A Report from the University of Vermont Transportation Research Center

The On-Board Tailpipe Emissions Measurement System (TOTEMS): Proof-of-Concept

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The On-Board Tailpipe Emissions Measurement System (TOTEMS): Proof-of-Concept

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A Report to the UVM Transportation Research Center

The University of Vermont School of Engineering:

Britt A. Holmén, *Associate Professor & Principal Investigator*

Mitchell Robinson, *Graduate Research Assistant*

Karen Sentoff, *Graduate Research Assistant*

Paul Montane, *Graduate Research Assistant*

Resource Systems Group, Inc.

Kevin Hathaway, *Senior Statistician and GIS methodologist*

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1 Introduction

An on-board tailpipe emissions instrumentation system was designed, assembled and tested as proof-of-concept for the University of Vermont's Transportation Research Center (TRC) Signature Project #2 "real-world" vehicle emissions data collection effort. This report summarizes the measurement system's status as of June 2009 and demonstrates that the study team can reliably collect on-board emissions/vehicle performance data. The purpose of the new instrumentation package is to collect real-world exhaust emissions for regulated (CO, HC, NOx) and unregulated (CO_2, air toxics, particle number) pollutant species as well as vehicle operating parameters, all at 1Hz temporal resolution, while a test vehicle is driven on the road network in Chittenden County, Vermont. Future data collected using the on-board system will be used to model the modal emissions of alternative vehicles. This report documents (i) the instrumentation system's components and the research team's proposed data collection methodology; and (ii) presents initial data sets collected by quantifying real-world emissions from a 1999 Toyota Sienna minivan that was used in previous studies conducted by the PI. Unlike previous studies conducted by the PI (see Section 8 references for more detail), however, the new instrumentation package collects: (i) the full *number distributions* of particle emissions using a particle spectrometer instrument that was not available previously; and (ii) quantifies *mobile source air toxic* (MSAT) gaseous emissions in addition to criteria pollutant (CO, NOx, HC) and greenhouse gas (CO_2, N_2O, CH_4) using a high-speed FTIR instrument specifically designed for on-board vehicle exhaust testing.

This report summarizes initial measurements made by the Signature Project #2 study team using **T**he **O**n-board **T**ailpipe **E**missions **M**easurement **S**ystem (hereafter, "**TOTEMS**") on-board the Toyota Sienna minivan as the "proof-of-concept" vehicle prior to initiating testing of two Toyota Camry study vehicles: one hybrid and one conventional. The Camry data will be used to build the first second-by-second, real-world emissions database for hybrid and conventional light-duty vehicles under cold climate and hilly terrain conditions experienced in Vermont.

As the data in this report document, TOTEMS is a fully functional set of instrumentation developed for quantifying tailpipe gas and particle pollutant concentrations, exhaust flow rates, exhaust temperatures, sampling temperatures, vehicle position, engine operating behavior, ambient conditions, and instrumentation condition. All instrumentation is powered by an on-board battery power supply system to prevent artificial loads on the vehicle engine.

Beginning on April 24, 2009, the instrumented vehicle and on-board emissions equipment was stored in the newly renovated Transportation / Air Quality Laboratory ("TAQ Lab") in Perkins 104C on the University of Vermont campus. This new laboratory space enables all of the TOTEMS setup, including all sampling train lines and power and communications cables to remain intact between individual sampling runs thereby preventing unnecessary changes to the setup over a sampling period. For the data collected here, however, some instrument malfunctions led to differences in the suite of fully operating instruments during the six Proof-of-Concept runs summarized in Table 1-1. Integer run numbers in Table 1-1 represent successful data collection with the full suite of vehicle operating and emissions instruments. Two other runs (1.5 and 1.75) were completed while the FTIR gas instrument was down. These QA/QC tests were conducted to quantify the particle spectrometer's sensitivity to road vibration (Run 1.5) and to evaluate the capabilities of a new tiltmeter/ accelerometer for real-time road grade measurements (Run 1.75).

Table 1-1. Proof-Of-Concept Driving Runs Completed using Toyota Sienna Minivan between April 1 and May 22, 2009.

Date	Run No.	Phases collected	Run Start	Run End	Run Description	Total Run Time	Battery Status	Average T (°C)	Average RH (%)
01-Apr-09	**1.00**	*pre QA/QC* *warm-up* *run* *post QA/QC*	14:30:22	16:14:03	Complete Run: FTIR lost much of its signal at midpoint of run, T2 malfunctioned	1:43:41	Run too long, cut short because battery voltage dropped below 11.6 volts	9.17	58.40
12-May-09	**1.50**	***Vibration Testing Only***	14:08:58	15:39:00	New route, Partial Run: Collected EEPS and CPC data over entire run with HEPA's on the inlets as well as ScanTool, GPS and Labview data	1:30:02	Batteries OK	15.32	39.61
14-May-09	**1.75**	***Tiltmeter & Vehicle Operation Only***	12:00:00	13:20:58	Partial Run: **No emissions instruments included**. Test of tilt meter and included ScanTool, Labview and GPS data	1:20:58	Batteries OK	14.93	69.40
17-May-09	**2.00**	*pre QA/QC* *cold start* *warm-up* *run* *post QA/QC*	15:31:38	16:37:17	Complete Run: FTIR lost much of its signal at midpoint of run. Problem determined to be caused by condensation (addressed and now fixed) GAR GPS would not acquire signal	1:05:39	Batteries OK: pre-run voltage = 12.45 post-run voltage = 11.88	18.77	28.42
21-May-09	**3.00**	*pre QA/QC* *cold start* *warm-up* *run* *post QA/QC*	15:42:38	16:49:12	Complete Run: CPC malfunctioned because of high ambient temperatures. GAR GPS would not acquire signal (problem pinpointed and resolved)	1:06:34	Batteries OK: pre-run voltage = 12.46 post-run voltage = 11.91	33.96	23.41
22-May-09	**4.00**	*pre QA/QC* *cold start* *warm-up* *run* *post QA/QC*	14:14:36	15:22:30	Complete Run: no instrument malfunctions	1:07:54	Batteries OK: pre-run voltage = 12.44 post-run voltage = 11.81	23.21	42.10

2 Methods: On-board Instrumentation Overview

2.1 Instrument Power Supply

An on-board battery system is used to power all instruments without drawing electrical power from the test vehicle itself, which would add load to the engine and thereby affect emissions from the tailpipe. Although the additional weight of the batteries adds load to the vehicle's engine during acceleration and climbing, this added load can be compensated for by simply expressing it as the difference in weight between a stock vehicle and our loaded test configuration.

