DRAFT

Characterizing Vehicular Contributions to $PM_{2.5}$ in Fairbanks, Alaska

Volume 4: On-Road Emission Testing

prepared for:

Alaska Department of Environmental Conservation

July 2011

prepared by:

Sierra Research, Inc.
1801 J Street
Sacramento, California 95811
(916) 444-6666

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Principal authors:

Frank Di Genova
Bob Dulla
Sung Hoon Yoon

Sierra Research, Inc.
1801 J Street
Sacramento, CA 95811
(916) 444-6666

and

Robert W. Crawford
Rincon Ranch Consulting

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the authors

Characterizing Vehicular Contributions to PM2.5 in Fairbanks, Alaska, Volume 4: On-Road Emission Testing

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1. EXECUTIVE SUMMARY

The main goal of this work in Fairbanks was to gain a better understanding of emissions in Fairbanks winters from vehicles that cannot readily be tested on a chassis dynamometer (e.g., medium- and heavy-duty vehicles) and/or for which little information exists on the sensitivity of PM emissions to low temperature (e.g., Diesels).

In the winter of 2009-10, a Borough SUV was equipped with bumper- and roof-mounted cyclones to sample on-road plumes from followed vehicles. Real-time analyzers were used to measure $PM_{2.5}$[*] and CO_2[†] concentrations; a GPS (satellite-based Geographical Positioning System) provided location; a computer displayed data real time; and supplemental manual, audio and video data were logged. The vehicle was operated for on-road "plume following" over a period of 15 days in February and March 2010. Based upon on-road measurements of $PM_{2.5}/CO_2$ ratios in the exhaust plumes of six vehicles previously tested on a dynamometer and upon a sampling of more than 1,000 plumes from pseudo-randomly selected on-road target vehicles of all types in Fairbanks, the following conclusions were reached:

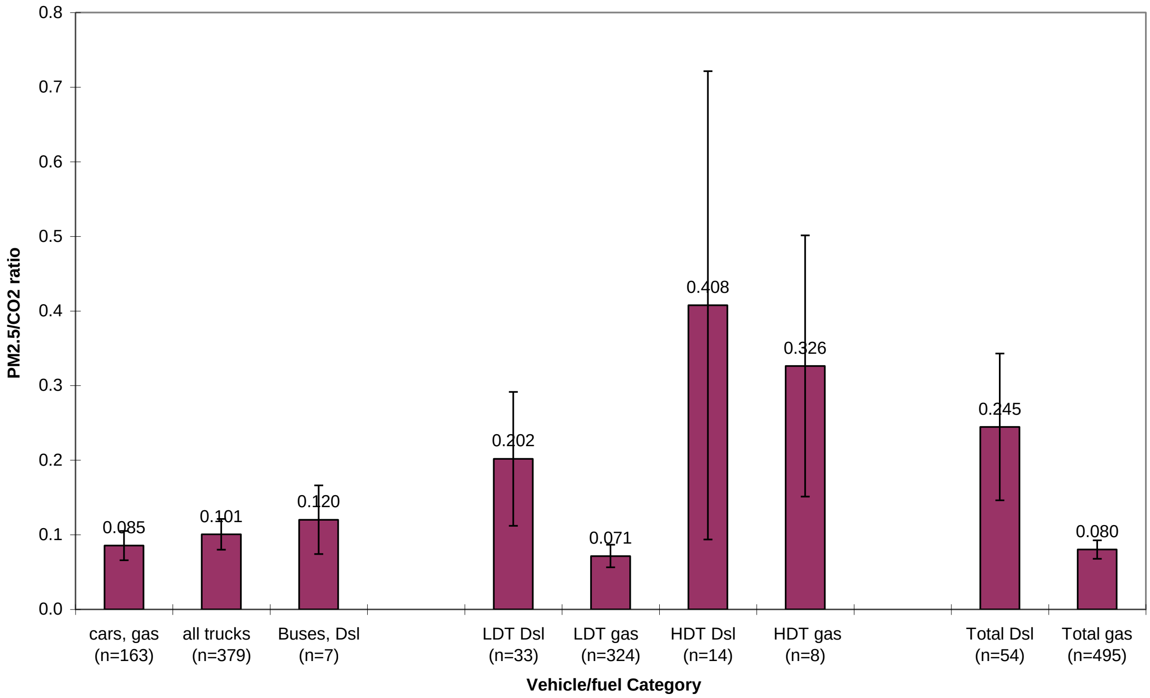
1. An on-road measured plume ratio[‡] of 0.215 ug/m^3 $PM_{2.5}$ per ppm of CO_2 during accelerations could be used to distinguish the two "high emitters" from the four "normal emitters" in the previously dynamometer-tested sample of light-duty gasoline-powered vehicles. Thus, it could serve as a threshold to distinguish normal from high emitters.

2. Based on the above threshold ratio and the results from sampling acceleration plumes from a pseudo-randomly selected sample of 630[§] on-road vehicle plumes, 7.5% of the on-road fleet in Fairbanks would be classified as high emitters.

Additional information from license plate lookups of 549 vehicles from the on-road sample of plume ratios revealed the following (see Figure 1-1):

[*] "$PM_{2.5}$" refers to particulate matter having an aerodynamic diameter less than 2.5 microns.
[†] Carbon dioxide concentrations provided a "tracer" for combustion plumes.
[‡] 5-second ratio of vehicle-emitted $PM_{2.5}$ and CO_2 concentrations after subtracting estimated background
[§] This represents the subsample whose license plates could be read, thereby permitting exclusion of duplicate counts of the same vehicle.

Figure 1-1
Avg. $PM_{2.5}/CO_2$ In-plume Ratios for On-Road Vehicle Accelerations
(n = 549 identified unique vehicles, by category, error bands show ±2 std devs)



3. The highest average emission ratio was for heavy-duty Diesel trucks (0.408), closely followed by heavy-duty gas trucks (0.326); plume ratios for these two categories were statistically indistinguishable from each other.*

4. The second-highest emissions ratio was for Diesel-powered vehicles (0.245), which was about three times that for gasoline-powered vehicles (0.080), ($p < 0.00\%$).

5. The average emission ratio for light-duty Diesel trucks (0.202) was about three times that for light-duty gas trucks (0.071), ($p < 0.00\%$).

6. The average emission ratio for heavy-duty gas trucks (0.326) was about 4.5 times greater than that for light-duty gas trucks (0.071) ($p<0.00\%$).

7. The average emission ratio for light-duty gas-powered trucks was comparable to that for (gas-powered) cars and Diesel buses.

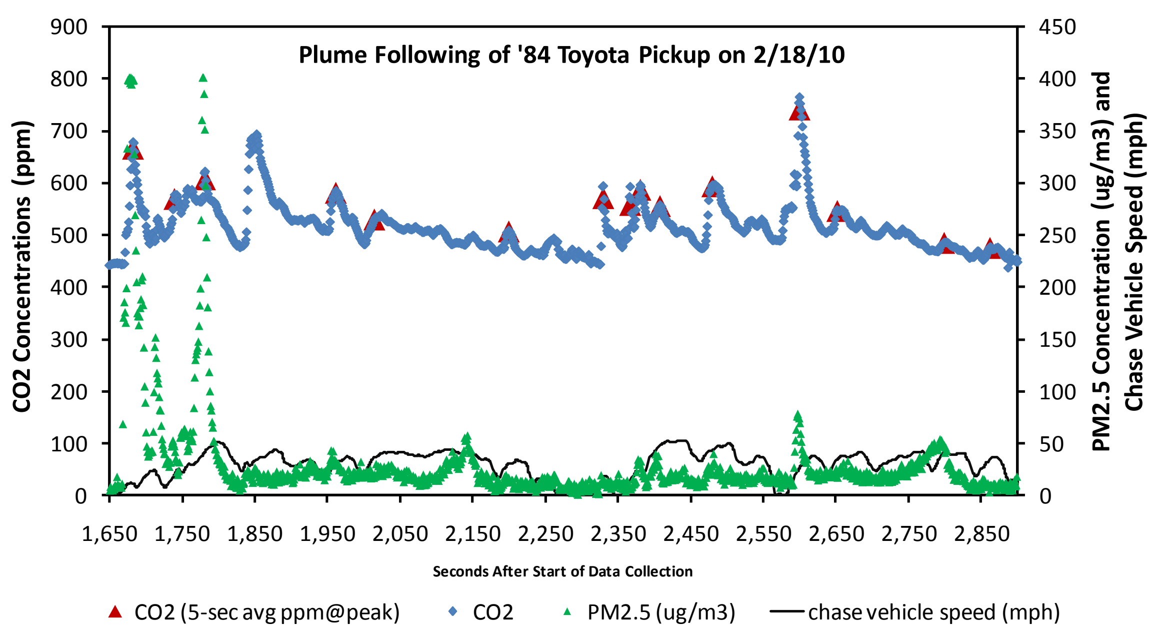
* For heavy-duty Diesel and gas trucks, and Diesel buses, fewer than 15 vehicles sampled; as a result, error bands on the estimated means are wide and the power to discern significant differences was reduced.

