonate impregnated cellulous fiber filters for sulfur dioxide (SO_2) can be separately placed downstream of the quartz fiber and Teflon filters. Particle morphology can be examined with PM collection on a Nuclepore filter operated in parallel.

Data from the real-time instrumentation are logged in real time through a Moxa serial port server on a laptop mounted on one of the handcarts. The FTIR Spectrometer communicates through an A/D PCMCIA card installed in the laptop. Table 3-2 shows the species measured by the FTIR, the wave number regions selected for detecting each gas, the typical concentration levels found in exhaust plumes, uncertainty estimates, and the calibration range.

Table 3-2. Gases measured with the FTIR, typical concentration ranges, and uncertainties.

Species	**Reference Region (cm^{-1})**		**Average In-Plume Concentration (ppm)**	**Uncertainty Standard Error (ppm)**	**Calibration Range (ppm)**	
	Min	Max				
CO_2	723.0	750.0	150	17	100	4730
CO	2133.5	2142.0	1.93	0.05	1.0	1005
NH_3	955.5	976.0	0.04	0.01	1.0	110
NO	1873.0 1880.5 1898.5 1926.0 1934.5	1878.5 1884.0 1901.5 1932.0 1940.0	0.12	0.13	0.2	20
H_2O	1200.0	1300.0	93	27	5.0	5294
C_4H_{10}	3041.5	2825.5	0.04	0.05	1.0	100
C_6H_{14}	3030.0	2818.0	0.06	0.04	0.2	200
C_2H_4	958.0	936.5	0.00	0.08	0.5	20
NO_2	1584.0 1597.5 1604.0 1610.5	1588.5 1600.0 1606.0 1614.0	0.00	0.11	0.2	20
SO_2	1112.5 1123.5 1138.5 1153.5 1166.5 1176.5 1188.0 1200.0 1227.0	1120.5 1134.0 1148.0 1164.0 1172.5 1185.0 1197.0 1209.0 1236.0	0.00	0.14	1.0	100

Figure 3-2 shows the measured PM volume size distributions (normalized to the total volume) collected on the ELPI stages 1 through 10 (particles less than 2.3 µm aerodynamic diameter) for low- and high-exhaust vehicles. Previous studies of tailpipe exhaust show that more than 90% of the exhaust particle mass comes from particles less than 0.5 µm in diameter. In contrast, road dust emissions are predominantly associated with particles greater than 1 µm in size.

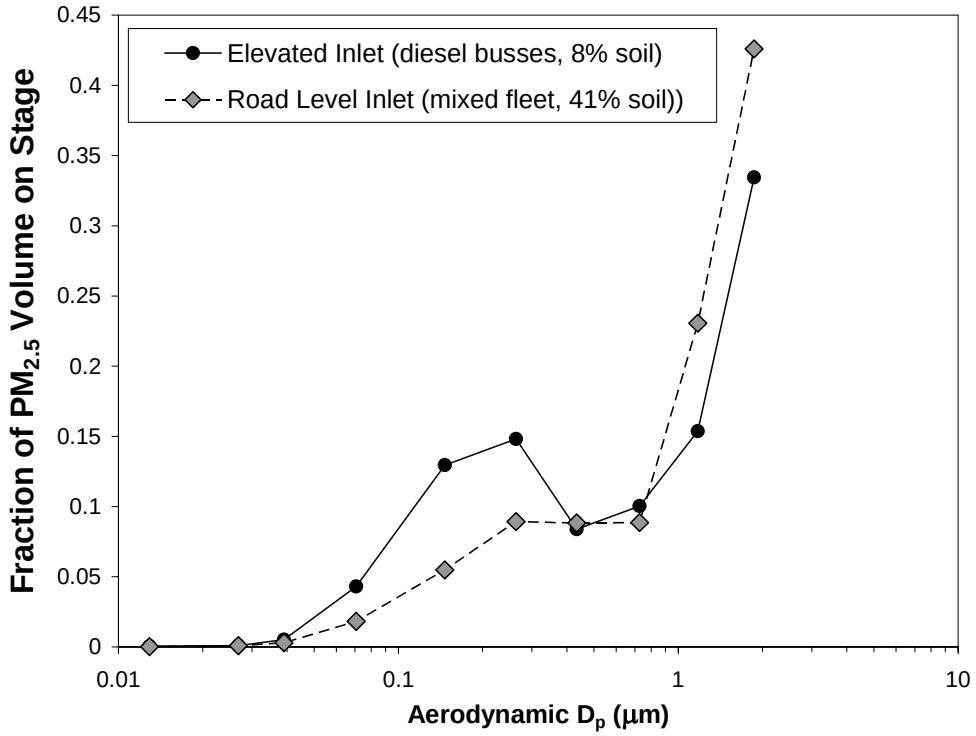


Figure 3-2. Size distributions measured for an elevated exhaust pipe on diesels and at road level for light duty exhaust plumes.

Both size distributions show a large increase in particle volume on Stages 9 and 10 (0.9 µm to 2.3 µm) accounting for more than 40% of the total particle volume. For road level experiments, an increase in particle concentrations on the upper stages of the impactor is expected because road dust is sampled along with the vehicle exhaust. This is not the case for the elevated inlet where the busses were stopped or traveling at speeds less than 10 km/hr and where soil contributed less than 10% of the $PM_{2.5}$ mass. The increase in particle concentrations on stages 8 and above appears to be an artifact of sampling fresh exhaust with large concentrations of nucleating particles and not an indication of coarse particles.

An example of the IPETS application for on-road measurement of different gases and PM is illustrated in Figure 3-3. Each CO_2 peak represents a passing vehicle plume. Emission ratios and emission factors can be calculated based on total carbon measured and carbon content in the fuel.

3.2 In-Plume Comparison with a Mobile Laboratory

The in-plume system was used in conjunction with the Heavy Duty Diesel Mobile Laboratory (HDDML) developed by CE-CERT (College of Engineering-Center for Environmental Research and Technology, University of California), Riverside, CA, in December 2004 (Watson et al., 2004, 2005). The HDDML is designed to measure regulated gas emissions, according to the standards specified by the federal Code of Federal Regulations for control of emissions from new and in-use highway vehicles and engines and for control of emissions from new and in-use nonroad compression ignition (CI) engines, respectively.

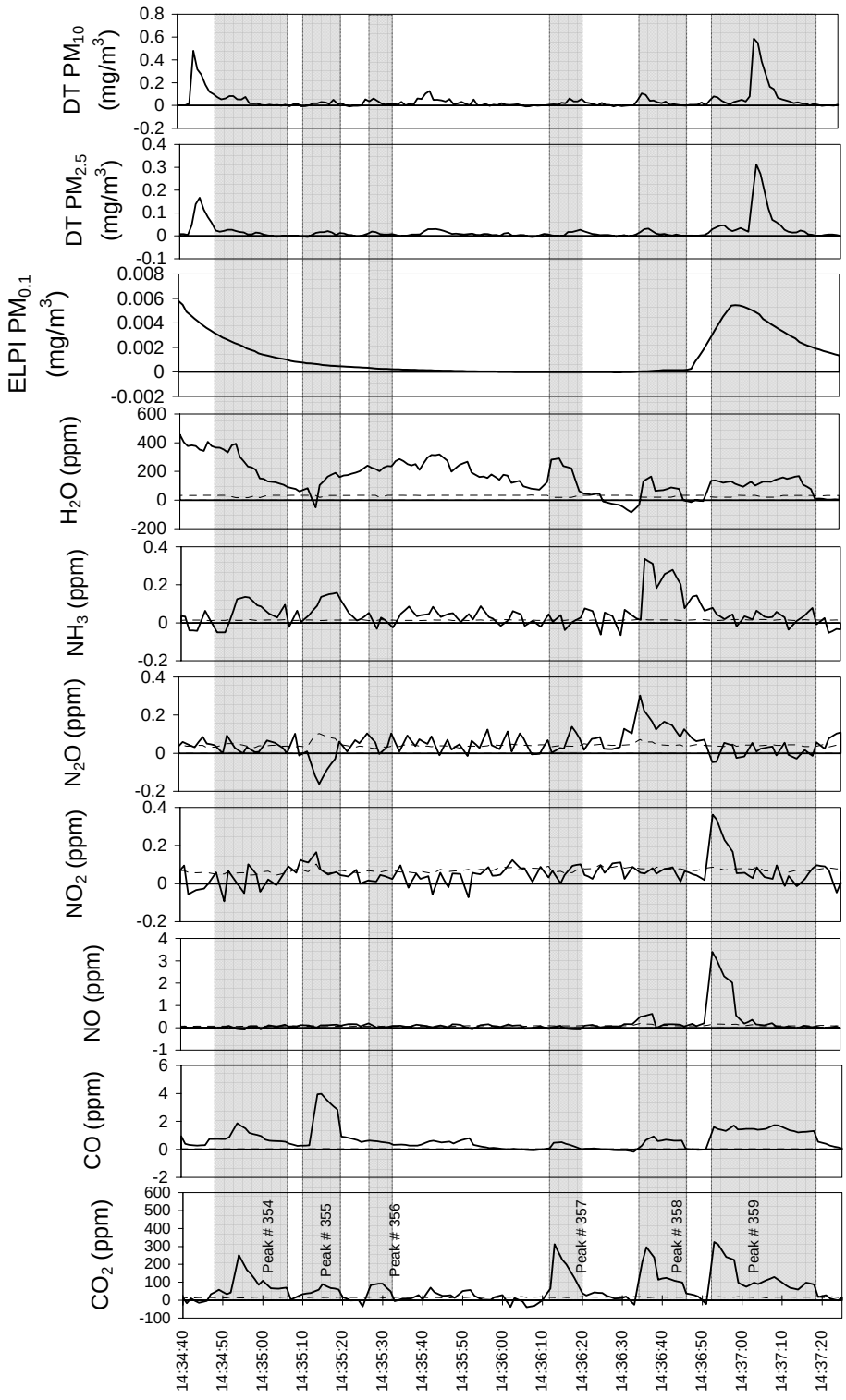


Figure 3-3. Time series of CO_2 and other gas and particle concentrations measured for passing vehicles. The grey areas are periods where the measured plume is linked to the passage of one or more vehicles. Dotted lines represent background concentrations for each species.