A pair of AGM (Absorbent Glass Mat) sealed lead-acid batteries provides the instrument power. This variety of battery is more durable, has a longer life-span, and is safer than other heavy-duty rechargeable battery types. The batteries are charged from utility power inside the TAQ Lab. Once the vehicle leaves the TAQ Lab, the batteries supply DC power to the inverters. The inverters then convert the DC battery power into AC power for use by the instruments, effectively providing a temporary power source that is equivalent to the standard 120 Volt, 60 Hz utility power that the instruments are designed to use.

Standard Operating Procedures (SOPs) documentation written by the project team describes the use (and daily maintenance) of the batteries, inverters, and chargers for the on-board vehicle tailpipe data collection. These detailed SOPs are available upon request from the PI.

2.1.1 Battery Life and Test Plan Constraints

Battery run time must be considered when determining both the run length and the number of runs that can be completed in one day. Through in-lab battery tests and from on-road data collection, 120 minutes was determined to be the maximum time the complete system should be run before battery recharging is required. This time was determined because 120 minutes is the TOTEMS operating time when the batteries drop below the 11.60 volt 60% battery power remaining threshold. The AGM batteries must not drop below this threshold in order to maintain their long-life. Because the driving route – including warm-up – takes about 90 minutes to complete, it will be challenging to complete more than one full run per day. Recharging the batteries takes about 6 hours, so the only opportunity to collect two runs in a day, including individual quality assurance/quality control (QA/QC) samples for each run, would be to collect the A.M. peak and P.M. off-peak. This scheduling will demand a considerable time investment on study team personnel for each run. Therefore, it is recommended that, for long-term sustainability of the sampling team, only one run be collected per day in the full study.

2.2 The On-Board Tailpipe Emissions Measurement System (TOTEMS)

The TOTEMS emissions measurement setup pulls engine exhaust from the tailpipe adapter (Figure 2-1) through the 191°C heated line at an exhaust sample flowrate of 13 liters/min (Lpm). At the end of the heated line is a 4-way fitting that splits the flow of undiluted exhaust: 12 Lpm to the FTIR and 1.0 Lpm to the particle measurement dilution system followed by both the EEPS and CPC (Figure 2-2).

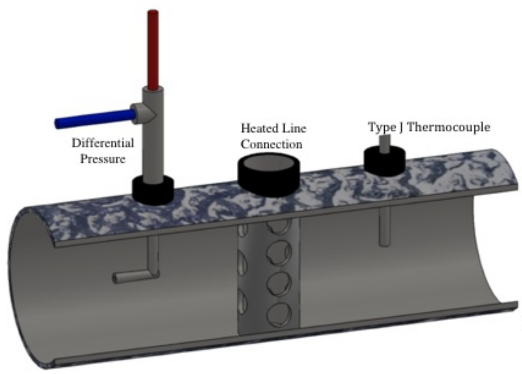

Figure 2-1. Schematic of the tailpipe adapter (TPA) that attaches to the test vehicle's tailpipe and enables exhaust flow rate and exhaust temperature collection, as well as transfer of the exhaust sample to each of the emissions instruments.

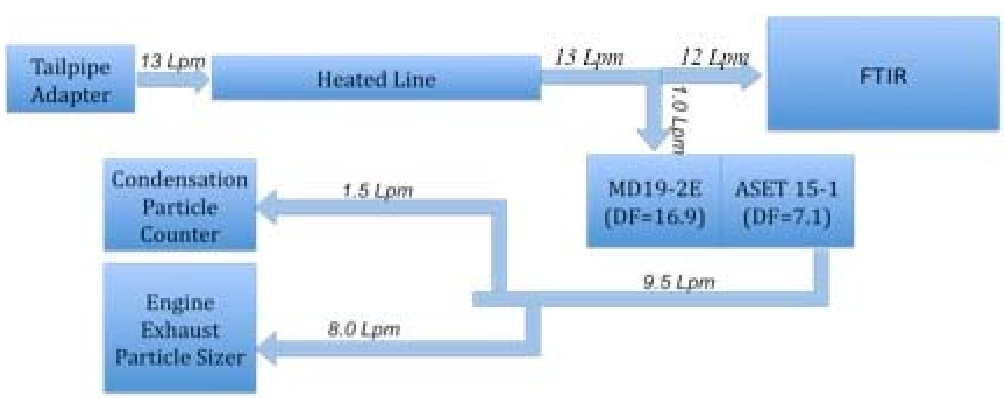

Figure 2-2. Overview of TOTEMS raw (for gases) and diluted (for particles) exhaust sample transfer lines with associated flow rates and dilution factors (DF).

2.3 On-board Instruments

Table 2-1 summarizes the sensors used to record data during vehicle test runs. Data from the accelerometer, differential pressure(via a pitot tube) sensors, thermocouples and MD19-2E monitoring pins are all obtained from Data Acquisition cards (DAQ) through a Labview interface. Data from all other instruments are collected through instrument-specific software via RS-232 serial cables. Two computers are run to collect all real-time data (1) the Dell OptiPlex GX620 desktop "Emissions PC" is outfitted with two data acquisition cards and 5 serial ports; and (2) for the high-speed FTIR instrument only, a special MKS Dell Latitude D630 laptop is equipped with direct Ethernet connection to the instrument.