In support of this effort, Sierra Research designed, configured, and tested, in northern California, a prototype "plume following" vehicle to conduct on-road emission testing. Equipment was then designed and configured for a similarly instrumented vehicle that was assembled at the Fairbanks North Star Borough. The Borough plume-following

vehicle was deployed on-road in Fairbanks to follow and measure emissions from (1) seven gasoline-powered vehicles that had just been dynamometer tested; (2) a selection of light-, medium-, and heavy-duty Diesel vehicles (data collected on several days); and (3) a pseudo-random sample of nearly 1,000 on-road vehicles, with data collected over 15 days from February 22 to March 31, 2010.

To illustrate how the method works, Figure 1-2 shows an example "snippet" of plume-following data from the Fairbanks winter sampling. This short data segment was collected behind a high-emitting Toyota pickup shortly after cold start. The (blue) upper points and (green) lower ones represent measured CO_2 and $PM_{2.5}$ concentrations, respectively, prior to subtraction of background concentrations (CO_2 includes the 350+ ppm global background). The smooth dark lower curve shows vehicle speed. Note that CO_2 spikes tend to coincide with accelerations, and $PM_{2.5}$ peaks tend to decrease over the course of this 10-mile drive, as the vehicle was warming up. Upper triangles (in red) show 5-second CO_2 averages that correspond to times of target CO_2 peaks that are associated with particular vehicle accelerations. See Chapter 3 for further details.

Figure 1-2
Sample Segment of On-Road "Plume Following" Trace



The remainder of this report describes the design and fabrication of the prototype and final plume-following vehicles, operation of the prototype and final plume-following vehicles, and the analysis and results from the on-road sampling.

###

2. DESIGN AND INSTRUMENTATION OF THE PLUME-FOLLOWING VEHICLES

2.1 Overview

The plume-following element was intended to complement the dynamometer-based laboratory testing, providing emissions data for Diesels and for medium- to heavy-duty vehicles of all types that could not practically be dynamometer tested using the available light-duty chassis dynamometer[*1] and to provide data, albeit more limited than the dynamometer tests, on a wider sample of gasoline-powered vehicles.

Although rigorously defined and universally accepted equipment and test procedures do not yet exist for on-road or nearby sampling of in-plume emissions, a number of investigators have successfully used on-road or in-plume techniques[2,3,4,5,6,7] to sample vehicle exhaust plumes and other plumes[8,9,10] under a range of conditions and for a variety of purposes. In at least one application, which has similarities to the current one, Park[11] used a plume-following vehicle, along with labor-intensive video review (not used here), to identify on-road "high emitters." However, to our knowledge, the plume-following technique has not previously been used for sampling vehicle exhaust on-road at ambient temperatures as low as -24°F.

The plume-following element of the current project had three specific objectives, as follows:

1. Collect on-road data for dynamometer-tested gasoline-powered vehicles to validate a plume-following methodology and to establish dynamometer to on-road calibrations, including consideration of cold start effects;

2. Measure on-road emissions, potentially including plug-in, cold start effects, for a sample of light-, medium-, and heavy-duty on-road Diesel-powered vehicles; and

3. Evaluate the fraction of high $PM_{2.5}$ emitting vehicles in the on-road fleet.

To accomplish the above, Sierra selected an instrument package consisting of the following key elements:

[*] The Borough's Real Time Dynamometer, Model EM-4: IM-240, has a lift capacity of 10,000 lbs, but a more restrictive simulated inertia weight range of about 1,500-6,200 lbs (for an acceleration of 3.3 mph/sec or less, corresponding to the maximum acceleration of the LA4 driving cycle).

- DataRAM4000[*] PM monitor and inline heaters (2, used in series),[†]
- BGI[‡] $PM_{2.5}$ cyclone (model 1.062, with calibration chamber),
- LI-COR[§] LI-820 CO_2 gas analyzer,
- GPS[**] system,
- Laptop[††] computer with custom Labview[‡‡] program (adapted from prior Sierra chase car work) to log and display data in real time,
- National Instruments PCMCIA-format analog to digital (A/D) conversion card,
- Custom 6-channel rotary switch box for supplemental manual data entry/logging,
- Pulse Pen[§§] (audio and event recorder, used for portions of the vehicle following),
- 300 watt power inverter,
- Sony[***] camcorder (used for selected portions of the vehicle following),
- Davis Instruments[†††] Carchip EX, and
- Omega[‡‡‡] temperature logger.

The vehicle instrumentation was designed to be operated by a two-person drive team, consisting of a driver and an "observer." The observer's primary jobs were to continually monitor the instruments using the laptop real-time display, to perform manual data entry to document times when "on target," and to collect other pertinent information about targets (e.g., license plates[§§§] and vehicle descriptions), sampling conditions, etc. This was done in real time using the digital (audio recording) Pulse pen and manual data entry box.

2.2 Prototype and Final Plume-Following Vehicles

Prior to conducting plume following in Fairbanks in the winter of 2009-10, a prototype setup was first assembled and tested in northern California using Sierra's instrumented Chevrolet Caprice.12 For this prototype "proof of concept" application, only a crude pre-drive CO_2 analyzer calibration was performed using on-hand calibration gases and, due to

[*] Thermo Fisher Scientific, Franklin, MA.
[†] For the current project, the choice of using a DataRAM 4000 and several other instruments was largely dictated by availability. The DataRAM and inline heaters were borrowed from FNSB, along with a GPS, Livescribe Pulse Pen, Omega temperature logger, power inverter, and other minor equipment items.
[‡] BGI Corp., Waltham, MA.
[§] LI-COR Biosciences, Lincoln, NE.
[**] Garmin International, Olathe, KS.
[††] Toshiba Satellite, Toshiba, Tokyo, Japan.
[‡‡] National Instruments, Austin, Texas.
[§§] Livescribe, Oakland, CA.
[***] Sony Corp., Tokyo, Japan.
[†††] Davis Instruments, Oakland, CA.
[‡‡‡] Omega Engineering, Stamford, CT.
[§§§] License plates were used only to gather additional information about target vehicles (e.g. make, model, model year, etc.) and to identify vehicles that had been sampled repeatedly. There was no enforcement activity of any kind during the study.

the moderate ambient temperatures in northern California, no in-line heaters were required. Additionally, the prototype used temporary installation of ¼ inch teflon sample line tubing (the final installation in Fairbanks used ¼ inch stainless steel tubing grounded to the vehicle chassis and connected by short segments of carbon-impregnated conductive tubing).[*] Otherwise, the prototype sampling train was functionally similar to the final sampling train, which is shown in Figure 2-1.

The sampling point in the prototype was a BGI triplex cyclone that was originally mounted at roof edge just outside a cracked window opening on the front passenger side of the Caprice about 5 feet above the roadway; however, after trial driving in Sacramento, the cyclone was moved to the front bumper near the Caprice centerline in order to provide closer coupling to the tailpipe area of the vehicle ahead. The latter sampling position, which is shown in Figure 2-2, was found to be preferable for capturing the exhaust emissions from vehicles accelerating ahead of the "chase car" and was later duplicated in Fairbanks with a bumper-mounted cyclone. (The behind-the-grill laser range finder visible in the photo was not used in the current project.)