With the HDDML, the whole diesel exhaust stream flows into a primary constant volume sampling (CVS) dilution tunnel (Model ESU 7000, Horiba, Ann Arbor, MI) at a total flow rate of 142 m^3/min (5,000 ft^3/min). A small fraction of the air in the primary dilution tunnel is extracted for the continuous measurements of CO, CO_2 CH_4, (Pierburg, Neuss, Germany), NO_x, and THC (total hydrocarbons) (California Analytical, Orange, CA) concentrations. A secondary dilution tunnel is used for collecting PM on Teflon membrane filters.

For this study the IPETS sampling inlet was located approximately at 1 m distance from the exit of the HDDML bypass fan. The sampling inlet location was adjusted with the help of the attached temperature and relative humidity (RH) sensors so that the exhaust is close to ambient temperature (±5℃) and RH (±10%). The time shift between the measurements of the real time instruments was determined by a "match" test at the beginning of each test and the end of each test. A match was lit at the inlet of the IPETS and was blown out immediately. The induced spike in air pollutant concentrations is used to synchronize signals of the instruments by determining the relevant time shifts.

A Kamatzu SA6D125E-2 diesel generator (Japan) was used as a source. It has a power output rated at 303 kW and 11 L displacement mounted in a 250 kW (actual electrical output) DEWYO Model # DF-3300K power generator. The engine was made in the year 2000 and had 316 service hours prior to this comparison study. The test protocol involved a 5-mode test cycle at 100%, 75%, 50%, 25% and 10% of the engine load. HDDML emission factors were determined from five minute measurements for each mode. Test fuel was directly fed to the engine from the fuel drum. After fuel switches, the engine was operated for 30-60 minutes at 100% load with the new test fuel to assure complete removal of the previous test fuel from the engine and fuel line.

The pollutant concentration in the background air may vary due to a number of factors including diurnal variations (increasing height of the mixing layer), changes in transport, and changes in local emissions. This is especially important for gases such as NO_2 that have low concentrations. These changes in background gas concentrations can result in measurement biases that may result in negative concentrations. Therefore, gas concentrations measured by the FTIR spectrometer were corrected to the lowest concentrations measured during each test period.

Three data reduction approaches were pursued to determine the emission factors:

- Approach A: The net changes of concentrations for a species relative to the ambient background levels are divided by the corresponding changes in the carbon content of CO_2 plus CO. Equivalent carbon in CO is added to the CO_2 value because it also derives from the carbon in the combusted fuel.

- Approach B: Use the least square linear fit of a species concentration versus the concentrations of CO_2 plus CO over the entire test event. The slope represents the emission ratio and the intercept is the offset of the concentrations of the two species.

- Approach C: Determine the mean of emission ratios of a species concentration to CO_2 plus CO.

Comparisons of CO, NO_2, and NO emission factors for IPETS and HDDML are summarized in Table 3-3. The CO emission factors from IPETS are highly correlated (R^2>0.89) with those from the HDDML with slopes close to unity, regardless of which data processing approach was followed. The mean of CO EF ratios between IPETS and HDDML was in the range of 0.87-0.92, with one standard deviation of the ratios between 0.23-0.19.

The FTIR measured NO_2 concentrations that were close to instrumental detection limits. Regression slopes determined by Approaches A and B were ~0.5 with only moderate to poor correlation (R^2= 0.49) for Approach A. Applying the criteria of selecting mean NO_2 emission factors with coefficients of variation than 0.25 in Approach C resulted in only six test cycles valid for comparison. The slope for Approach C is 0.78 with a moderate-to-high correlation of 0.82.

Table 3-3. Comparison measures between IPETS and HDDML emission factors (EF) for CO, NO_2, and NO using different data processing approaches.

Species	Statistics	Approach A	Approach B	Approach C
CO	EF Regression Slope	1.03	0.95	1.02
	R^2	0.99	0.89	0.99
	Intercept (g/kg fuel)	-0.34	0.04	-0.34
	N (tests)	13	13	10
	Mean of IPETS EF to HDDML EF	0.88	0.92	0.87
	Standard Deviation of IPETS EF to HDDML EF	0.23	0.34	0.20
NO_2	Regression Slope	0.46	0.52	0.78
	R^2	0.49	0.84	0.82
	Intercept (g/kg fuel)	0.74	-0.05	-0.30
	N (tests)	13	13	6
	Mean of IPETS EF to HDDML EF	1.03	0.45	0.67
	Standard Deviation of IPETS EF to HDDML EF	0.74	0.17	0.10
NO	Regression Slope	1.68	1.61	1.37
	R^2	0.89	0.60	0.89
	Intercept (g/kg fuel)	-2.19	-1.83	-1.95
	N (tests)	13	13	13
	Mean of IPETS EF to HDDML EF	1.54	1.50	1.55
	Standard Deviation of IPETS EF to HDDML EF	0.09	0.18	0.09

The IPETS and HDDML NO emission factors are highly correlated, but the IPETS NO emission factors are 50% higher than those from HDDML. It is unlikely that such systematic bias is due to the interference of H_2O in FTIR spectroscopy when quantifying NO concentrations. The fact that the CO comparisons are good indicates that dilution ratios and gas losses are negligible. These data are still under examination to determine the causes of these discrepancies for NO.

The mean $PM_{2.5}$ emission factors based on HDDML filter mass, ELPI and DustTrak PM mass measurements are shown in Table 3-4. Good reproducibility (<15%) was observed for both ELPI and DustTrak $PM_{2.5}$ emissions factors for replicates of the same engine load.

Table 3-4. Comparison statistics for $PM_{2.5}$ emission factors (EF) determined from the HDDML filter measurements and from the ELPI and DustTrak $PM_{2.5}$ measurements from the in-plume system. Group refers to individual emissions tests on the diesel generator.

Group	PM2.5 EF ratio ELPI to filter in HDDML	HDDML Filter based PM EF (g/kg fuel)	ELPI PM2.5 EF (g/kg fuel)*	Stdev of ELPI PM2.5 EF (g/kg	DustTrak PM2.5 EF (g/kg fuel)*	Stdev of DustTrak PM2.5 EF (g/kg fuel)*
JP8-1-100	4.36	8.9E-01	3.9E+00	4.6E+00	6.8E+00	6.4E+00
JP8-2-100	3.03	1.0E+00	**3.1E+00**	2.0E+00	**4.9E+00**	2.1E+00
JP8-1-050	3.51	4.6E-01	**1.6E+00**	1.3E+00	**1.8E+00**	7.0E-01
JP8-2-050	3.58	4.4E-01	**1.6E+00**	7.6E-01	**1.7E+00**	4.8E-01
JP8-1-025	3.60	4.1E-01	1.5E+00	9.8E-01	1.0E+00	3.3E-01
JP8-2-025	4.47	3.6E-01	1.6E+00	7.5E-01	1.0E+00	2.5E-01
JP8-1-010	4.93	2.8E-01	1.4E+00	1.5E+00	6.4E-01	4.2E-01
JP8-2-010	4.26	2.8E-01	1.2E+00	5.2E-01	6.4E-01	1.4E-01
ULSD-1-050	3.32	4.0E-01	**1.3E+00**	1.1E+00	**1.6E+00**	5.6E-01
ULSD-2-050	3.63	3.6E-01	**1.3E+00**	6.9E-01	**1.6E+00**	4.9E-01
ULSD-1-025	3.52	4.6E-01	**1.6E+00**	9.3E-01	**1.4E+00**	4.4E-01
ULSD-2-025	7.64	2.1E-01	**1.6E+00**	7.6E-01	**1.5E+00**	3.7E-01
ULSD-1-010	4.09	6.2E-01	2.5E+00	2.7E+00	1.7E+00	1.1E+00

* assuming 0.86 g C/g fuel, and a factor 24.13 and 1.42 were applied to correct for ELPI and DustTrak mass concentration measurements

The coefficient of variation for of $PM_{2.5}$ emission factors for the ELPI and DustTrak were in the range of 0.5-1 and did not seem to change, regardless the number of measurements taken. ELPI $PM_{2.5}$ emission factors were generally 3.5-5 times higher than those determined by filter mass concentrations from HDDML dilution method. The higher IPETS values are probably real and are caused by differences in the test methods. Several studies have suggested that residence time in dilution methods may be important to account for PM mass contributed from condensable species. Condensational growth of particles depends on the chemical properties of condensable species, characteristics of pre-existing particles in the exhaust, and the different fraction and concentration of condensable to solid PM of different emission source types.

The temperature of the sample air and filter for PM collection in HDDML were maintained slightly lower than 52°C, while the sample air temperature for IPETS was close to ambient, ranging from as low as 4°C in the morning to 23°C at noon. The lower sample temperature in the IPETS allows more condensation of vapors on the particles prior to collection.

3.3 Comparison of In-Plume and Cross-Plume Systems

The cross-plume VERSS and the IPETS were used for the same on-road experiment that compared school Idaho school bus emissions for regular diesel and biodiesel (Kuhns et al., 2005).

Daily average emission factors were calculated for days during which both measurement systems were operational. In this comparison, no peak identification was used for the in-plume system. Instead, the integrated (i.e., daily average) CO_2 and the integrated PM were calculated after background subtraction. The overall average PM emission factor was calculated by dividing the PM daily average emissions factor by the CO_2 daily average emissions factor. For this calculation, the CO concentration was < 5% of the carbon emissions from gasoline vehicles and < 1% for diesel vehicles, so it was not added to the CO_2 concentrations.

Daily averaged PM emission factors are compared in Figure 3-4. The fleet average PM emissions from Phase I of this, when the busses operated on pure diesel fuel, are in good agreement with each other. In addition, there is very good agreement between the two independent measurement methods. This is a significant result since the two sets of emission factors are calculated using very different techniques for particle measurement. The cross-plume system uses light scattering from particles as the fundamental PM measurement whereas the in-plume system uses a count of particles of different aerodynamic sizes to infer PM mass concentrations.