Brief descriptions of these instruments are given below. More detailed information is found in the SOP documentation for each instrument that is available from the PI upon request.

Table 2-1. TOTEMS Instrument Descriptions

Instrument	Make / Model	Instrument Acronym	Measurement Rate	Purpose
Engine Exhaust Particle Sizer Spectrometer	TSI, Inc./3090	EEPS	10 Hz	Size and count the particles (5.6 to 560 nm)
Ultrafine Condensation Particle Counter	TSI, Inc./3025A	UCPC	1 Hz	Count total (3nm to 3um) particles
MD19-2E Rotating Disk Diluter	Matter Engineering/379020	RDD	1 Hz	First stage of dilution (DF = 16.9)
Air Supply Evaporation Tube 15-1	TSI, Inc./379030	ASET	N/A	Second stage dilution (DF = 7.1)
Fourier Transform Infrared Spectrometer	MKS/MG2030HS	FTIR	5 Hz	Quantify 27 gaseous species
Type J thermocouple	Omega/GJMQSS-125E-3	N/A	1 Hz	Tailpipe exhaust temperature
Type T thermocouple	Omega/GTMQSS-125E-2	N/A	1 Hz	Exhaust temperature at (i) end of heated line and (ii) at FTIR inlet
Accelerometer	Crossbow/CXLO2LF3	N/A	1 Hz	Records acceleration in x, y, and z directions
Scan Tool	AutoEnginuity	SCN	1 Hz	Record engine operating parameters
Garmin GPS Reciever	Garmin/GPS16-HVS	GAR	1 Hz	Records vehicle location
Geologger	Geostats/DL-04, Ver. 2.4	GEO	1 Hz	Vehicle location (backup)
Pitot Tube & Differential Pressure Transducers	United Sensor Corp/ Type PC Omega Engineering/ PX-277	N/A	1 Hz	Records exhaust flowrate
Tailpipe Adapter	Custom Built	N/A	N/A	Connects instruments to tailpipe for exhaust measurement
Video Camera	Canon/Optura 30	N/A	N/A	Record audio and video of run
Relative Humidity and Temperature Sensors	HOBOware/pro v2 U23-001	RHT	1 Hz	Collect in- and out-of-vehicle relative humidity and temp
FTIR Laptop	Dell/Latitude D630	N/A	N/A	Records concentration and spectra from the FTIR. Intel Core 2 Duo CPU, T7700 at 2.40 GHz, 1.0 GB of RAM
On-Board Emissions PC	Dell/Optiplex GX620	N/A	N/A	Records all data except the FTIR output. Intel Pentium D CPU, 3.60 GHz, 3.49 GB of RAM

2.3.1 Accelerometer

The Crossbow 3-axis accelerometer unit measures real-time vehicle acceleration in the x, y, and z directions, where the x-axis is "forward" (in the vehicle's body frame coordinate system), y is "lateral", and z is "vertical". This data is recorded by the LabView software that runs on the "Emissions PC" (a Windows PC that remains within the vehicle during testing). The significance of the vehicle acceleration data is to provide a profile of the kinetic state of the vehicle over time with which to compare the data on tailpipe emissions. In-house SOP documentation gives Signature Project #2-specific procedures for installation, software setup, and data acquisition for this sensor.

2.3.2 On-Board Diagnostic (OBD) Vehicle Communications

The ScanTool used for these Proof-of-Concept runs was the "AutoEnginuity ScanTool OBD-II Connector". This device is attached to the On-Board Diagnostics (OBDII) communication system of the vehicle, and records data on user-selected parameters directly to the on-board computer using dedicated scantool data acquisition software "AutoEnginuity ScanTool 4.1.0". Parameters recorded for Proof-of-Concept runs were: vehicle speed (miles/hr), engine RPM, throttle position (%), and Mass Air Flowrate (Lb/min) to the engine. Mass Air Flowrate (MAF) is used to compute air-to-fuel ratio for second-by-second fuel consumption rate (see details in Section 4.4 below). It should be noted that the 1999 model year Proof-of-Concept vehicle's computer limited the number of vehicle parameters that could be logged at 1Hz temporal resolution. For future studies, newer vehicles with faster network speeds should enable logging of more vehicle parameters every second.

2.3.3 Garmin GPS and Data TimeStamp Synchronization

The Garmin GPS16-HVS receiver provided real-time vehicle location information and was used to synchronize the two computer clocks. From the data available through this sensor, the vehicle velocity, direction, and acceleration could also potentially be determined, but with much less accuracy than is available from other instruments. Therefore, in this application the GPS sensor is only used for determining the vehicle's position (Latitude and Longitude). The position enables use of GIS data so that vehicle performance can be related to road characteristics.

The Garmin antenna is Wide Area Augmentation System (WAAS) enabled. WAAS is a type of GPS correction that uses precision base stations to measure GPS error and then broadcast corrections via satellite. According to the Vermont Center for Geographic Information (VCGI), WAAS has limited value in Vermont, however, due to the large distance to the nearest base station. Therefore, post processing is used as the preferred method of correction. The software used to collect data from this sensor was Fugawi version 3.1.4.881.

2.3.4 Geostats Geologger

The Geologger is an automated GPS data-recording device. It is generally less precise in comparison to the Garmin GPS unit, but tends to have less missing data. It is therefore used as an ancillary (or backup) sensor to fill in gaps in the Garmin GPS data. The Geologger was a GeoStats GPS Data Logger, Model DL-04, Version 2.4, and the software used to acquire the data was Geologger Download Utility 4.0.9.