As used in Fairbanks, the flow rate of the DataRAM was set to provide the desired flow rate and $PM_{2.5}$ cutpoint at the cyclone outside the vehicle cabin (based on typical outdoor vs. instrument temperature difference) and was checked using a BGI cyclone calibration cup and BGI flow meter. Previous on-road sampling in Fairbanks with the same BGI cyclone model and a similar sampling setup showed sampler flow rate to vary little with vehicle speed.13

Sample flow was transported by the pump integral to the DataRAM and, after being pulled through the cyclone and DataRAM, was exhausted to a "T" where a portion of it was bled off and the remainder, nominally 1 lpm, was pushed through a PM filter and the LI-COR CO2 analyzer and exhausted through a rotameter (used to set the bleed rate). For the implementation in Fairbanks, zero (N_2) and CO_2 span gas bottles[†] were provided in the vehicle, allowing for convenient instrument calibration, which was performed at the start of each drive. In addition, the Fairbanks implementation used an identical second, solenoid-switched BGI cyclone (not shown in the diagram, but in Figure 2-3), that was mounted on a tower on the roof of the sampling vehicle, about 11.5 feet above road level, for sampling of emissions from vehicles with high stacks. Figures 2-4 through 2-7 show other views of the interior and exterior of the plume-following vehicle, including a closeup of the front bumper mount primary BGI cyclone.

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[*] TSI, Inc.

[†] Air Liquide, Anchorage, Alaska.

Figure 2-1
Sampling Train for Plume-Following Vehicle

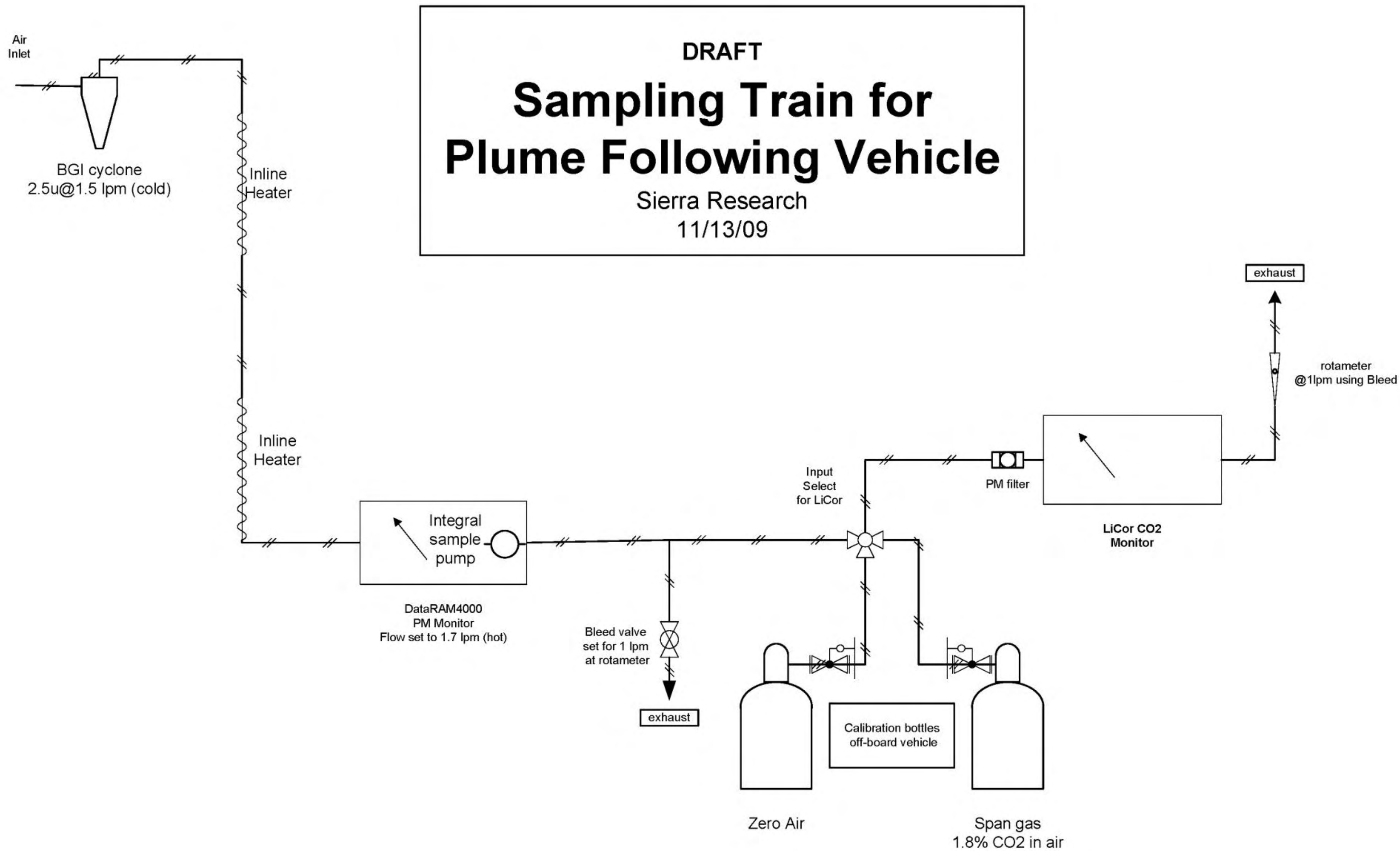


Figure 2-2
Caprice (prototype plume follower) Front Bumper Mount of BGI Cyclone

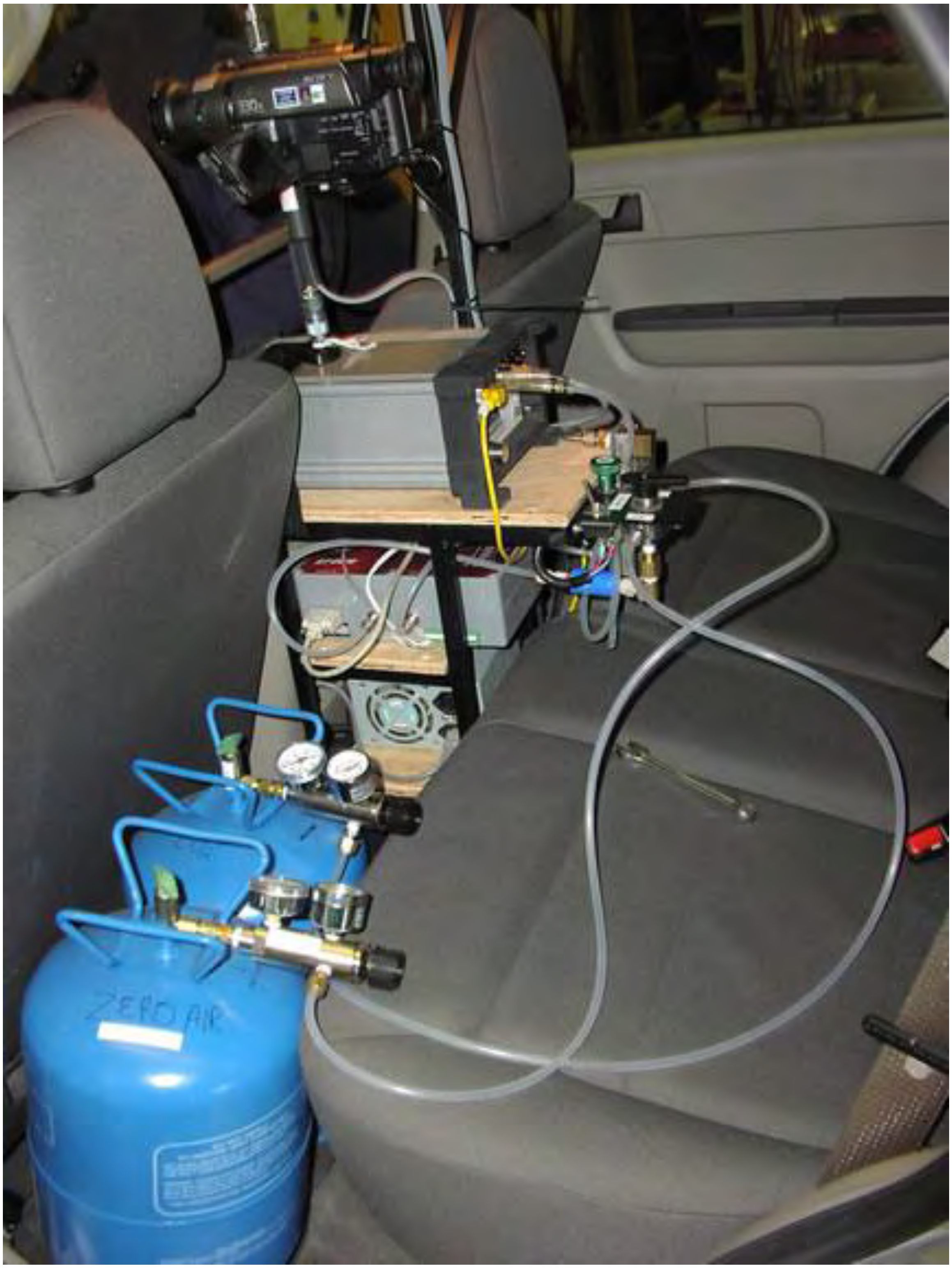
Figure 2-3
Roof Tower-Mounted Sampling Cyclone on FNSB Plume-Following Vehicle