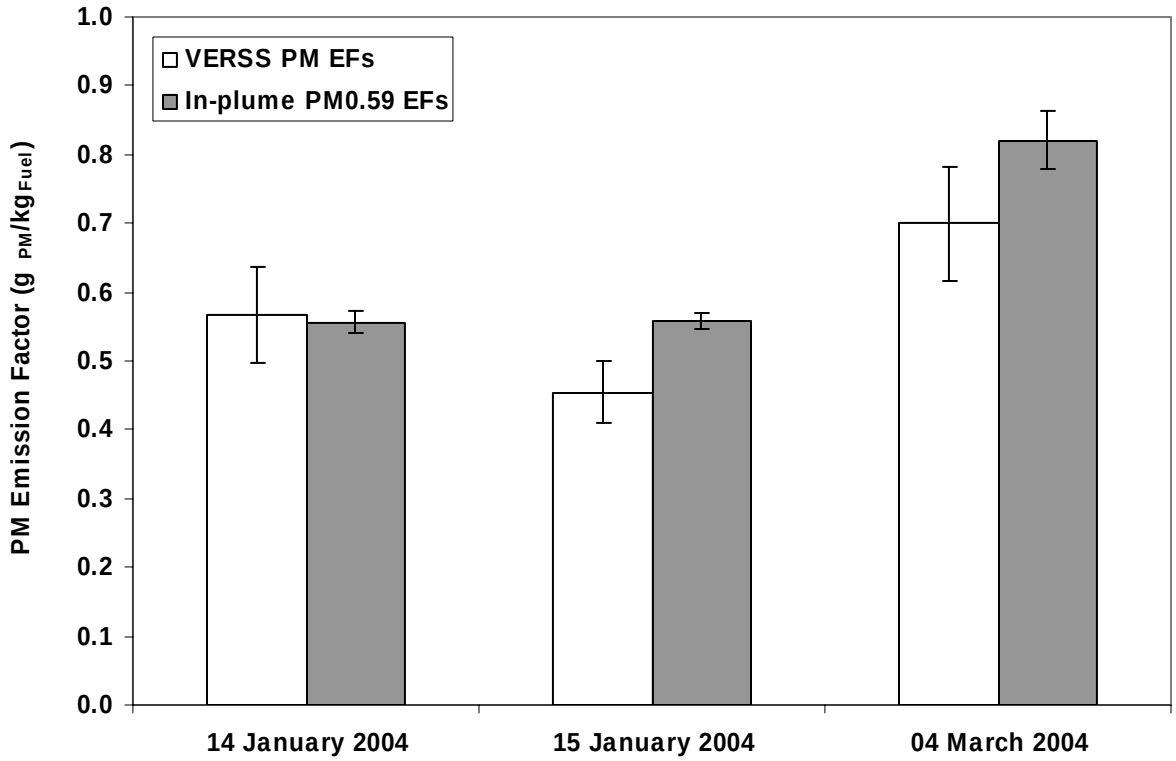


Figure 3-4. Comparison of PM emission factors (EF) measured by the cross-plume (VERSS) and the in-plume system using ELPI data for particles <0.59 μm aerodynamic diameter. Error bars are the standard error of the mean.

For CO emission factors, the linear regression slope is 0.86 with a correlation coefficient of 0.75. The average CO emission factor for the cross-plume system was 60 ± 8 g_{CO}/kg_{Fuel} compared with 69 ± 7 g_{CO}/kg_{Fuel} from the in-plume system. For NO emission factors, the linear

regression slope was 1.0 with a correlation coefficient of 0.68 for the two methods. The average NO emission factor was 18±1 g_{CO}/kg_{Fuel} for tie cross-plume measurement and 17±1 g_{CO}/kg_{Fuel} for the in-plume measurement.

The in-plume system was further tested for roadside measurements of vehicle exhaust and wood burning at Lake Tahoe (Kuhns et al. 2004b) as well as for additional on-road tests in Las Vegas, Nevada (Green et al., 2004).

4. LAS VEGAS AMBIENT AIR QUALITY STUDIES

4.1 Visibility and $PM_{2.5}$ Characterization Study

A pilot study for the Southern Nevada Air Quality Studywas conducted in 2000-2002 (Green et al., 2002) that intended to: 1) characterize the level of fine particulate matter ($PM_{2.5}$) and its chemical composition at urban, suburban, and background (transport) sites for the Las Vegas Valley; 2) determine background levels of $PM_{2.5}$ chemical components transported into the Las Vegas Valley; 3) estimate chemical component contributions to haze (i.e., sulfate [$SO_4^{=}$], nitrate [NO_3^{-}], carbonaceous compounds, and crustal material; and 4) estimate relative contributions of locally generated haze and transported haze.

The results showed that haze and $PM_{2.5}$ levels at the urban site (East Charleston) were much higher than those at the suburban (Palo Verde) and background (Jean) sites. This effect was most pronounced during winter stagnation conditions. The suburban site was influenced by local sources, but its levels of haze and $PM_{2.5}$ were closer to those of the background site than those of the urban site. At the urban site, haze and $PM_{2.5}$ were highest in winter; at the background site, haze and $PM_{2.5}$ tended to be lower in winter. Contributions to $PM_{2.5}$ by major chemical components at East Charleston by sampling day are shown in Figure 4-1. Note the predominance of carbonaceous compounds (organic compounds [OMC] and elemental carbon [EC]) and crustal (soil) material.

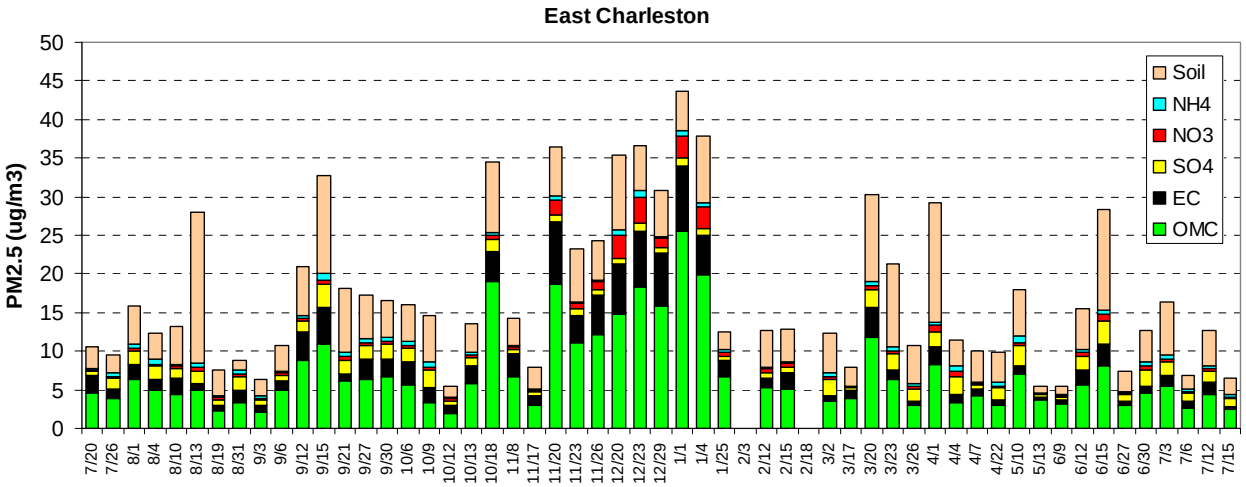


Figure 4-1. Chemical component contributions to $PM_{2.5}$ at the East Charleston site, July 2000 – July 2001.

Background sources outside the valley were estimated to contribute about two-thirds of the $PM_{2.5}$ and a little over one-half of the haze at the suburban Palo Verde site, on average. At the urban East Charleston site, over three-quarters of the $PM_{2.5}$ and haze were caused by local (Las Vegas urban area) sources. The local and background contributions to haze at the east Charleston site are shown for each chemical component in Figure 4-2. The major components are OMC, EC, sulfates, nitrate, fine soil, and coarse mass (mainly crustal or dust). The fine soil and coarse mass components are mainly due to disturbed land, construction activity, and road dust.

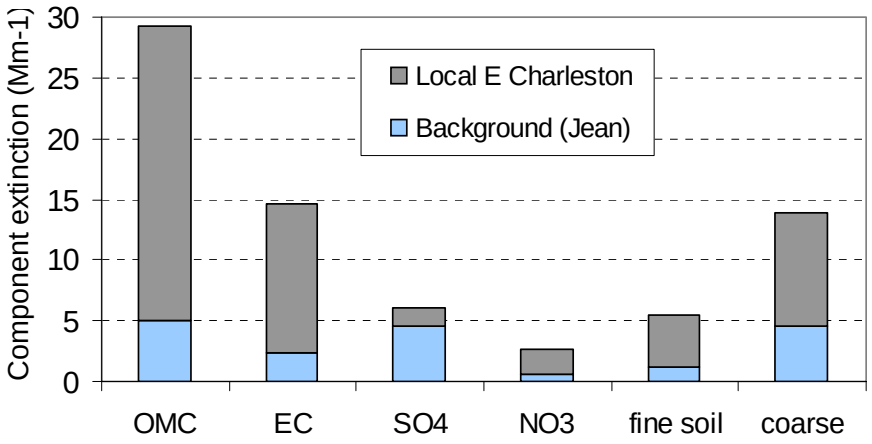


Figure 4-2. Local and background contributions to haze at East Charleston by chemical component.

Most of the increase in $PM_{2.5}$ and haze over the background level was due to particles containing organic carbon (OC), EC, and crustal material. At the East Charleston site, OC and EC compounds account for over half of the $PM_{2.5}$ mass and about 60% of the haze. Crustal material was estimated to contribute 25% of the $PM_{2.5}$ and 27% of the haze at East Charleston.

4.2 Wintertime Source Apportionment Study

Although this yearlong study provided a good understanding of the temporal, spatial, and chemical nature of the $PM_{2.5}$, it took place before the in-plume system was available for acquiring samples for source profiles. Since $PM_{2.5}$ concentrations were found to be highest during the winter, a follow-up field program was conducted during January, 2003 (Green et al., 2004).

$PM_{2.5}$ speciation study was operated at four locations shown in Figure 4-3: City Center (CC), J.D. Smith Elementary School (JD), Orr Middle School (OR), and East Charleston (MS). The MS site is located about 50 meters (m) north of East Charleston Street, a secondary thoroughfare. Businesses along East Charleston include a Mexican restaurant, which is east of the site; apartment buildings and detached houses are north of the site. The CC site is in a residential area northeast of downtown Las Vegas, immediately northeast of the intersection of US-95 and I-15. It is also approximately 5 m below US-95, which is elevated in the area near the monitoring site. A commercial area is located to the south, across I-515. The JD site is adjacent to J.D. Smith Elementary School, which is in a residential area. The OR site is on the property of Orr Middle School. The immediate vicinity is residential, although a large shopping center (The Boulevard Mall) is approximately 400 m to the west.

Selected ambient concentrations were submitted to intensive chemical analysis to obtain marker compounds that could be related to the source samples acquired by the in-plume sampling system operating on Las Vegas highways.