2.3.5 Pitot Tube and Tailpipe Adapter

The tailpipe adapter (TPA, see Figure 2-1) is a custom-built fitting used to connect a collection of sampling and data lines to the vehicle's exhaust pipe. Instruments that attach to the TPA include:

a. Pitot Tube and Differential Pressure Transducers, for exhaust flow rate
b. Thermocouple, for exhaust temperature
c. Heated Transfer Line, for gas and particle emissions

Because both the gas and particle instruments record their measurements as concentrations per unit volume, the exhaust flow rate (or exhaust volume/time) is needed to calculate second-by-second exhaust emission rates (mass (or number)/time). The pitot tube (United Sensor Corp, Type PC) differential pressure reading is used to provide the needed measurements on the exhaust flow rate. LabView 7.0 captures the data from the four variable range differential pressure transducers (Omega Engineering Model PX-277) that are connected via manifold to the static and dynamic pressure ports of the pitot tube. Regular calibration of the pitot tube using a Sierra Instruments Model 620S Fast-Flo Insertion Mass Flow Meter determines the voltage-to-flow rate relationships (see details in Section 4.2) and is an integrated part of the test procedures.

2.3.6 Thermocouples

The temperature sensors used for this application are either Type T or Type J exposed junction thermocouples (Omega Engineering), which each come with a 2-inch long, 0.125-inch diameter probe. Type T thermocouples are used at (i) the 4-way fitting connected to the heated transfer line, and (ii) at the inlet of the FTIR gas instrument. Type T thermocouples operate normally between -200 and 300°C with a 1°C limit of error. A Type J thermocouple is used on the tailpipe adapter because of its higher operating range (normally between 0 and 700˚C with a 2˚C limit of error). This variety of thermocouple is resistant to corrosion and electrical interference due to its non-magnetic Copper-Constantan alloy conductors and shielded thermocouple wiring. The sensitivity of this device's output is 43 microV/^{o}C. An exposed probe tip is used with the thermocouple to provide the fastest response, but this makes it somewhat more fragile in comparison to a sheathed-tip thermocouple.

2.3.7 Relative Humidity and Temperature Sensors

TOTEMS uses two identical Onset HOBO U23-002 Data Logger remote operation relative humidity and temperature sensors; one is located inside the vehicle and the other is attached outside the vehicle. The sensors monitor and record the air relative humidity and temperature at a time resolution of 1 second.

2.3.8 Fourier Transform Infrared Spectrometer

The MKS Inc. MultiGas 2030 High-Speed Analyzer Fourier Transform Infrared (FTIR) Spectrometer is used to quantify gas species in tailpipe exhaust . The minivan's exhaust composition was analyzed based on the manufacturer's calibrations of a predetermined set of the 27 compounds listed in Table 2-2 at a temperature of 191^{o}C. Therefore, prior to measurement, the exhaust sample passes through a Atmoseal Heated Line IGH-120-S6/X-G13 heated transfer line from the tailpipe adapter to the inlet of the FTIR instrument.

Sample flow through the sample cell of the FTIR instrument at 12 LPM allows for one-second-sample turnover for second-by-second gas compound analysis. The 12 LPM flow is achieved by drawing exhaust through a series of filters and into the FTIR unit by a SKC Leland Legacy personal sampling pump. Filters are used at the inlet of the instrument to prevent particulate from entering the sample cell, which contains delicate gold-plated mirrors and potassium bromide windows. The filters include two inline filter housings containing diesel grade filters rated at 2 micron and 0.01 micron.

The FTIR passes infrared light through the exhaust sample over a 5.11-meter path length. Each compound within the sample has a distinct light absorption fingerprint in the IR spectra and is quantified at a specified wavelength by the MKS software. Detection limits vary between compounds, depending on the calibrations existing within the MG 2000 software package and the absorbance spectrum of each compound relative to other interfering species. For the Proof-of-Concept tests, manufacturer recommended suite of gas species was analyzed. It should be noted that raw infrared absorbance spectra are saved and can be re-analyzed at a later date when new gas calibration data become available. Appendix A has manufacturer upper and lower calibration standard limits and quantification regions for each gas species.

Table 2-2. Emissions species quantified by FTIR.

Gas Species	Unit
1,2,4-Trimethylbenzene	ppm
1,2-Propadiene	ppm
1,3,5-Trimethylbenzene	ppm
1,3-Butadiene	ppm
2-Methyl-2-Butene	ppm
2-Methylpropene	ppm
Acetylene	ppm
Methane	ppm
Carbon Monoxide (1 of 2)	ppm
Carbon Monoxide (2 of 2)	%
Carbon Dioxide	%
Ethane	ppm
Ethanol	ppm
Ethylene	ppm
Formaldehyde	ppm
Water	%
IsoOctane	ppm
m-Xylene	ppm
Methanol	ppm
Nitrous Oxide	ppm
Ammonia	ppm
Nitric Oxide	ppm
Nitrogen Dioxide	ppm
Octane	ppm
Propylene	ppm
Propyne	ppm
Sulfur Dioxide	ppm
Toluene	ppm

2.3.9 Two-Stage Exhaust Dilution System: MD19-2E and ASET 15-1

The dilution system for particle measurement includes two separate components – the Matter Engineering, Inc. MD19-2E Rotating Disk Mini-diluter and the Air Supply Evaporation Tube (ASET 15-1) – designed to work together, providing first stage (MD19-2E) and second stage (ASET 15-1) dilution in one self-contained device. Where the MD19-2E's main purpose is to dilute the raw exhaust gas, the ASET 15-1 provides the flow rate required by the connected particle instruments. This second dilution stage is necessary due to the 5 Lpm flow rate limit of the MD19-2E.