Figure 2-4
Bumper-Mounted Primary Sampling Cyclone on FNSB Plume-Following Vehicle

Figure 2-5
Interior of FNSB Vehicle
Camcorder, 2nd of two in-line heaters, DataRAM, GPS, thermocouple datalogger, Toshiba laptop, and Rotary Switchbox (backside)

Figure 2-6
Laptop Inside FNSB Plume-Following Vehicle
Provided 20-second real time display of CO_2 and $PM_{2.5}$ Concentrations
(PCMCIA A/D card plugs in at left, attached to ribbon cable)

Figure 2-7
Back Seat Area of FNSB Plume-Following Vehicle
Camcorder, in-line Heater, DataRAM, LI-COR, Power Supply, and Calibration Gases



Two different Garmin GPS systems were used in the study (to obtain vehicle position and speed, along with other information). In the prototype testing and originally in Fairbanks, Sierra used a Garmin GPSIII+ to collect second-by-second position data; however, in the final implementation of the plume-following vehicle, the GPSIII+ was replaced by the newer Garmin eTrex Summit, which was both more accurate and more familiar to Borough staff from prior work.

The vehicle platform used in Fairbanks was a model year 2009 Ford Escape SUV. Installation of all equipment in the vehicle was ably performed by Kelly Shaw, of the FNSB Air Quality staff. Mr. Shaw modified the vehicle as follows:

- Removed the right rear passenger seat (to allow more room for equipment);
- Installed a secondary 12 volt battery and inverter to power instruments;
- Installed instrument shelves and secured laptop computer and instruments;
- Fabricated and installed ¼ inch stainless steel sample lines and installed sampling cyclones;
- Fabricated (welded) and installed the rooftop tower and solenoid-switched sample line, control solenoid and wiring; and
- Installed a manually controlled 3-way valve to control zero and span gas flow to the LI-COR analyzer.

Upon completion of its preparation, the FNSB plume-following vehicle was immediately placed into service in February 2010 for staff training by Sierra, for on-road "plume following" measurements of the seven dynamometer-tested vehicles (on 2/18/10), for following of selected Diesel vehicles on a colder and then a warmer day, and for following of essentially randomly selected on-road vehicles of all types over a period of about two weeks.

2.3 On-Road Trials of the Prototype Plume-Following Vehicle in California

This section briefly describes the results from trial drives of the prototype Chevrolet Caprice plume-following vehicle that were conducted in Sacramento on several days in December 2009, and vehicle following of a known smoky vehicle, a 1975 two-stroke Suzuki GT750 motorcycle, in Napa, California, on December 24, 2009.

Vehicle-following in the Sacramento area occurred over several days in December 2009, during which initial equipment layouts received "shakedown" testing and a variety of plume-following procedures, roadway types, and target types were tried. During this period of testing, most of the on-road targets were seen to have clearly distinguishable CO_2 plumes at close range and upon acceleration, but plumes generally could not be distinguished from background levels at typical freeway speeds and driving conditions. Therefore, under the more optimal conditions of stop-and-go city driving, data were collected on more targets, with attention to identifying both $PM_{2.5}$ and CO_2 plumes.

During this period of testing, there were, in several cases, opportunities to follow several target vehicles for a period of a few minutes each. One of these was an apparently clean Yuba Transit bus and the other was a relatively dirty (visibly smoking) dump truck. The contrast in measurements of these vehicles appeared to confirm that the system was successfully distinguishing a visible emitter from a non-visible emitter (distinct elevated $PM_{2.5}$ and CO_2 concentrations vs. elevated CO_2 only); to confirm this, a known high-emitting target vehicle was sought for plume following under varying conditions. To this end, a 1975 two-stroke Suzuki GT 750 motorcycle was recruited and its owner retained to conduct on-road trials.

The motorcycle chase confirmed that the prototype setup did allow a high PM emitting vehicle to be clearly distinguished under certain conditions. Specifically, the motorcycle exhibited prominent PM spikes during startup and accelerations that were far in excess of what had been seen previously in earlier trial drives in Sacramento. However, even for this high emitting two-stroke powered vehicle, PM emissions could not be reliably distinguished during steady-state freeway driving. The drive team did see, both visually and in the DataRAM readings, somewhat regular wisps of smoke during steady-state speed operation on the freeway, even after nearly an hour of driving, i.e., when fully warmed up. (Similar wisps of smoke were seen and measured behind a Mercedes Diesel on the freeway drive from Sacramento to Napa on the motorcycle testing day.)

Details and results from the motorcycle following are documented in Appendix A with a brief narrative, graphs, and contemporaneous notes. However, because only a crude CO_2 calibration was performed prior to the motorcycle following and due to time constraints, no attempt was made to analyze $PM_{2.5}/CO_2$ ratios or other aspects of the resulting data.

2.4 Collecting On-Road Data from Dynamometer-Tested Gasoline-Powered Vehicles to Validate the Plume-Following Methodology

On February 18, 2010, after overnight plug-in* outside, the six primary dynamometer-tested test vehicles and the backup Dodge Caravan were each started and immediately "plume followed" one or more times over a preselected drive of about 5 miles. The main purpose of this exercise was to determine whether the plume-following vehicle and associated procedures could be used to distinguish the dynamometer-measured high-emitting vehicles from the cleaner vehicles in sample fleet.

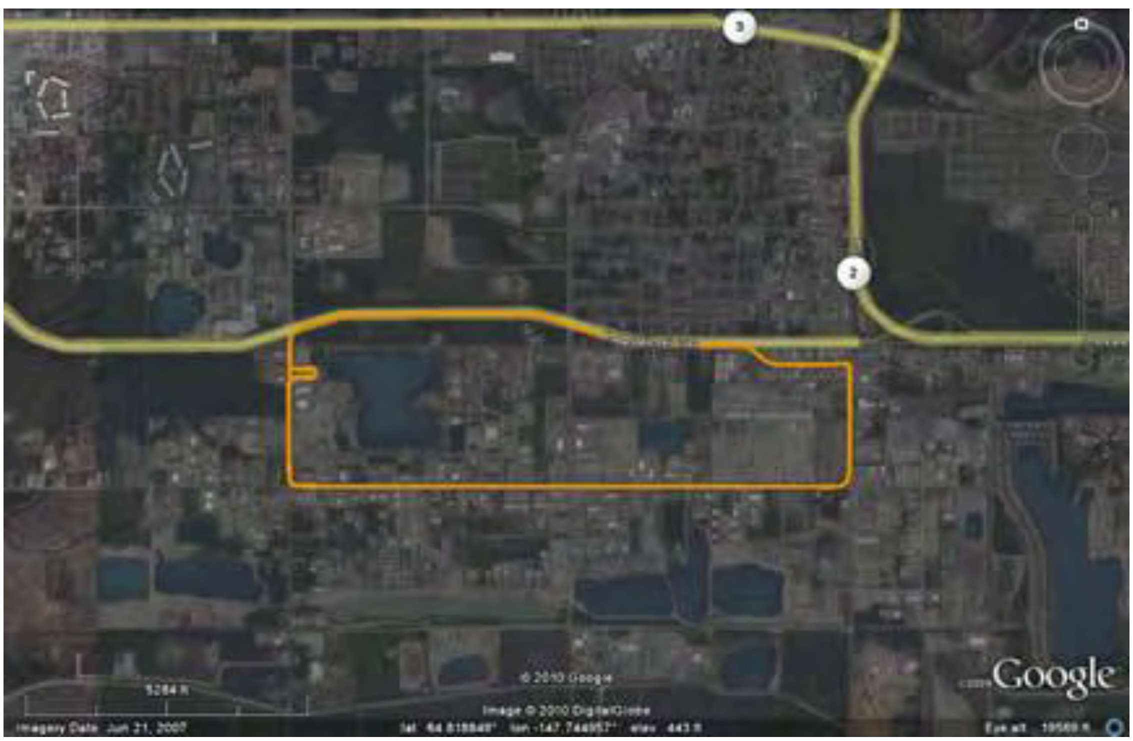
The drive route was selected to roughly approximate the distance and time of the ADC (4.7 miles, 816 seconds) and included both stop-and-go and freeway driving. For most