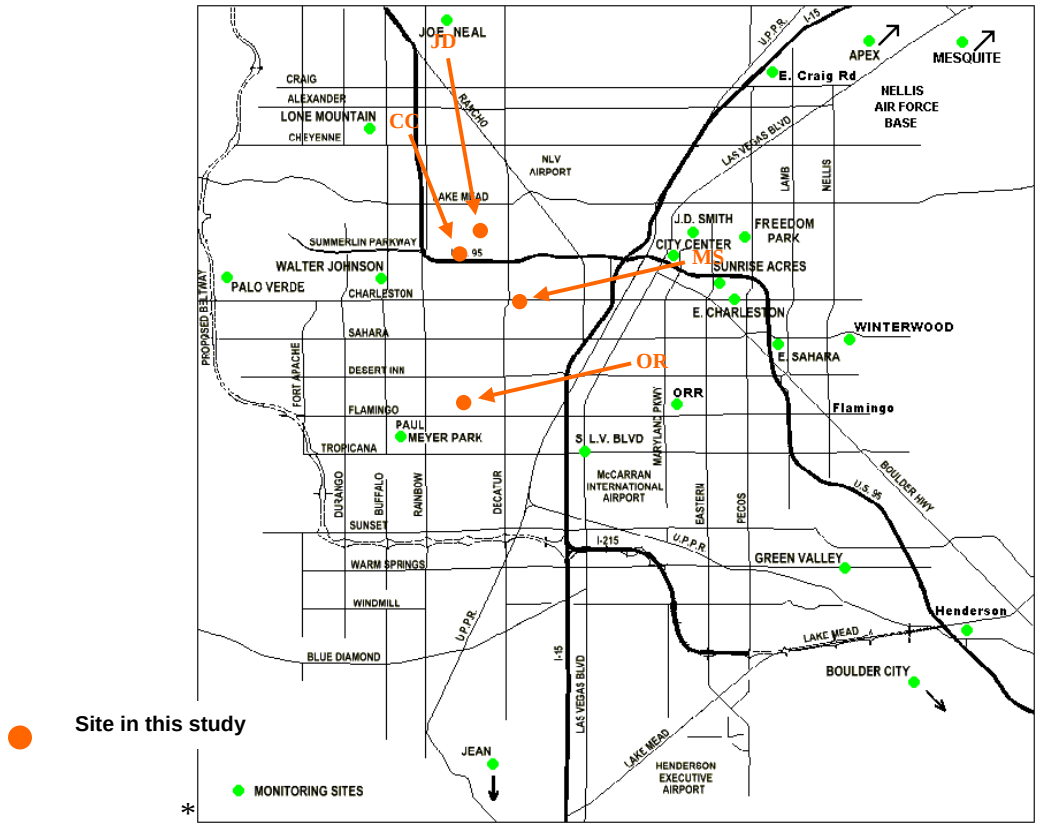


Figure 4-3. Ambient air monitoring locations during the winter mini-intensive study (not to scale). CC = City Center; JD = J.D. Smith Elementary School; OR = ORR Middle School; MS = East Charleston.

4.3 In-Plume Source Measurements

For on-road gasoline vehicle emissions, the IPETS was set up approximately 15 m southwest of the intersection of Flamingo Road and Swenson Road. The location is about 3 km east of the Las Vegas Strip and the traffic is dominated by light duty gasoline vehicles. Vehicles turned right or left from Flamingo Road to Swenson Road at speeds of 20–50 km/hr with slight acceleration. Average vehicle counts were 8–12 vehicles per lane per minute. There was no observable difference in vehicle counts between rush hours (7–9 a.m. and 4–6 p.m.) and noon. Two to three samples were collected daily from 7 a.m. to 7 p.m. Samples were taken both in winter and during summer.

Heavy duty diesel vehicle exhaust was measured at the North Regional Transportation Commission (RTC) bus depot. Approximately 250–280 buses return to the North RTC bus depot for overnight parking after the last service route at night and depart for their first service route in the morning. More than 85% of the buses leave the bus yard between 3:30 a.m. and 5:45 a.m. daily. Prior to leaving the bus yard, the drivers are handed documents to be signed off at the security gate. Each bus decelerated, stopped, idled, and accelerated, the time for which ranged from 10 to 30 seconds. The IPETS was set up at the security gate and the inlet was supported by a 3 m long PVC tube, as shown in Figure 4-4. The inlet of the sampling system was

approximately 3–5 m away from the bus tailpipe, where the exhaust plume was fully mixed with ambient air. Each filter sampling period was approximately 30–45 minutes, depending on the frequency of bus traffic.

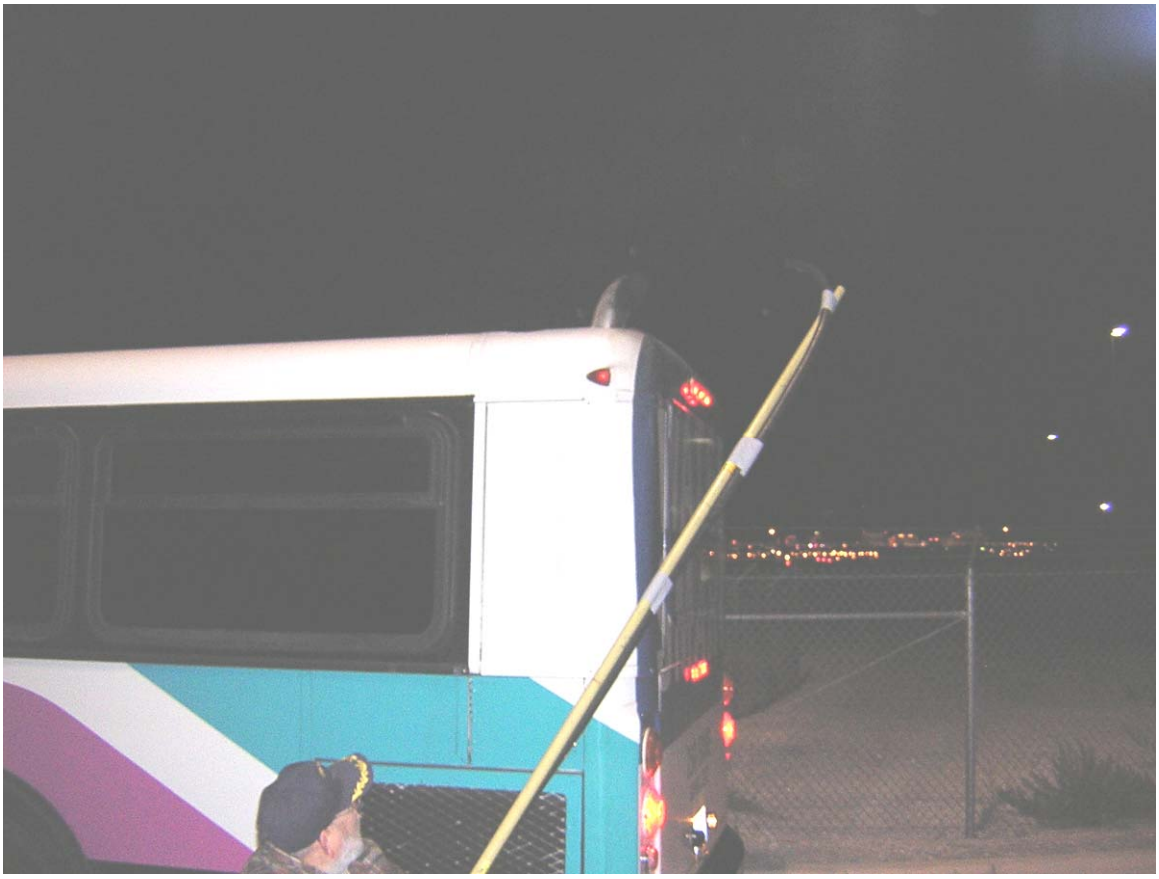


Figure 4-4. Sampling of on-road diesel vehicles at RTC bus depot, Las Vegas, NV.

Non-road diesel engine emission measurements were conducted on December 12, 2003, at Ahern Rentals, 1785 West Bonanza Road, Las Vegas, NV. Five samples were collected from 21 different types of non-road diesel engines. Each diesel engine was brought to the trailer where the IPETS was located. The engines were operated from cold start to an rpm level that they would reach during typical us. The inlet of the in-plume system was approximately 1.5 m away from the exhaust pipes, where the exhaust was cooled and mixed with ambient air, yet were not too diluted (i.e., CO_2 was detectable).

Table 4-1 summarizes the emission factors. For on-road mixed fleet vehicles, the average CO emission factor of 30.127 g CO/kg fuel in winter was 31% less than in summer (39.390 g CO/kg fuel). The reduction of the average CO emission factor in winter mixed fleet on-road vehicles is probably due to the oxygenated gasoline fuel used in wintertime program in Las Vegas Valley, which results in better combustion efficiency. There is no significant difference in the average CO emission factors between winter (18.173g CO/kg fuel) and summer (16.994g CO/kg fuel) on-road diesel vehicles. The average CO emission factor for non-road diesel engines is equivalent to on-road mixed fleet vehicles.

Table 4-1. Fuel-based emission factors measured by the in-plume system in Las Vegas, Nevada.