The ASET 15-1 draws diluted exhaust from the MD19-2E at a constant flow of 1.5 Lpm (± 3%). This dilution stream is sent through a HEPA filter, ensuring no outside influence from ambient particulate matter. It is also heated to 120˚ Celsius to prevent water from condensing out of the gas when the dilution air mixes with the raw exhaust gas. Pockets of raw gas from the MD19-2E are mixed with the steady clean, ambient air dilution stream, creating the first stage of diluted gas with a dilution ratio of 1:16.9. The diluted gas then enters the evaporation tube (ET) which is also heated to 120˚ Celsius. At the outlet of the ET, the second stage of dilution takes place with a dilution ratio of 1:7.1, resulting in the total dilution ratio of 1:120 (one part raw exhaust to 120 parts particle-free ambient air).

2.3.10 Engine Exhaust Particle Sizer (EEPS) Spectrometer

The particles are counted (± 20% accuracy) and sized (± 10% accuracy) with the TSI, Inc. Model 3090 Engine Exhaust Particle Sizer (EEPS) spectrometer. The EEPS operates using the theory of electrical mobility. As particles flow into the instrument, they pass through a positive charger which applies a positive charge to the particles, reducing the potential for overcharging by the negative charger. The particles then flow past the negative charger – which applies a predictable charge based on particle size – and then enter the electrometer column. In this column, there are 24 electrometer rings, 22 of which actively measure and the other two act as spacers at the top of the column. The 22 active rings record across 32 different particle diameter channels from 5.6 to 560 nanometers (channel widths are provided in

Table B-1 in Appendix B). The midpoint of each channel is the reported particle size (or mobility diameter) for a given channel. The EEPS can record particle number distribution data at a rate of 10 Hertz, but reported values for Signature Project #2 are at a 1 Hertz rate. The 1 Hertz measurements are simply the discrete average of all measurements within a given second and are recorded to the on-board emissions PC using TSI EEPS version 3.1.0 software .

Maximum total concentration (i. e., the sum over all particle channels) limits are not provided for the EEPS. This is because the maximum concentration for each individual channel is of greater importance, and the maximum is different for each channel. Figure B-1 in Appendix B graphically displays the concentration limits for all 32 channels. In general, the maximum concentration for channel 1 is 1 x 10^7 #/cm^3 and decreases linearly on a log scale to 1 x 10^5 #/cm^3 for channel 32. If the maximum concentration is exceeded during sampling, the concentration reported for that specific channel is clipped at the maximum value.

Two types of errors are taken into account in the EEPS instrument software. The first error type deals with the potential for particles of similar sizes to receive different charges, resulting in particles of the same size being classified as different sizes. The second error type deals with the lag time between the measurement of different size particles. Particles that enter the instrument at the same time will not strike the electrometer rings at the same time if they are different sizes because of the physical geometry of the instrument. Smaller particles hit the top of the column first while larger particles continue to fall towards the bottom and strike the electrometers at a later time. An inversion algorithm in the software accounts for both of these error types.

2.3.11 Ultrafine Condensation Particle Counter

A TSI, Inc. Model 3025A Ultrafine Condensation Particle Counter (UCPC) was used in parallel with the EEPS to count the total particles in vehicle exhaust every second. This measurement was made partly due to accuracy limitations of the EEPS, but also to validate the EEPS concentration, to compare results to previous on-board studies and to validate EEPS response to sudden concentration changes. The UCPC counts the particles in the range of 3 to 3000 nanometers with a detection efficiency of 90% at and above 5 nanometers. The data is recorded to the computer at 1 Hertz using TSI AIM version 8.1.0 software.

The UCPC counts particles by first sending the aerosol through a saturator filled with butanol-laden air. The butanol subsequently condenses onto the particles, growing them to a light-scattering detectable size. After the aerosol passes through the condenser chamber, it passes through a laser optical detector that counts the particles. The total concentration limit on the UCPC is 9.99 x 10^4 #/cm^3.

3 Methods: Data Collection

Individual emissions tests consist of a single driver operating the vehicle under real-world driving conditions over a specified driving route. Prior to beginning the route, a series of quality assurance/ quality control (QA/QC) measurements and operations are performed in order to collect accurate instrument and vehicle baseline data for each run. This section briefly summarizes these data collection procedures. More detailed information is available in the Standard Operating Procedure (SOP) documents.

3.1 Pre- and Post-Run Quality Assurance/ Quality Control Activities

A "full run" consists of 5 phases as follows. For the Proof-of-Concept runs, Table 3-1 summarizes the start and end times of each of these phases.

Pre-run QA/QC: Collection of instrument blanks and tunnel blanks. Vehicle engine is off.

Cold Start: Instrumentation collects emissions during engine start. The duration of this phase depends on ambient temperature.

Warm-Up Run: A ~ 3 mile drive, including a steep upgrade is used to bring the vehicle's engine coolant to a specified temperature that indicates the engine is operating in stabilized mode.

Run: The real-world driving route is run, collecting data from all TOTEMS instruments. As discussed in Section 3.2, the route consists of three types of driving: urban stop-and-go, highway, and rural/suburban arterial.

Post-run QA/QC: After vehicle engine is off, repeat collection of instrument and tunnel blanks.