* Note that the Airport temperature on the afternoon of 2/18 was about 20°F, and therefore the block heater of the Silverado (which is thermostatically set to operate only above 0°F) was not expected to activate on this day. This was confirmed by the relatively low starting coolant temperature of the Silverado (37.40°F), compared to those of the other two "carchipped" vehicles (116.6°F and 75.2°F).

vehicles the route was driven twice[*] (to simulate crudely a drive of the cold ADC and hot ADC on the dynamometer, although no engine shutdown and 10 minute soak was done in between). The driving, which started and ended at the Fairbanks North Star Borough's Transportation Department at 4175 Peger Rd., was performed in a clockwise direction along the route shown in Figure 2-8. A typical repeat drive of the route, conducted by the Chevrolet Silverado test vehicle and recorded by Carchip, is depicted in Figure 2-9. The average speed was about 30 mph, and the distance for each clockwise loop was 5.2 miles.

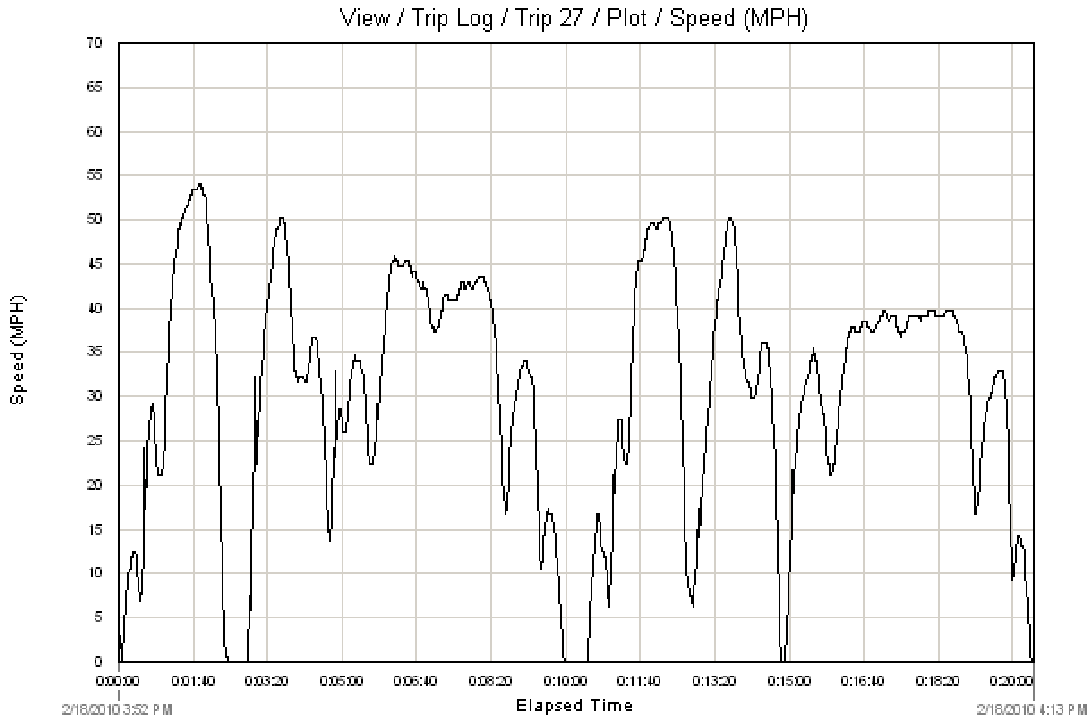
During the test driving, which was videotaped from the plume-following vehicle, the target and plume-following vehicles were driven by Borough staff members, and Sierra's on-board "observer" recorded notes including the time of each acceleration event. The observer also noted which accelerations appeared to uniquely capture the plume from the target vehicle as compared to other accelerations where the target plume was judged to probably be mixed with those from one or more other nearby accelerating vehicles (video review was performed in this case to assist in time-aligning the data and help confirm some of these other-vehicle plume impact assessments).

Figure 2-8
Drive Route for Plume Following of Dynamometer Tested Vehicles



[*] Only one drive was performed for several vehicles that "cleaned up" sufficiently that their PM emissions were not distinguishable from background (at least in real time) by the end of the first drive.

Figure 2-9
Speeds (from Carchip) for Plume Following of the Silverado



2.5 Measuring Emissions from a Sample of Light-, Medium-, and Heavy-Duty On Road Diesel Powered Vehicles

In addition to the on-road testing of the dynamometer-tested gasoline-powered vehicles, on-road tests were conducted for a small sample of light- and medium-duty Diesel vehicles from a used car lot, a Borough transit bus, and a number of heavy-duty vehicles operated by Lynden Transport of Fairbanks.

The light- and medium-duty Diesels were cold–started on-site at Affordable Used Cars,* which kindly provided study access to any vehicles on their lot. On-road testing of these vehicles (and the transit bus) was conducted on March 1, 2010.

The light- and medium-duty vehicle following generally used a (single) loop similar to that used for the dynamometer-tested vehicles, while the Borough transit bus was followed for a portion of its normal drive route. In the case of the bus, plume following on a normal service route was limited in some cases at passenger stops where the "tail" of the bus was not fully out of the roadway and continued plume-following could have presented a safety hazard.†

* Affordable Used Cars, 2525 South Cushman St., Fairbanks, Alaska, 99701-6642.
† The bus driver was informed about the plume-following exercise in advance of the drive.

Plume-following of heavy-duty Diesel trucks* was done on two days, March 18 and 30, 2010, which were a colder and warmer (but windy) day, respectively, in an attempt to obtain a temperature comparison of emissions. However, the second-day measurements and comparison were largely unsuccessful because it was too windy, which both compromised efficient plume capture and resulted in increased fugitive dust that interfered with the collection of unique plume measurements. Furthermore, the available vehicles on the second day did not include any of the heavy-duty vehicles sampled on the first day. For these reasons, no further analysis was done with the Lynden data.

2.6 Evaluating the Fraction of High $PM_{2.5}$ Emitting Vehicles in the On-Road Fleet

Properly maintained and operated late-model gasoline-powered vehicles are generally expected to have very low warmed up $PM_{2.5}$ emissions, typically in the range of 1-5 mg/m based on the Kansas City results, for example. However, the same study and others (including the current Sierra study) show that high emitters can emit hundreds of mg/m. Therefore, in order to quantify fleet emissions accurately, it is important to determine the fraction of the fleet which is high-emitting. The plume-following approach potentially allows for sampling a relatively high number of vehicles, each with small snippets of data, especially during acceleration, to determine if they are high emitters.

For this element, a two-person Borough plume team was deployed each day for about two weeks to collect data on plumes from accelerating vehicles. As described later, this effort logged more than 1,000 plumes and was used, together with information from plume following of the dynamometer tested vehicles, to estimate the fraction of high emitting vehicles in the on-road fleet in Fairbanks in winter.

2.7 Procedures Used for Plume Following

There are several potentially serious confounding factors that could, if not addressed, limit the applicability of plume following in Fairbanks in winter. Probably the most important is the warm-up conditioning of the target vehicle.

EPA's data from Kansas City showed that even relatively low-emitting vehicles generally have much higher emissions when they are cold (bag1) as compared to when they are more fully warmed up. However, past CO emission studies at Fairbanks winter temperatures have shown that even though most catalysts "light-off" in the first minute or two after cold start, a few vehicles, particularly those with larger engines, may not fully warm up until much later.

Outlined below are four ways in which the warm-up issue was addressed in the current study.

---

* Vehicle following of heavy-duty vehicles was performed through the assistance of Lynden Transport.

1. The procedure was adopted to sample vehicles until they were determined[*] to be clean (i.e., not high emitters), or a pre-determined time limit was reached. Specifically, vehicles that appeared at first to be high emitters were followed for a longer period (up to about 5 minutes as a practical limit[†]) to see if their emission ratios (during acceleration) decline over time. If emissions remained high for an extended period, they were presumed to be high-emitters rather than simply not fully warmed up.