	Winter									Summer					
	on-road vehicles, mixed fleet, Swenson and Flammingo			on-road diesel bus, North RTC, Las Vegas			non-road diesel engines (AHERN)			on-road vehicles, mixed fleet			on-road diesel bus		
	average	Median	Standard Deviation	average	Median	Standard Deviation	average	Median	Standard Deviation	average	Median	Standard Deviation	average	Median	Standard Deviation
gNH3/kgfuel	0.845	0.837	0.083	0.056	0.043	0.036	0.083	0.097	0.098	0.371	0.369	0.035	0.027	0.045	0.041
gCO2/kgFuel	3024.124	3020.418	14.171	3048.121	3053.512	11.671	3013.294	3019.771	28.561	2999.201	3004.350	13.586	3050.555	3045.806	9.711
gCO/kgFuel	30.127	31.414	8.960	18.173	15.522	6.974	27.537	35.538	11.639	39.390	36.058	7.575	16.994	18.840	5.864
gEthylene/kgFuel	1.117	1.088	0.165	0.214	0.202	0.068	0.634	0.712	0.339	0.766	0.754	0.067	0.122	0.145	0.128
gFormaldehyde/kgFuel	2.270	2.124	0.583	0.448	0.404	0.231	6.402	1.939	4.602	1.719	1.654	0.136	0.263	0.292	0.292
gHexane/kgFuel	1.367	1.468	0.492	0.891	0.693	0.484	4.898	1.138	3.879	3.500	3.352	0.584	0.563	0.654	0.826
gNO/kgFuel	4.535	4.743	0.836	31.419	34.021	2.940	18.595	19.036	6.916	3.292	3.276	0.320	21.537	18.366	3.264
gNO2/kgFuel	1.739	1.799	0.257	2.947	2.897	0.504	8.534	8.266	2.352	1.678	1.638	0.157	0.680	1.271	0.765
gN2O/kgFuel	0.638	0.599	0.364	0.356	0.413	0.236	1.555	0.604	1.202	0.648	0.680	0.151	0.201	0.195	0.029
gPropane/kgFuel	1.446	1.435	0.405	0.195	0.196	0.167	2.799	0.616	2.142	2.719	2.758	0.223	0.337	0.325	0.074
gSO2/kgFuel	7.593	7.028	1.560	0.760	0.576	0.419	2.878	2.298	1.654	6.152	6.141	0.454	0.723	1.019	1.113
gPM2.5 (DustTrak) /kgFuel	0.382	0.321	0.186	0.299	0.266	0.126	1.799	1.930	0.729	0.238	0.221	0.224	0.051	0.005	0.028
gPM0.1(ELPI)/gFuel	0.001	0.001	0.001	0.003	0.003	0.001	0.004	0.005	0.005	0.001	0.001	0.001	0.001	0.001	0.001
gPM1.0(ELPI)/kgFuel	0.080	0.069	0.060	0.241	0.249	0.036	0.507	0.607	0.610	0.114	0.095	0.062	0.367	0.154	0.193
gPM2.5 (ELPI)/kgFuel	0.668	0.392	0.615	0.985	1.028	0.095	2.451	2.863	2.425	0.377	0.373	0.191	0.606	0.277	0.308

The average CO emission factor for on-road mixed fleet vehicles is within 10% of that of 39–55 g CO/kg fuel recorded in Las Vegas Valley during 2000–2002, as reported in Section 2 (Mazzoleni et al., 2004). The slightly lower average CO emission factor in this study may be explained by newer cars and/or better maintained vehicles. The average CO emission factors based on in-plume methodology and cross-plume technologies show excellent agreement, even though they were derived from completely different experiments and measurement methods.

NH_3 emissions are precursors for both ammonium sulfate and ammonium nitrate (NH_4NO_3) secondary $PM_{2.5}$. A comparison of the average NH_3 emission factors shows that it is twice as high in winter than in summer for on-road mixed fleet vehicles and on-road diesel vehicles. NH_3 emission factors are 10 times higher for on-road mixed fleet vehicles than for on-road diesel vehicles, regardless of season. The NH_3 emission factor for non-road diesel engines is 50% higher than that of on-road diesel vehicles.

The NO_x emission factor is the sum of NO, nitrous oxide (N_2O), and nitrogen dioxide (NO_2) emission factors, and the THC emission factor is the sum of ethylene, hexane, and propane emission factors. The NO_x emission factor was higher in winter than in summer, probably due to lower temperature and cold starts in winter. The NO_x emission factor for on-road diesel vehicles was four to five times higher than for mixed fleet on-road vehicles. The NO_x emission factor in summer for on-road diesel vehicles was slightly less than 8.4 g NO/kg fuel, as measured by the cross-plume study. The THC emission factor for mixed fleet on-road vehicles was higher than that for on-road diesel vehicles. The THC summer emission factor determined by the in-plume method was slightly higher than THC determined by the cross-plume study. There is substantial variation, as can be seen in the standard deviation derived from each type of sample collected during the study.

PM emission factors for on-road mixed fleet vehicles measured with the in-plume method need to be considered within the context of the sampling system. Unlike dynamometer testing, where sampling probes are connected directly to the exhaust pipe of a vehicle, the location of the in-plume sampling inlet in the middle of the road results in the simultaneous sampling of road dust, brake/tire wear material, and engine exhaust. Chemical analysis of aerosol filter samples collected with the in-plume system indicated that as much as 50–60% of the $PM_{2.5}$ is composed of geologic material (i.e., oxides of Fe, Al, Si, Ca, and Ti), and secondary aerosols of ammonium bisulfate ($[NH_4]\cdot HSO_4$) and NH_4NO_3.

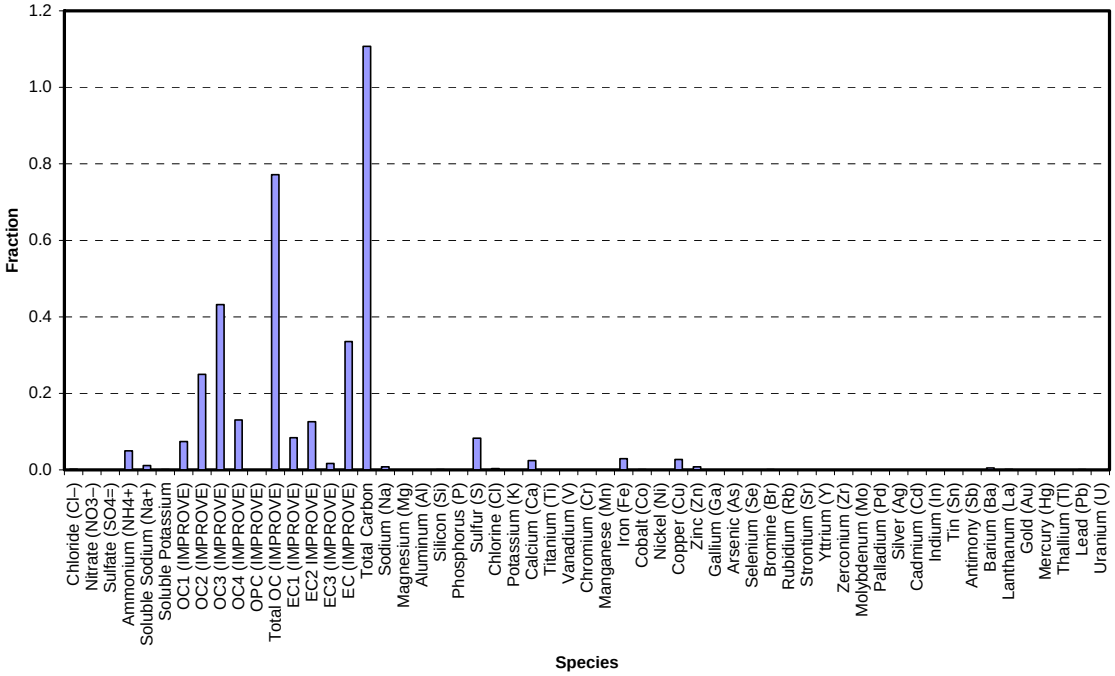
A limitation of the system is that for vehicles with bumper-level exhaust pipes, plumes of exhaust are immediately mixed with road dust suspended by the vehicle's tires. Consequently, elevated levels of combustion products (i.e., CO_2, CO, and NO) are accompanied by increased levels of both road dust and exhaust PM. Road dust, as determined by elemental concentrations on the filters, accounted for 44.51 ± 4.8% of $PM_{2.5}$ mass during winter and 63.1% ± 19.0% during summer. Emission factors of PM were estimated by measurements from DustTrak and ELPI. It is more appropriate to use the emission factor of $PM_{1.0}$ than $PM_{2.5}$ when the ELPI is used to estimate the $PM_{2.5}$ emission factor. The largest ELPI $PM_{2.5}$ emission factor was measured for non-road diesel engine exhaust (0.5 $PM_{1.0}$/kg fuel) and was lowest for on-road mixed fleet vehicles. The ELPI $PM_{2.5}$ emission factors in summer were 50% higher than those in winter for both on-road mixed fleet and diesel vehicles. Mass emission factors for ultrafine particles (particles with aerodynamic diameters less than 0.1μm) were very low (<0.001 g ultrafine PM/kg fuel), approximately 1% to $PM_{2.5}$.

The most important component of the in-plume system for source apportionment is the acquisition of integrated $PM_{2.5}$ samples on filters that can be in a CMB receptor model. Source profiles derived from this study are illustrated in Figure 4-5. These profiles result from samples composited from each type of source: four samples of summer mixed fleet on-road vehicle exhausts; four samples of winter on-road mixed fleet vehicle exhausts; four samples of summer on-road diesel bus; four samples of winter on-road diesel bus; and five samples of winter off-road diesel engines.

Prior to sample compositing for profiles of summer and winter mixed fleet on-road vehicles, the CMB model was applied to remove contributions of geological material and secondary aerosol in the ambient air background. The source profiles used in CMB were from the DRI source profile database. Only crustal species (Al, Si, Ca, and Fe), bisulfate, and NO_3^- are used as fitting species. The calculated concentrations of both the fitting and non-fitting species were then subtracted from the original roadside motor vehicle sample concentrations. The source profile for each sample was calculated and normalized based on residual mass (i.e., the difference between the measured and CMB calculated contribution of mass and chemical species).