Table 3-1. Proof-of-Concept Run Summary of Date and Times for Each Run Phase

Sampling Summary -- START AND STOP TIMES FOR RUN PHASES													
		Pre-Instrument Blank		Pre-Tunnel Blank		Warm-Up		Sampling Run		Post-Tunnel Blank		Post-Instrument Blank	
Run No.	Date	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Start	Stop
1	1-Apr-09	12:37:01	12:47:00	13:08:01	13:18:00	13:19:00	14:41:21	14:30:22	16:14:03	16:44:01	16:44:21	17:05:01	17:15:00
1.5	12-May-09	N/A	N/A	N/A	N/A	N/A	N/A	14:08:58	15:39:00	N/A	N/A	N/A	N/A
1.75	14-May-09	N/A	N/A	N/A	N/A	N/A	N/A	11:59:15	13:20:58	N/A	N/A	N/A	N/A
2	17-May-09	12:42:01	12:52:00	14:30:01	14:40:00	15:15:00	15:31:37	15:31:38	16:37:17	16:56:20	17:06:19	17:31:28	17:41:27
3	21-May-09	14:12:01	14:22:00	14:46:01	14:56:00	15:15:16	15:42:37	15:42:38	16:49:12	17:06:39	17:16:38	17:40:56	17:50:55
4	22-May-09	12:46:01	12:56:00	13:40:00	13:49:59	14:01:27	14:14:35	14:14:36	15:22:30	15:39:15	15:49:14	16:11:41	16:21:40

3.2 Driving Route

A driving route incorporating a variety of road types and terrain was selected to incorporate different types of real-world driving conditions. The route, shown in Figure 3-1, consists of a 41-mile loop within Chittenden County, Vermont, that is sectioned into different run "phases".

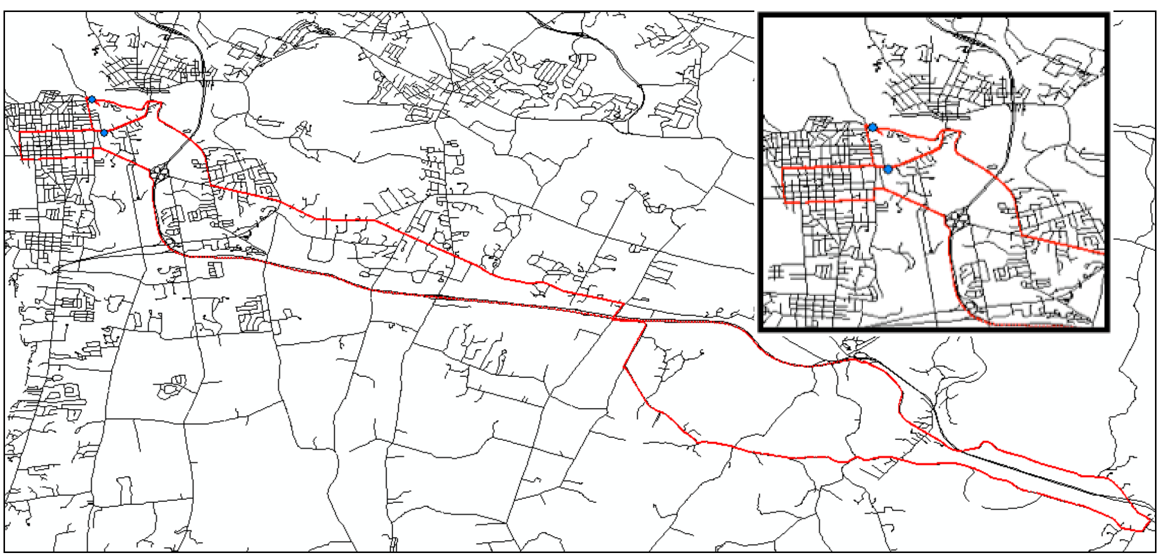

Figure 3-1. Real-world driving route beginning in Burlington, Vermont. Inset shows close-up of downtown Burlington section of route. Red lines indicate the full route and blue dots are the start point on Colchester Avenue and the gas station on Riverside Avenue.

The **Warm-Up** phase begins at the start of the engine after the Pre-Run QA/QC data collection is complete. The driver maneuvers the vehicle on urban streets from the TAQ Lab to the Cumberland Farms gas station on Riverside Avenue, 0.8 miles from the starting point. The **Warm-Up** continues for a total of 2.5 miles.

The **Run** phase is divided into sections, including *urban*, *highway*, and *rural/surburban arterial* driving. The urban driving section continues from 33 Colchester Avenue (sample run starting point), west down Pearl Street, south on Battery Street, and then heading east up Maple Street. Maple Street provides significant sections of elevation gain and provides stop-and-go driving with stop signs at each block. At the top of Maple Street, travel northbound on South Prospect Street to Main Street (westbound) until arrival at the Main Street/Route 2 junction with I-89 completes the *urban* driving phase.

The *highway* driving section begins with the Exit 14 on-ramp heading southbound on I-89. Driving continues on the highway for 10.4 miles to Exit 11 in Richmond.

A section of *rural arterial* roads takes the vehicle through Richmond and Jonesville on Route 2, crossing the Winooski River at Cochran Road. The route loops back towards Richmond on the southern side of the river and continues out on Huntington Road toward Hinesburg Road. Hinesburg Road to East Hill Road provides a section of steep, steady incline. The return trip to Burlington includes a short section of rural roads returning the vehicle to Route 2 in the town of Williston. From there, Route 2 brings the vehicle as far as South Burlington before turning westbound onto Patchen Road. The last significant feature of the route is the hill away from the Winooski River on Colchester Avenue. The **Run** phase ends at 33 Colchester Avenue, but the vehicle continues on past the 33 Colchester Avenue endpoint approximately 0.8 miles more to the gas station on Riverside Avenue. A fill-up at the gas station indicates the amount of fuel used during the course of driving. The detailed full driving directions are provided in Table C-1 in Appendix C.