2. For vehicles with extended periods of on-road following (item 1), only the final measurement (presumed to be at the most warmed up engine state) was used for the analysis.

3. On-road data collection was usually conducted mid-day, during which time first cold starts of the day were presumed to be less likely.

4. The data analysis using dynamometer-tested vehicles was designed to distinguish cold normal emitting vehicles from warmed-up high emitting vehicles (this was assumed to be the worst case).

Additional potential issues for plume following include quality of plume capture, possible interference from other stationary and mobile emission sources, and determination of background concentrations. To address these concerns, the following additional steps were taken:

1. Sampling was generally conducted only on days when winds were light or absent[‡] and avoided known stationary sources that could affect measurements;

2. Sampling was done at times and locations where traffic was generally light (to optimize for measurement of individual plumes);

3. Detailed plume analysis was performed only during individual acceleration events when identified CO_2 peaks were well above "background" and could be associated with identified targets;

4. Teams were instructed to take note of any potentially interfering visible plumes and sources[§]; and

[*] This involved simply contemporaneous inspection by the observer to confirm that an elevated CO_2 plume was present, and to determine whether there was a clearly identifiable $PM_{2.5}$ plume; in the vast majority of cases, there was no $PM_{2.5}$ plume.
[†] From the dynamometer testing, five minutes was long enough for most vehicles to warm up to the point where emission factors would decline significantly.
[‡] This is not a serious limitation in Fairbanks in winter, where "calm" is the most common wind condition.
[§] In Fairbanks, wood burning is common, and wood smoke plumes, many of which were noted by the Borough observers, have a very noticeable and characteristic smell. The same Borough staffers who conducted the plume following maintain a record of known wood- and coal -burning sources.

5. As in other plume-following studies, an algorithm was chosen that allowed for calculation of variable background concentrations during and between drives.

Along with all of the above, the Borough drive team used Pulse pens (a digital audio recording device) to contemporaneously log the time; target description, including license plate; and $PM_{2.5}$ and CO_2 peak concentrations, available to the observer from the real time laptop display. Audio logs were later transcribed by the observers and used to assist in the analysis of the second-by-second $PM_{2.5}$ and CO_2 measurements. Additional details about the compilation and analysis of the data by Sierra and Rincon Ranch Consulting are described below.

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3. DATA COLLECTION AND ANALYSIS

Plume-following data collection and data analysis are conceptually simple, but approaches vary markedly from study to study, depending upon the study objectives. For the current study, the major focus was not so much to measure or characterize absolute emissions from on-road targets as to distinguish "high" from "normal" emitters during accelerations in order to determine the high emitter fraction. Furthermore, only a relatively simple photometric measurement of $PM_{2.5}$ was available. Yet, even with these simple constraints, a significant analytical effort was required to derive useful results.

To begin, the DataRAM, LiCor, and GPS measurements (one or more files of each type for every day of testing) were converted as necessary and compiled in a time-aligned Excel 2007 spreadsheets.[*] DataRAM files were retrieved using Thermo Fisher's DR4-COM utility (version 3.0.4.0). LiCor files were recorded to laptop using LI-820 Gas Analyzer Software (version 2.0.0). Garmin GPS files were recorded by the handheld GPS units and then downloaded and converted to text using either GPSVisualizer[†] or GPSBabel.[‡]

3.1 Plume-Following of Dyno-Tested Vehicles

The plume-following data from six dynamometer-tested test vehicles provide the starting point for classifying on-road vehicles as either high emitters or normal emitters.

The analysis began by constructing a time plot of the second-by-second $PM_{2.5}$ concentrations and CO_2 mixing ratios during the drive of February 18, 2010, when the six vehicles were followed in a successive series of drives. The time series were then examined using an algorithm that identified the precise CO_2 peak associated with each recorded major acceleration based on the recorded acceleration event timing from the observer's log. The ten-second average $PM_{2.5}$ and CO_2 concentrations centered on the peaks were then determined and a computation was made of the respective background concentrations. Backgrounds were estimated as the minimum one-second reading within the one-minute period centered around the CO_2 peak. The ratios of the peaks, less background, were then computed, a sample of which is shown in Figures 3-1 and continuation Figure 3-2, for following of the high-emitting Toyota pickup. The same

[*] Due to the relatively large amounts of data, two spreadsheets were created: one for the on-road following of dyno-tested vehicles, and one for all other on-road plume following.
[†] GPSVisualizer.com.
[‡] GPSBabel.org.