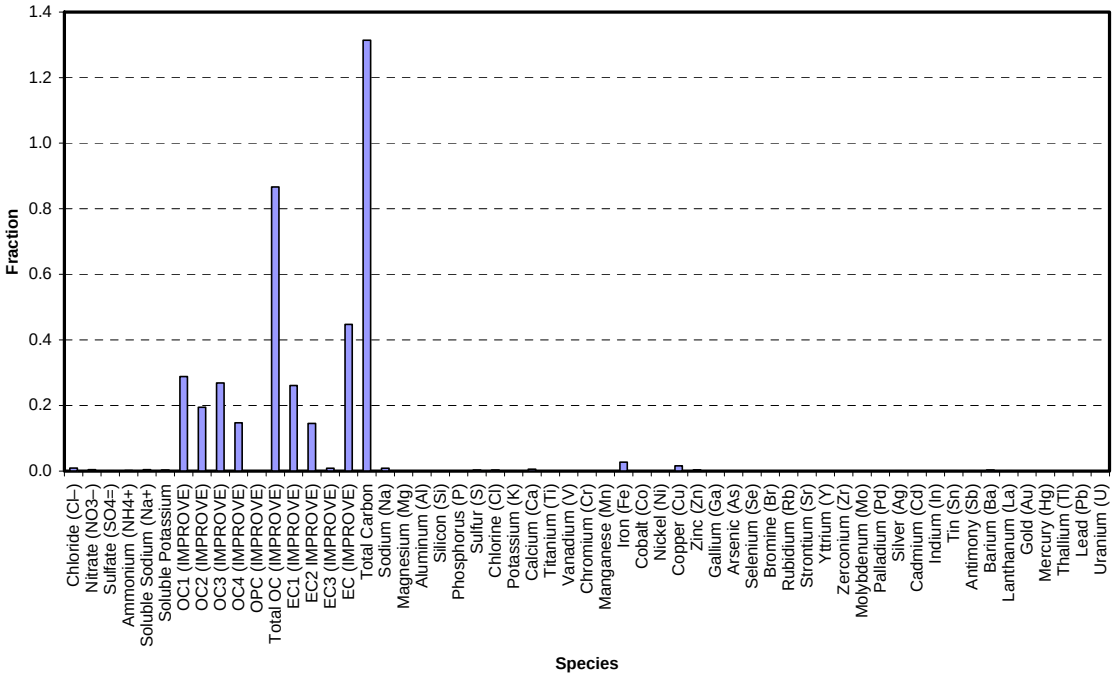
The most abundant species for $PM_{2.5}$ chemical speciation profiles are carbonaceous compounds (more than 80%) for all sources. The high-temperature OC (i.e., OC-OC1-OC2) carbon fraction comprises 56% of the mixed fleet on-road vehicle profile in summer and 47% in winter. High-temperature OC comprises 36.5% of $PM_{2.5}$ in summer on-road diesel vehicle profile, 53% in winter on-road diesel vehicles, and 64% in winter non-road diesel engines. The high-temperature OC fraction is substantially lower for both on-road diesel bus profiles for summer (18%) and winter (15%). The high-temperature OC fraction in summer is higher than winter for both mixed fleet on-road vehicles and on-road diesel vehicles. EC/OC ratios can be used to identify the impact of sources from diesel engines and oil combustion. In general, the EC/OC ratio for diesel exhaust is larger than the unity and is higher than those from on-road gasoline vehicle exhaust. The EC/high-temperature OC ratio was 0.6 for summer on-road vehicles, 1.09 for winter on-road vehicles, 3.24 for summer on-road diesel vehicles, 3.04 for winter on-road diesel vehicles, and 1.24 for non-road diesel engines. EC/high-temperature OC ratios for on-road diesel vehicle profiles were higher than those for mixed fleet on-road vehicles.

Abundance of Chemical Species in $PM_{2.5}$ from summer on-road mixed-fleet vehicles

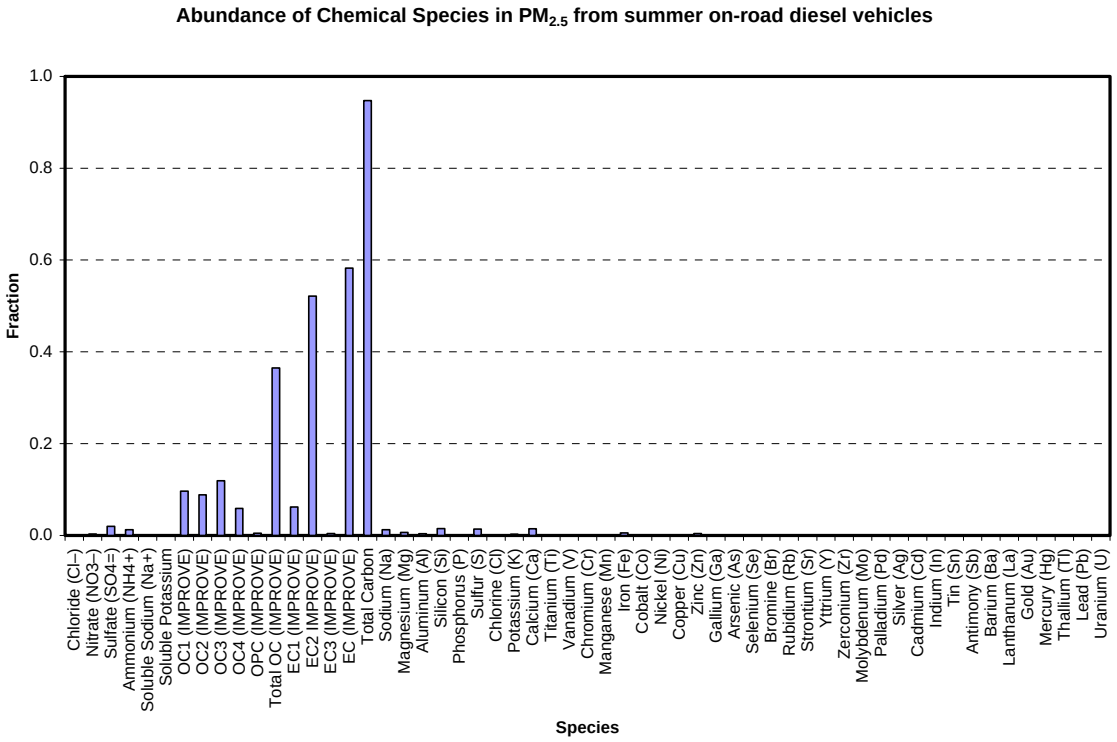


b)

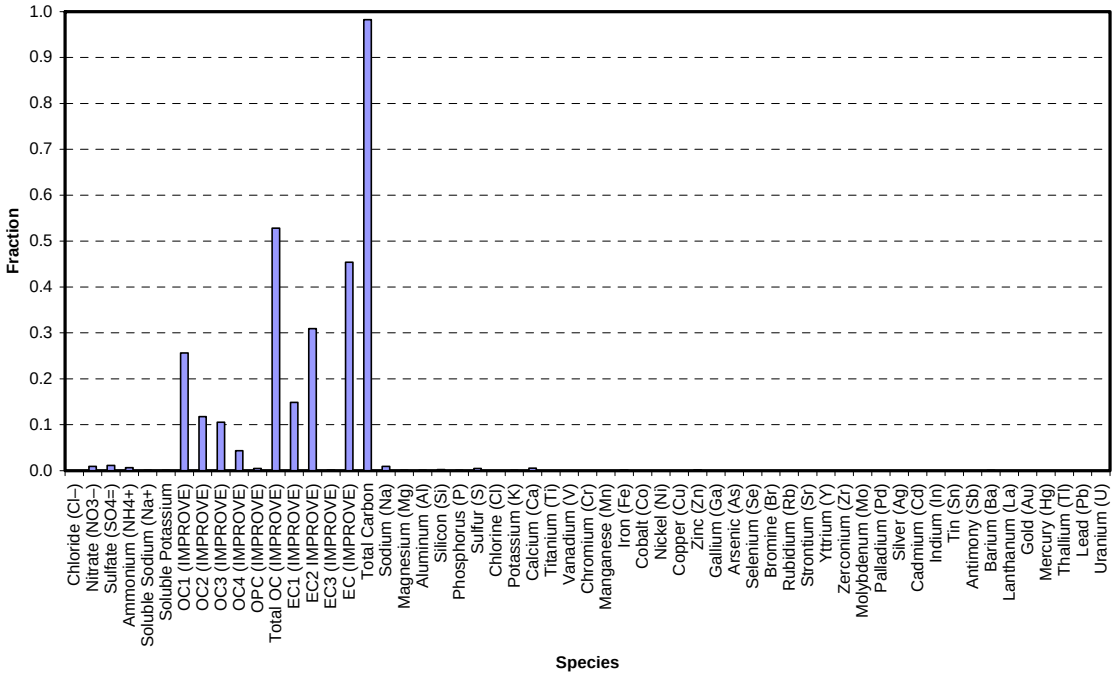
Abundance of Chemical Species in $PM_{2.5}$ from winter on-road mixed fleet vehicles



c)


Abundance of Chemical Species in PM2.5 from summer on-road diesel vehicles
Fraction
1.0
0.8
0.6
0.4
0.2
0.0
Species
Chloride (Cl–)
Nitrate (NO3–)
Sulfate (SO4=)
Ammonium (NH4+)
Soluble Sodium (Na+)
Soluble Potassium
OC1 (IMPROVE)
OC2 (IMPROVE)
OC3 (IMPROVE)
OC4 (IMPROVE)
OPC (IMPROVE)
Total OC (IMPROVE)
EC1 (IMPROVE)
EC2 IMPROVE)
EC3 (IMPROVE)
EC (IMPROVE)
Total Carbon
Sodium (Na)
Magnesium (Mg)
Aluminum (Al)
Silicon (Si)
Phosphorus (P)
Sulfur (S)
Chlorine (Cl)
Potassium (K)
Calcium (Ca)
Titanium (Ti)
Vanadium (V)
Chromium (Cr)
Manganese (Mn)
Iron (Fe)
Cobalt (Co)
Nickel (Ni)
Copper (Cu)
Zinc (Zn)
Gallium (Ga)
Arsenic (As)
Selenium (Se)
Bromine (Br)
Rubidium (Rb)
Strontium (Sr)
Yttrium (Y)
Zerconium (Zr)
Molybdenum (Mo)
Palladium (Pd)
Silver (Ag)
Cadmium (Cd)
Indium (In)
Tin (Sn)
Antimony (Sb)
Barium (Ba)
Lanthanum (La)
Gold (Au)
Mercury (Hg)
Thallium (Tl)
Lead (Pb)
Uranium (U)

d)


Abundance of Chemical Species in PM2.5 from winter on-road diesel vehicles
Fraction
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Species
Chloride (Cl–)
Nitrate (NO3–)
Sulfate (SO4=)
Ammonium (NH4+)
Soluble Sodium (Na+)
Soluble Potassium
OC1 (IMPROVE)
OC2 (IMPROVE)
OC3 (IMPROVE)
OC4 (IMPROVE)
OPC (IMPROVE)
Total OC (IMPROVE)
EC1 (IMPROVE)
EC2 IMPROVE)
EC3 (IMPROVE)
EC (IMPROVE)
Total Carbon
Sodium (Na)
Magnesium (Mg)
Aluminum (Al)
Silicon (Si)
Phosphorus (P)
Sulfur (S)
Chlorine (Cl)
Potassium (K)
Calcium (Ca)
Titanium (Ti)
Vanadium (V)
Chromium (Cr)
Manganese (Mn)
Iron (Fe)
Cobalt (Co)
Nickel (Ni)
Copper (Cu)
Zinc (Zn)
Gallium (Ga)
Arsenic (As)
Selenium (Se)
Bromine (Br)
Rubidium (Rb)
Strontium (Sr)
Yttrium (Y)
Zerconium (Zr)
Molybdenum (Mo)
Palladium (Pd)
Silver (Ag)
Cadmium (Cd)
Indium (In)
Tin (Sn)
Antimony (Sb)
Barium (Ba)
Lanthanum (La)
Gold (Au)
Mercury (Hg)
Thallium (Tl)
Lead (Pb)
Uranium (U)

e)