4 Data Management and Analysis

4.1 MATLAB Programming

A set of MATLAB programs were developed to combine and process the data collected by the TOTEMS instruments. Standard operating procedure (SOP) documents describe the steps to be performed for data management prior to running the MATLAB programs, including required file formats, parameters, file naming, and file placement. The documentation also gives details on operating the MATLAB programs and how to read and interpret the program outputs. The first program's function is to combine the data from the different TOTEMS instruments into a single output file containing all of the raw data from every instrument synchronized according to time stamp. The second program performs calculations on some of the raw data to automate part of the analysis. The calculations that are performed include the following:

1. Exhaust Flow Rate based upon differential pressure sensor data
2. Temperature-compensated Exhaust Flow Rate
3. Fuel Efficiency, based on Carbon Mass Balance using the concentration of CO_2
4. Fuel Efficiency, based on two scantool parameters, MAF and vehicle speed

The procedure for managing the TOTEMS data begins with all instruments being configured to write their data to individual output files. Each of these output files has specific format requirements (i.e. must be in text file format, tab delimited, and have consistent column ordering for the data). At the end of each test, the collection of data files from each instrument is stored in a directory labeled by testing date. The data management program can then be executed for the set of files contained within that directory. The program reads the entire set of data files one line at a time, reformats some of the data, and then prints a single output file having a homogeneous format with all of the data sorted according to the data time stamp. The sorting by time is accomplished by converting each of the original time stamps to integer values in units of *seconds of the year*.

After the raw data has been organized by time stamp and compiled into a single file, the second MATLAB program is used to read this data into a set of matrices and perform "batch" calculations on the data as a means towards providing some automated analysis. The following sections summarize these calculations.

4.2 Exhaust Flow Rate

4.2.1 Raw Exhaust Flow rate

The exhaust flow rate at the tailpipe is calculated using the differential pressure transducer raw recorded voltage information. The four differential pressure transducers used each simultaneously measure a different differential pressure range as shown in Table 4-1 below.

The program preferentially uses the data from the most sensitive pressure sensor (Sensor 4). If Sensor 4 is at its maximum voltage (10 V) value, then the program uses the data from Sensor 3. Similarly, if Sensor 3 is at its maximum, then Sensor 2 is used, and if Sensor 2 is at its maximum, then Sensor 1 is used to compute raw exhaust flow rate. In this way, the data used for flow rate calculations is always based upon the most accurate measurement that was available.

Table 4-1. Differential pressure sensors and their corresponding flow rates based upon pitot tube calibration procedure.

	Volts		Flowrate (L/min)	
	Min	Max	Min	Max
Sensor 1	0	9.498	0	8736.27
Sensor 2	0.023	10	71.51	2486.68
Sensor 3	0.198	10	107.7	1100.09
Sensor 4	6.765	10	190.653	422.114

Calibration equations are derived for each sensor relating the flow rate (Lpm) to the measured voltage assuming a linear relationship during laboratory calibration of the pitot tube system with a Sierra Instruments 620S Fast-Flo Insertion Mass Flow Meter (Sierra Instruments, Monterey, CA). From the best-fit slope and intercept based upon the calibration data collected by each pitot sensor, the volumetric flow rates are expressed as the following *example* equations:

$$Flowrate_1 = (919.801)V_1 \quad (4\text{-}1)$$
$$Flowrate_2 = (242.074)V_2 + 71.51 \quad (4\text{-}2)$$
$$Flowrate_3 = (101.244)V_3 + 107.7 \quad (4\text{-}3)$$
$$Flowrate_4 = (71.549)V_4 + 190.653 \quad (4\text{-}4)$$

The variables V_1, V_2, V_3, and V_4 represent the voltages measured from differential pressure transducers 1, 2, 3, and 4 and corresponding $Flowrate_i$ values are in liters per minute (Lpm).

4.2.2 Temperature-compensated Exhaust Flow rate

The exhaust flowrate calculation is subject to differences in the assumed exhaust temperature and the actual laboratory temperature during pitot tube calibration measurements. A simple calculation (derived from the ideal gas law) adjusts for the actual instantaneous temperature at the tailpipe during sampling:

$$TC\_flowrate = Calculated\_flowrate * (T_1 / 25) \quad (4\text{-}5)$$

The variable T_1 represents the instantaneous (1-sec resolution) measured temperature at the tailpipe in degrees Centigrade.

4.3 Real-Time Fuel Consumption Rate and Fuel Economy Estimates

4.3.1 Fuel Consumption Rate (g/sec) Derived From Carbon Mass Balance

A calculation for the instantaneous fuel consumption rate (gal_{fuel}/sec) of the vehicle can be made via mass balance computations based on carbon species output (specifically in the form of CO_2, the carbon-bearing exhaust gas species of highest concentration; CO and hydrocarbons) per unit quantity of fuel input (gasoline, C_xH_y). The FTIR instrument provides 1Hz measurement of the concentration of CO_2, CO and hydrocarbon species in the exhaust. By determining the proportional relationship between these major carbon-containing compounds in the exhaust and the fuel consumed, the fuel consumption rate can be calculated on a second-by-second basis, using only the measured exhaust concentrations of CO_2, CO and hydrocarbons, engine exhaust flowrate (TC_flowrate) and an assumed gasoline composition

Several assumptions were applied to derive a relationship between fuel consumption rate and exhaust gas composition. The assumed gasoline composition, $C_1H_{1.8}$, and density (6.15 lb/gal) were chosen to be in close agreement with the Code of Federal Regulations value of 2421 grams of carbon per gallon of gasoline (CFR, 1977). It was also assumed that the only significant carbon-containing species in vehicle exhaust were CO_2, CO and hydrocarbons, with the propane measured by FTIR as the proxy for total hydrocarbons (HC).