Figure 3-1
Plume Following of the High-Emitting Carbureted Toyota Pickup

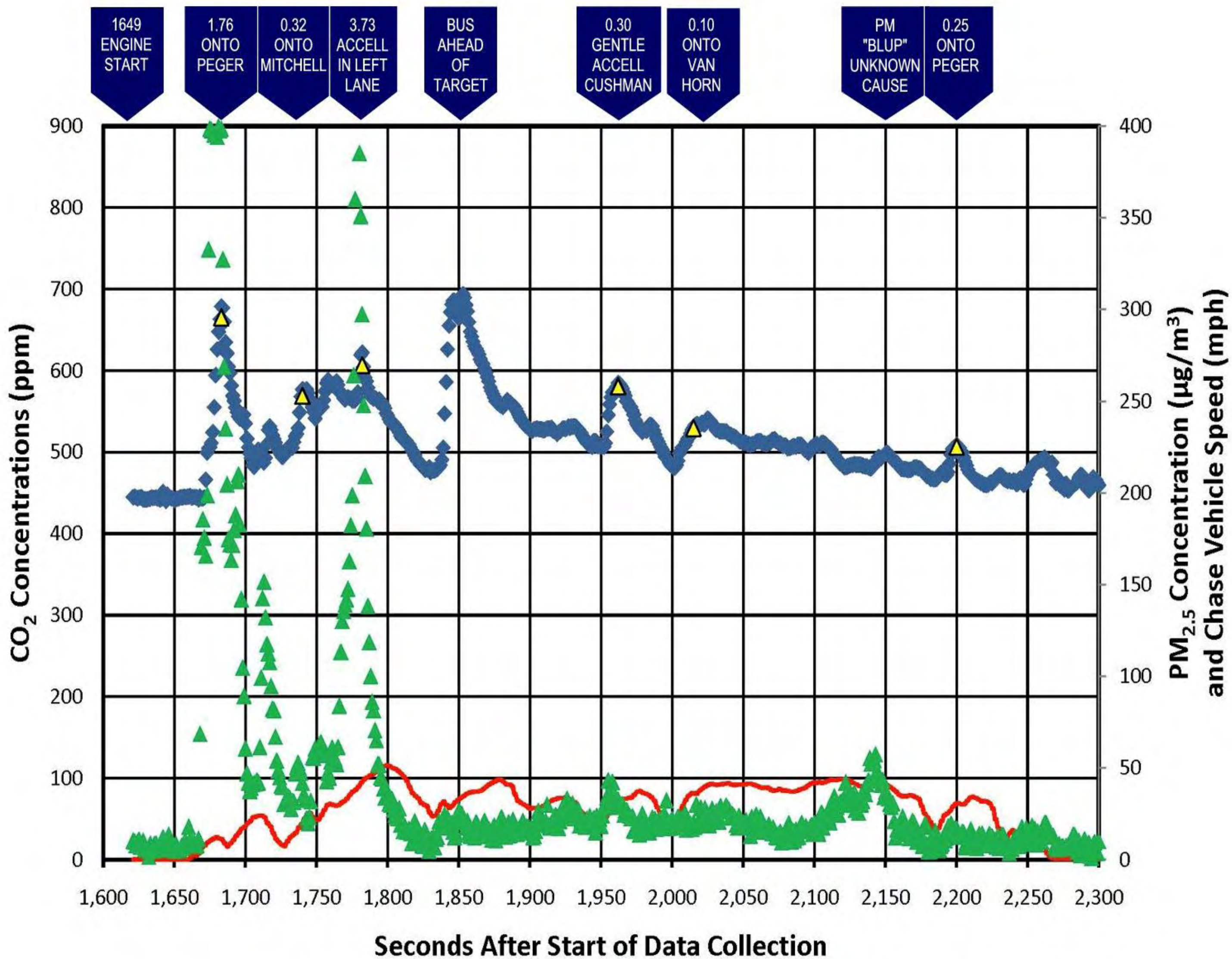
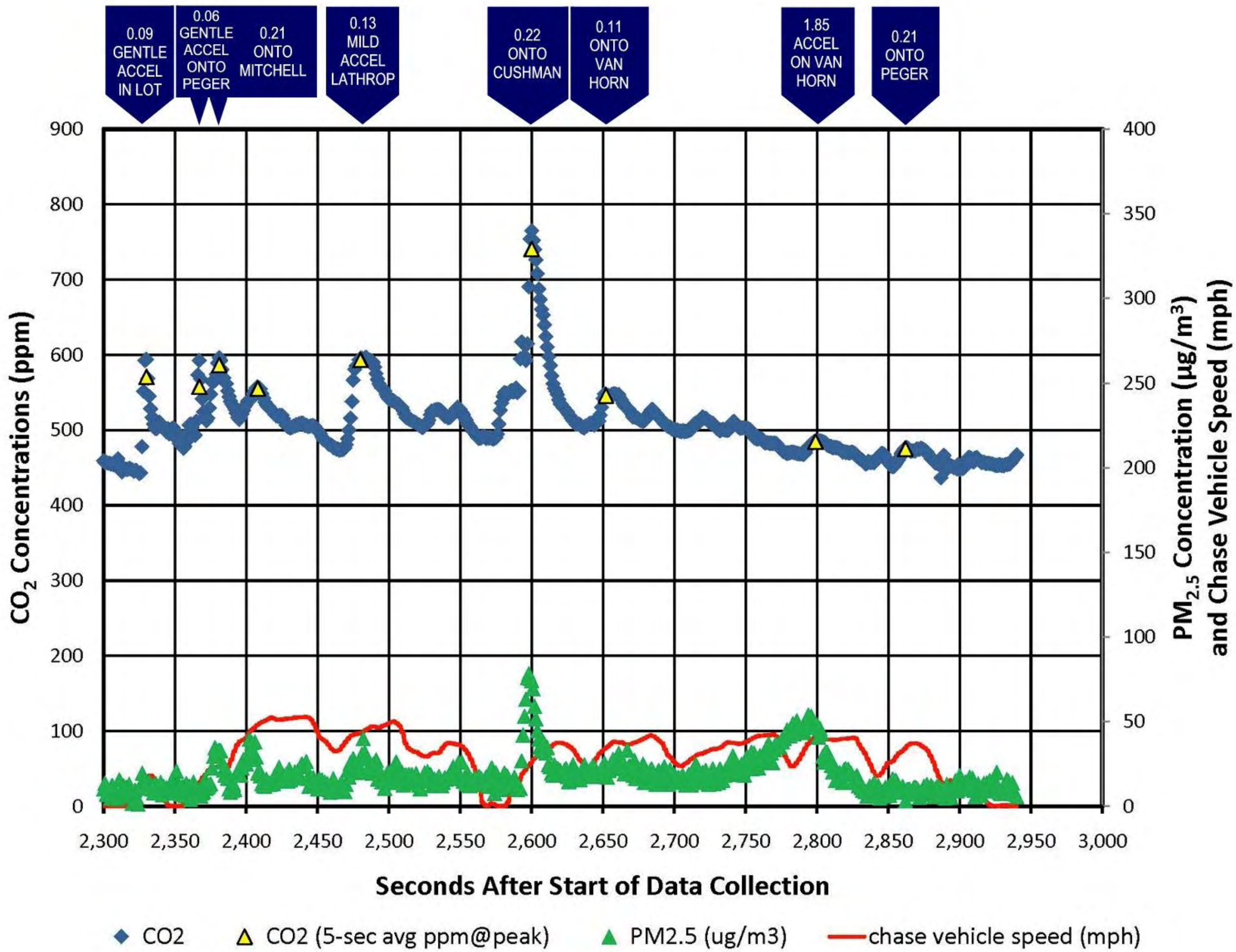


Figure 3-2
Plume Following of the High-Emitting Carbureted Toyota Pickup (continuation)



thing was done for the other five dyno-tested vehicles. For each vehicle, the ratios from the first (cold) drive and (presumed warmed up) second drive were compiled in separate bins.

Next, a methodology was developed by estimating the threshold ratio that best distinguishes the two normal emitters from the four high emitters. The ratio chosen was that of the on-road measured $PM_{2.5}$ concentration (uncalibrated DataRAM mass concentration output, expressed in ug/m^3) to the on-road measured CO_2 mixing ratio (ppm) for each major and distinct* acceleration event. Ten-second averages were used for both numerator and denominator. This ratio is assumed to be proportional to PM emissions indices normalized for fuel consumption,[2] so as to render data for different vehicles more comparable. From inspection of the on-road sampling data, it was clear that the ratios for normal emitters tend to be highest after cold-start (i.e., during the first lap of the test course), while the ratios for high emitters are lowest after they have warmed up (i.e., during the second lap). The problem of discriminating between normal and high emitters was stated as finding the threshold between these values (cold emissions of normal emitters versus warm emissions of high emitters), because that test is where the vehicles would be most similar and the discrimination most difficult.

The threshold was determined by examining the distribution of emission ratios for the individual accelerations of the test vehicles. A normal distribution was fit to the second (presumed warm) drive cycle data for high emitters, excluding the two highest ratios observed, because that was found to give the best fit to the low end of the emissions distribution. A log-normal distribution was fit to the first (cold) lap data for normal emitters because that was found to give the best fit to the data between ratios of 0.20† and 0.50, where the desired threshold would clearly be located. Calculations were then performed to understand the distribution of classification errors as the threshold was varied. At any threshold value, some high emitters will be missed because their emissions ratio is below the threshold, while some normal emitters will be counted because their ratios are above. This threshold depends not only on the distributions of emissions for both groups, but also upon an *a priori* estimate of how often normal and high emitters will be encountered (i.e., the high emitter fraction in the fleet). When the errors of commission offset the errors of omission, the resulting threshold will give an unbiased estimate of the high emitting fraction in the fleet.

3.2 Plume-Following of Other On-Road Vehicles

It was necessary to analyze the randomly selected vehicle plumes collected over several weeks by Borough staff in a somewhat different manner, for two reasons. First, video analysis of all onroad plume following would have been prohibitively time-consuming and costly; second, a different level of detail was provided by the drive teams' data collection. Specifically, in the plume-following of pseudo-randomly selected targets, the

* Only events where the observed CO_2 peak in the dataset could be identified unambiguously as coming from the target vehicle without obvious interferences from other sources were included.

† Formally, the ratio is of a mass concentration divided by a mixing ratio, so the units are in ug/m^3 of $PM_{2.5}$/ppm of CO_2; however, for convenience, the units have been omitted in this discussion.

drive team recorded approximate CO_2 and $PM_{2.5}$ peaks, along with times and license plates (where possible). With this information, the approach outlined below was used to associate individual vehicle acceleration events with CO_2 plumes in the data record.

1. Using the operator's transcribed notes for each recorded acceleration event, a time window was identified within which the acceleration CO_2 plume was expected to lie.

2. The peak CO_2 concentration within the time window was identified and a check was made that this matched, at least approximately, the recorded CO_2 peak for the event (the matches were generally very close).

3. The ten-second average CO_2 concentration centered on the plume was computed.

4. The background CO_2 concentration (estimated as described earlier for the dyno-tested vehicles) was subtracted from the peak.

5. Using the same small time offset found in the analysis of plume-following data for dyno-tested vehicles, the timing and time-centered ten-second average $PM_{2.5}$ concentration was determined.

6. The ratio of average background-corrected $PM_{2.5}$/ CO_2 was calculated.

Up to this point, the approach for sampling vehicles from the general population provided one or more ratios for each vehicle plume logged. The next steps involved identifying any instances with multiple "hits" of the same vehicle and selecting only the latest hit (so as to capture the vehicle in the most warmed up state). In addition, a license plume lookup was performed on the vehicle registration database in order to obtain detailed information about each vehicle type, including make, model, model year, vehicle identification number (VIN), fuel type, etc. Finally, a VIN-decoder was applied to obtain yet more information about each vehicle.