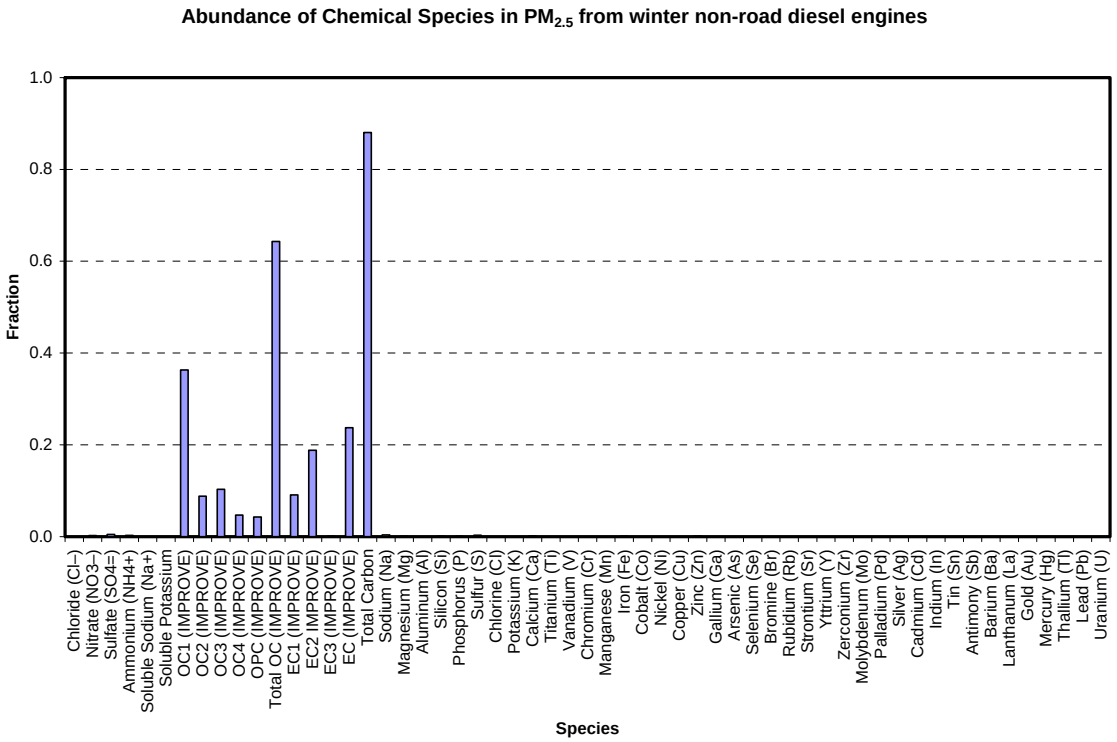


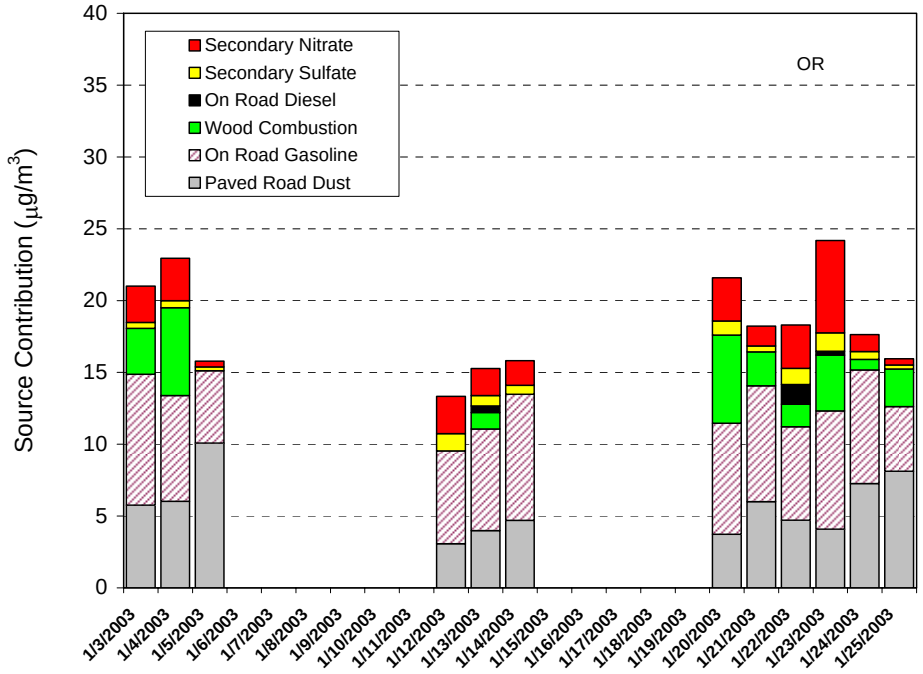
Figure 4-5. Abundances of chemical species in $PM_{2.5}$ from (a) summer on-road mixed fleet vehicles, (b) winter on-road mixed fleet vehicles, (c) summer on-road diesel vehicles, (d) winter on-road diesel vehicles, and (e) winter non-road diesel engines.

4.4 Source Contributions to Ambient $PM_{2.5}$ Concentrations

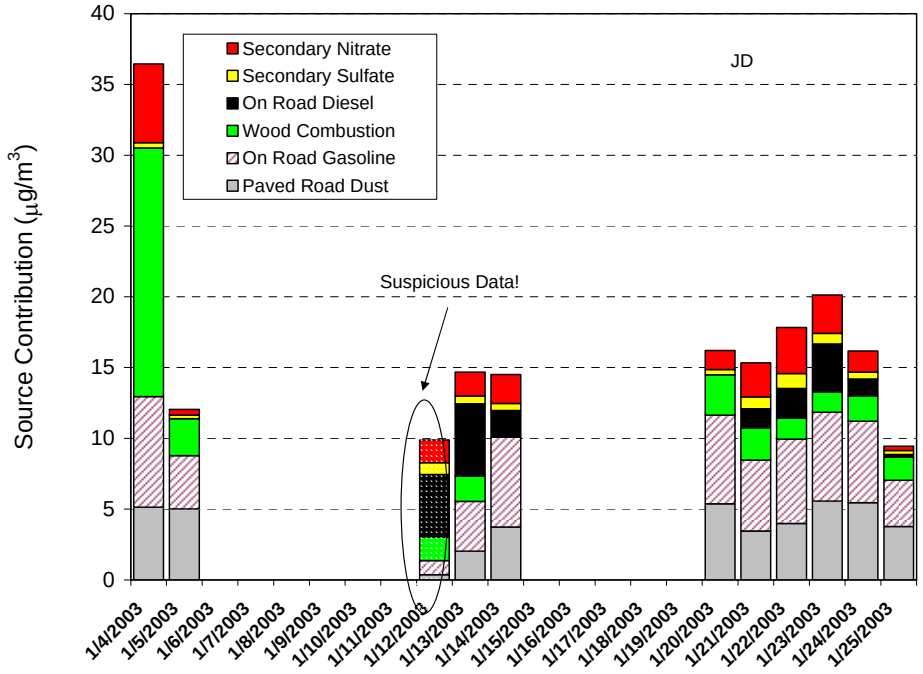
The CMB was applied to the source and receptor measurements following the EPA application and validation protocol (Watson et al., 1998). Source contributions to individual $PM_{2.5}$ samples are shown in Figure 4-6. During this study, roughly grouped into three periods—1/3/2003–1/5/2003, 1/12/2003–1/14/2003, and 1/20/2003–1/25/2003—the source contributions at OR are dominated by contributions from paved road dust and on-road mixed fleet gasoline vehicles. There is little contribution from on-road diesel vehicles at the residential OR site. The JD and CC sites are northeast of highway US-95 (I-515) and east of I-15. Considering the southeasterly prevailing wind for most of the sampling period, these two sites are expected to be impacted by the mobile emissions from highway traffic.

Increased on-road diesel vehicle contributions were observed during the second and third periods at the CC and JD sites. During the third period, the on-road diesel vehicle contribution nearly equals that of on-road mixed fleet vehicles at CC. However, the on-road diesel vehicle contribution is very low during the first episode. The period of 1/3/2003–1/5/2003 was the extended weekend following New Year's Day (Wednesday), and this may explain the absence of on-road diesel vehicle emissions at the very end of the holiday season. Another feature of the first period is the elevated contribution from wood/vegetative combustion at JD and MS.

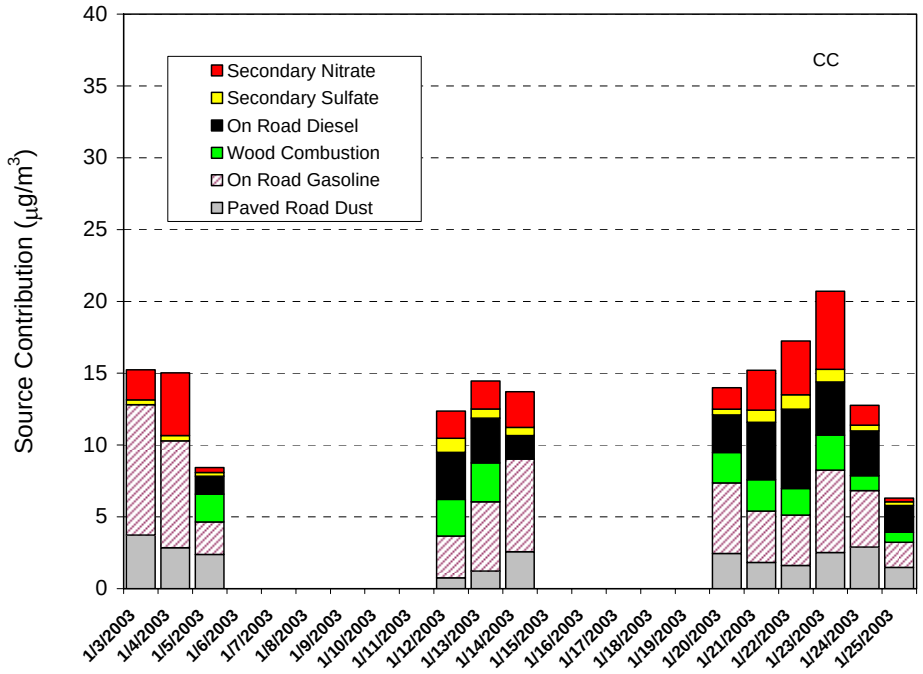
a)