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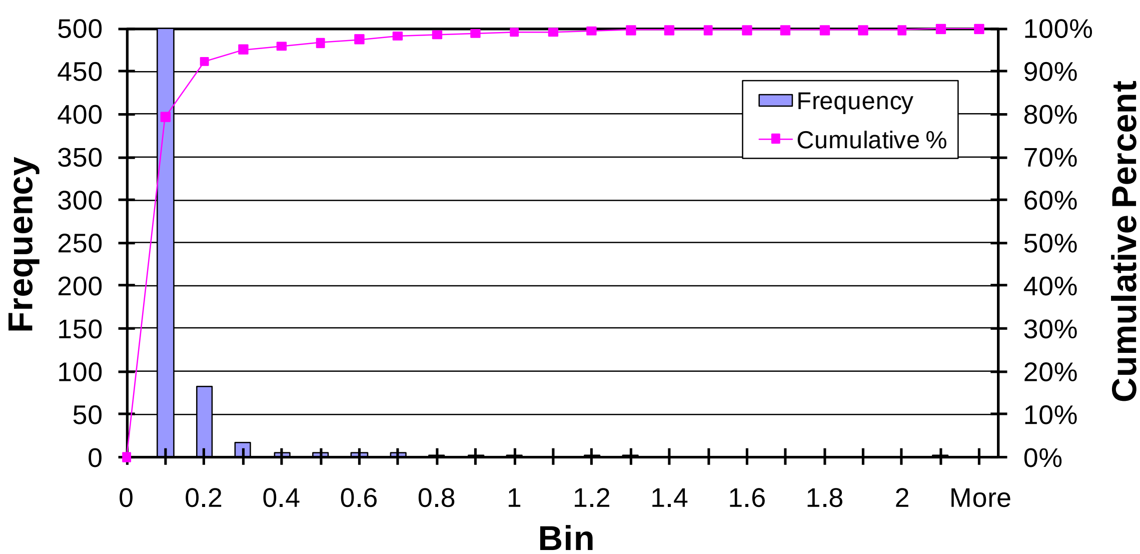
4. PLUME-FOLLOWING RESULTS

Over a period of 15 days of on-road data collection, the on-road plume-following provided about 89 hours of measurements, from which 1,188 significant target vehicle accelerations with associated CO_2 plumes and $PM_{2.5}$ concentrations were identified. (Time plots showing the resulting measurements and identified CO_2 plume matches are provided in Appendix E.) Of these, 994 had associated license plates, of which 862 (87%) could be matched to Department of Motor Vehicle registrations. After removal of duplicate measurements of the same vehicles and vehicles chosen *a priori* for special purpose sampling, 630 plume captures remained; of these, detailed lookup information could be obtained for 549 vehicles. The distribution of plume ratios (less background) for the 630 captured plumes is shown in Figure 4-1.

Figure 4-1
Distribution of $PM_{2.5}/CO_2$ Ratios
(630 On-Road Plume Captures)



To begin the analysis, it was assumed that, based on the knee of the distribution curve, approximately 5% of the fleet consisted of high emitters. Given this input, a threshold ratio of 0.24 was found to equalize the classification errors. When this threshold was applied to the full 630-vehicle plume-following dataset, a larger fraction of vehicles (7.2%) were classified as "high emitters." After iterative adjustments, it was determined that a threshold ratio of 0.215 would be consistent with having 7.5% of vehicles in the fleet being high emitters, while both equalizing classification errors and matching the classification of vehicles in the full on-road dataset. This number—7.5% of the fleet—is the best, unbiased estimate of the high emitter fraction that can be developed using the data. The estimate is subject to substantial uncertainty given the small number of test vehicles that were followed and used to develop the threshold. A formal error analysis was not performed for the high emitter fraction, but the one standard deviation range is likely to be ± 2% (i.e., 5.5% to 9.5% high emitters) and could be larger.

Additional information about the on-road fleet was inferred from the associated license plate lookups and VIN decodes, and supplemented here by information provided from Borough staff notes and information from other sources. However, several caveats apply, as noted below.

- DMV lookups sometimes yielded fuel types for particular vehicles that conflicted with VIN decode. Such conflicts were resolved by consulting Borough staff notes and various knowledgeable sources, and the resolutions in all cases favored the VIN-based information (which was also much more detailed).

- The DataRAM's response to atmospheric PM (on which the measurements are in part based) can vary according to emission source types and environment, and any comparisons of the measured ratios across source types are therefore subject to this additional uncertainty.

With these cautions in mind, Figure 4-2 compares the relative $PM_{2.5}/CO_2$ ratios observed for the various target categories. The figure lists three broad categories of vehicle types, four truck/fuel combination categories, and two fuel types. For each vehicle and fuel category, the mean ratio for each category is plotted as a bar, labeled with the mean value of the ratio and with error bands showing the 95% confidence interval (+ two standard deviations) of the mean.

Outlined below are several observations from the data.

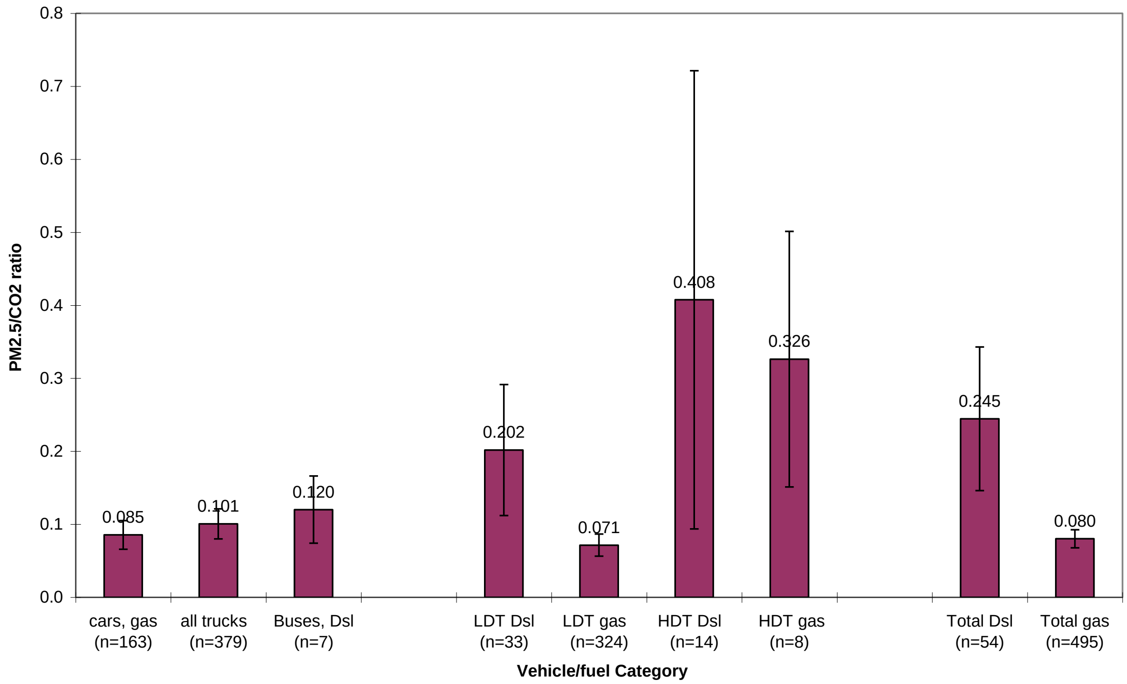
- The highest average emission ratio was for heavy-duty Diesel trucks (0.408), closely followed by heavy-duty gas trucks (0.326); these two categories were statistically indistinguishable from each other.

- Notwithstanding the above, the next highest average emission ratio was for Diesel-powered vehicles (0.245), which was about 3 times that for gasoline powered emissions vehicles (0.080) ($p < 0.00\%$).

- The average emission ratio for light-duty Diesel trucks (0.202) was about 3 times that for light-duty gas trucks (0.071) ($p < 0.00\%$).

- The average emission ratio for heavy-duty gas trucks (0.326) was about 4.5 times greater than that for light-duty gas trucks (0.071) ($p<0.00\%$).

Figure 4-2
Avg. $PM_{2.5}/CO_2$ In-plume Ratios for On-road Accelerations in Selected Categories



Note: n = 549 identified vehicles with known characteristics, no repeats; error bands show +2 standard deviations

The average emission ratio for light-duty gas-powered trucks was comparable to that for (gas-powered) cars and Diesel buses.

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