Secondary Nitrate
Secondary Sulfate
On Road Diesel
Wood Combustion
On Road Gasoline
Paved Road Dust
OR
Source Contribution (µg/m3)
0
5
10
15
20
25
30
35
40
1/3/2003
1/4/2003
1/5/2003
1/6/2003
1/7/2003
1/8/2003
1/9/2003
1/10/2003
1/11/2003
1/12/2003
1/13/2003
1/14/2003
1/15/2003
1/16/2003
1/17/2003
1/18/2003
1/19/2003
1/20/2003
1/21/2003
1/22/2003
1/23/2003
1/24/2003
1/25/2003

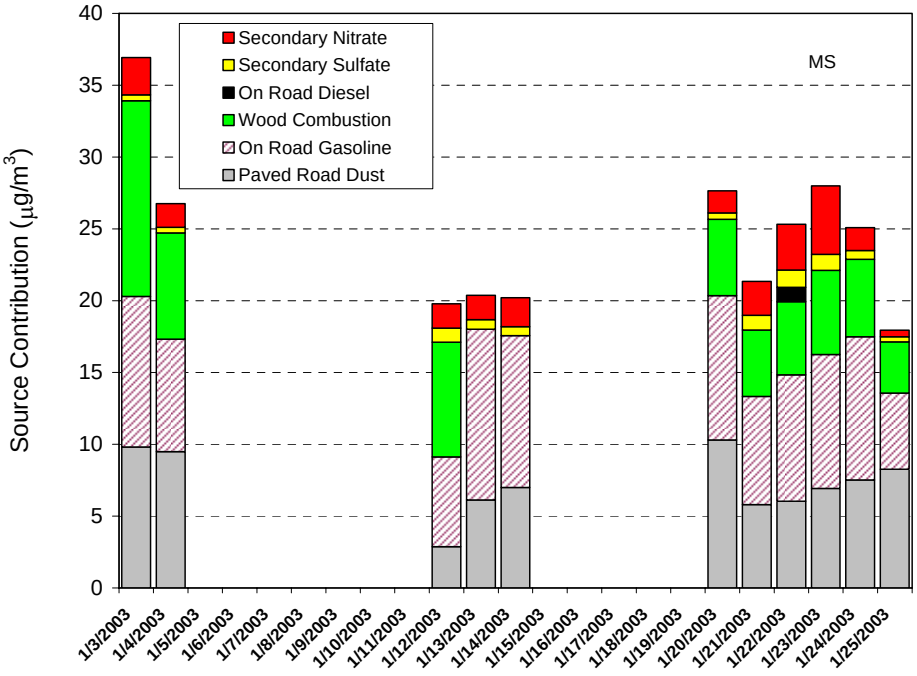
b)


Secondary Nitrate
Secondary Sulfate
On Road Diesel
Wood Combustion
On Road Gasoline
Paved Road Dust
JD
Suspicious Data!
Source Contribution (µg/m3)
0
5
10
15
20
25
30
35
40
1/4/2003
1/5/2003
1/6/2003
1/7/2003
1/8/2003
1/9/2003
1/10/2003
1/11/2003
1/12/2003
1/13/2003
1/14/2003
1/15/2003
1/16/2003
1/17/2003
1/18/2003
1/19/2003
1/20/2003
1/21/2003
1/22/2003
1/23/2003
1/24/2003
1/25/2003

c)



d)



d)

Figure 4-6. Source contributions to $PM_{2.5}$ mass as a function of time at: a) OR b) JD c) CC and d) MS. One sample from JD (1/12/2003) is marked suspicious since the $PM_{2.5}$ mass closure is >>100%.

The spatial and temporal variations of contributions from these six sources to the ambient concentration agree with the site specification and sampling timeline for the most part. Table 4-2 summarizes the overall average contribution from each source to $PM_{2.5}$ at each site. On-road mixed fleet gasoline vehicle emission was the most dominant source, accounting for 32.6–40.0% of the $PM_{2.5}$ mass. Most of the gasoline vehicle emissions contribute OC. At residential sites such as OR and MS, on-road diesel vehicle contributions are low (<2%). The low contributions of on-road diesel vehicle emissions to $PM_{2.5}$ at MS and OR might be explained by the older automobile fleet in the neighborhood of MS and OR, emission characteristics of which are more similar to that of on-road diesel vehicles. At the JD and CC, diesel exhaust contributed 17.6–34.1% of EC. Wood combustion accounted for ~10% of OC and only ~5% of EC on average. The frequency of utilizing residential heating facilities depends on the ambient temperature.

Table 4-2. Average source contributions to $PM_{2.5}$ at different sampling sites.

$PM_{2.5}$ Mass	**OR (12 d)**	**JD (10 d)**	**CC (12 d)**	**MS (11 d)**
Paved Road Dust	31.8 ± 13.9%	27.5 ± 9.7%	16.8 ± 7.2%	30.0 ± 8.3%
On-road Gasoline	40.0 ± 8.2%	32.6 ± 6.5%	33.7 ± 12.1%	37.2 ± 9.7%
Wood Combustion	11.3 ± 9.8%	15.9 ± 12.9%	11.1 ± 8.0%	20.8 ± 12.5%
On-road Diesel	1.0 ± 2.2%	9.5 ± 10.8%	18.6 ± 10.5%	0.4 ± 1.2%
Secondary Sulfate	3.9 ± 2.2%	3.4 ± 1.5%	4.2 ± 1.6%	3.0 ± 1.4%
Secondary Nitrate	12.0 ± 6.9%	1.2 ± 5.1%	15.5 ± 7.8%	8.6 ± 3.9%

4.5 Las Vegas Field Study Findings

Other important findings from the January, 2003 field study include:

- Average 24-hour $PM_{2.5}$ concentrations for the winter stagnant meteorological condition (slow mixing) were observed to be 40% higher than the annual $PM_{2.5}$ average in 2000-2001, and were the highest at East Charleston among the four sites.

- The most abundant chemical species were total carbonaceous compounds (organic matter [OC x 1.4] + EC), which comprises more than 80% of $PM_{2.5}$. The highest concentrations of organic matter and EC were observed at East Charleston. However, the relative contribution of total carbonaceous compounds to $PM_{2.5}$ and the EC/OC ratio were highest at City Center. This is probably because the City Center site is the immediate "receptor" site of PM emitted from vehicles on US-95.

- Diurnal variations of EC concentrations determined by aethalometer show peak concentrations from 6 a.m. to 8 a.m., lowest concentrations at noon, and rising to another peak from 4 to 7 p.m. at East Charleston, City Center, and Orr Middle School. These follow the daily traffic patterns.

- The diurnal patterns of hourly CO, CO_2, EC, and light scattering, tracked each other closely at East Charleston where all of these were measured. This was also consistent with the traffic patterns.

- The contribution of paved road dust to both OC and EC was 5% to 10% at the four sites.

- On-road diesel vehicles contribute 22% of the OC and 34% of the EC at City Center, which is located immediately downwind of US-95.

- The contribution of on-road diesel vehicles to haze decreased 50% as the distance between the source (US-95) and receptor increases (i.e., from the City Center site to the J.D. Smith Elementary School site).

- Residential wood combustion is a more important contributor at the East Charleston and Orr Middle School sites than on-road diesel vehicles, probably due to their residential neighborhoods.

5. PROJECT SUMMARY

The preceding sections have summarized the methodology and major conclusions from the Southern Nevada Air Quality Study. This section examines how well the project objectives were achieved by the different study components.

5.1 Objective 1: Develop, test, and evaluate advanced measurement methods to determine real-world vehicle emissions

Cross-plume and in-plume measurements systems were designed, built, tested and applied to real-world traffic emissions. Emission factors from the cross-plume system compared favorably with those from EPA emissions models. The in-plume system demonstrated that it is possible to obtain emissions factors for other species of interest, such as ammonia, sulfur dioxide and ultrafine particles, in addition to the emission factors for standard components such as carbon monoxide, nitrogen oxide and volatile organic compounds. Emission factors for the in-plume and cross-plume systems compared favorably when applied to the same school bus emissions. They also compared favorably when applied at different times and places to real-world emissions in Las Vegas, Nevada. The in-plume system showed highly correlated results with a mobile laboratory certification system, but there were systematic biases for NO and $PM_{2.5}$ emission factors. The reasons for these discrepancies are still being investigated.

5.2 Objective 2: Quantify on-road motor vehicle exhaust emissions for directly emitted $PM_{2.5}$, VOC, and CO and establish methods for identifying high emitters

Tests were conducted in Las Vegas, Nevada, using both the cross-plume and in-plume systems. Although these tests occurred at different times and places, and used different measurement methods, similar results were found for average emission factors. Emission distributions were highly skewed for high emitters. The tests added value to the emissions models by demonstrating that the distribution of emissions is highly skewed toward higher emitting vehicles. Although this was known for gas emissions, this air quality study provided the first evidence that this is also true of $PM_{2.5}$ emissions. The simultaneous measurements of $PM_{2.5}$, CO, and NO demonstrated that most of the high CO emitters did not correspond with the high $PM_{2.5}$ and NO emitters. This indicates that periodic smog tests measuring only CO and VOC will not identify high $PM_{2.5}$ and NO emitters.

5.3 Objective 3: Determine relative contributions of transportation and other sources to ambient pollutant concentrations for the Las Vegas metropolitan area

Chemical source profiles were measured with the in-plume system and applied to a Chemical Mass Balance source apportionment of ambient samples in Las Vegas during January, 2003. This modeling showed that gasoline vehicle exhaust was the largest contributor to carbon in $PM_{2.5}$ at most of the monitoring sites. Residential wood combustion was an important contributor at residential sites, but not at the commercial sites near highways. Diesel exhaust was only a large contributor at sites near major highways. The zone of influence for these emissions sources was found to be relatively small and appeared to decrease with distance from the major roadways.

5.4 Objective 4: Expand the application of technology developed during this air quality study to other areas with air quality problems

The in-plume and cross-plume systems were applied to source characterization at Lake Tahoe to determine source profiles for wood smoke, cooking, and vehicle exhaust. It was also used to determine the differences in emissions from diesel school buses using regular diesel and biodiesel. In this study, it was found that real-world emissions from biodiesel were higher, probably due to contamination of the fuel during transport and distribution. Continued sponsorship was achieved from the Department of Defense to characterize emissions from non-road stationary and mobile diesel sources used on military bases. The program is now self-sustaining, and FTA resources are still being leveraged to provide a more advanced understanding of transportation contributions to urban and regional pollution levels.

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