Equation 4-6 was used to calculated the fuel consumption rate (FCR) based on the calculated exhaust emission rates (g/s) of the three carbon-containing tailpipe constituents and their carbon containing mass fractions.

$$FCR\left[\frac{gal}{s}\right]=\frac{\left(0.273\left[\frac{g_C}{g_{CO_2}}\right]*CO_2\left[\frac{g_{CO_2}}{s}\right]\right)+\left(0.429\left[\frac{g_C}{g_{CO}}\right]*CO\left[\frac{g_{CO}}{s}\right]\right)+\left(0.817\left[\frac{g_C}{g_{HC}}\right]*HC\left[\frac{g_{HC}}{s}\right]\right)}{2421\left[\frac{g_C}{gal}\right]} \quad (4\text{-}6)$$

In Equation 4-6, the gas emission rates [g/s] were computed as the product of the measured FTIR gas concentrations [ppm], and the temperature-compensated exhaust flow rate (L/sec; Equation 4-5) as determined based on exhaust temperature and pitot tube data (see Section 4.2).

4.3.2 Fuel Economy Derived From ScanTool Parameters

The ScanTool provides information at approximately 1 Hz sample frequency on vehicle speed (in miles/hr) and mass air flowrate (MAF) to the engine. These two parameters can be used to give an estimate of the vehicle's fuel economy (miles/gal), assuming constant gasoline density and stoichiometric air-to-fuel ratio during combustion:

$$\text{Fuel\_Economy [mi/gal]} = \frac{VehicleSpeed\left[mi/hr\right]*6.15\left[lb/gal\right]*14.7\left[lb_{air}/lb_{fuel}\right]}{MAF\left[lb_{air}/\min\right]*60\left[\min/hr\right]} \quad (4\text{-}7)$$

MAF represents the mass air flow rate. Because light-duty vehicle air-to-fuel (A/F) ratio is a major determinant of fuel consumption rate, Equation 4-7 only approximates the fuel economy because of the assumption of a fixed stoichiometric A/F ratio.

4.4 Data Transfer to Resource Systems Group, Inc.

After the data collection team assembles the data file into MATLAB, they will upload the file to a website built by RSG. This will allow the UVM user to browse their local computer for the data file. The raw data uploading process will also automatically read the data into an SQL Server database and perform a series of simple error checks and output basic statistics for each run. These statistics can be provided back to UVM as needed.

In preliminary trials of data transfer, RSG observed issues with file delimiters, null columns, and column names. Data storage formats should be decided before RSG receives the file (e.g. string, integer, float, date time etc.). Finally, if UVM has a choice, the empty data flag of "-999" could be left blank.

5 Proof-of-Concept Data Collection and Analysis

5.1 Summary of Proof-of-Concept Runs

A total of six runs were completed for the Proof-of-Concept testing. In addition to the run summaries provided in Table 1-1 and Table 3-1, Tables 5-1 and 5-2 summarize the mean and range of parameters measured for each run (Table 5-1) and the odometer readings, fuel economy and brief run notes (Table 5-2).

Table 5-1. Mean Values of selected parameters for Proof-of-Concept Runs*

Parameter	Units	Run 1	Run 1.5	Run 2	Run 3	Run 4
––––––––––MEAN––––––––––						
EEPS Total Conc.	(#/cm^3)	6670.13	1252.47	3876.24	4164.28	2026.99
CPC Total Conc.	(#/cm^3)	4035.09	0.0471	3168.7	N/A	1788.26
CO	ppm	722.14	N/A	1104.29	598.18	556.50
CO2	%	12.74	N/A	12.9	10.44	10.27
Toluene	ppm	7.16	N/A	6.33	0.69	0.49
1-3 butadiene	ppm	2.09	N/A	1.99	2.04	2.12
formaldehyde	ppm	14.86	N/A	0.38	0.05	0.21
NH3	ppm	12.45	N/A	32.78	32.00	31.30
Acetylene	ppm	4.78	N/A	3.07	1.04	0.67
NO	ppm	172.54	N/A	118.11	107.01	81.84
NO2	ppm	0.42	N/A	0.84	0.48	0.76
In-car Temp	ÞC	13.78	19.22	19.72	35.81	27.01
In-car RH	%	41.08	31.41	26.05	21.44	33.14
Out-of-car Temp	ÞC	9.17	15.32	18.77	33.96	23.21
Out-of-car RH	%	58.4	39.61	28.42	23.41	42.1
Exhaust Temp.	ÞC	206	201	249	229	239
Speed	MPH	32.06	27.28	33.19	31.21	31.17
Acceleration	MPH/sec	-0.01	-0.002	-0.002	-0.003	-0.003
––––––––––RANGE––––––––––						
Acceleration	MPH/sec	-7.0–5.0	-10.0–7.0	-7.0–5.0	-7.0–6.0	-8.5–6.0
Engine RPM	RPM	633–3452	633–4578	634–3891	631–4240	627–4230
Mass Air Flow	lb/min	0.40–8.49	0.41–15.63	0.39–11.91	0.37–11.08	0.40–11.96
Speed	MPH	0.00–70.00	0.00–75.00	0.00–73.00	0.00–73.00	0.00–75.00

* Run 1.5 was particle instrument noise measurement run (both instruments had HEPA filters on their inlets).

Table 5-2. Proof-of-Concept Run Summary of Fuel Economy and Brief Run Notes

Proof-of-Concept Run Summary --- FUEL ECONOMY & RUN NOTES								
		Odometer		Fuel Used	Miles Traveled	Fuel Economy	
Run No.	Date	Start	Stop	Gallons	mi	mi/gal	Notes
1	1-Apr-09	148424	148483	2.323	59	25.4	Initial driving route
1.5	12-May-09	Not recorded	Not recorded	N/A	N/A	N/A	Missing the warm-up loop, initial end of route
1.75	14-May-09	Not recorded	Not recorded	N/A	N/A	N/A	Run with GP2X accelerometer
2	17-May-09	148619	148661	7.83	N/A	N/A	New route: run 1
3	21-May-09	148661	148702	1.808	41	22.7	New route: run 2
4	22-May-09	148702	148743	1.324	41	31.0	New route: run 3

5.1.1 Sampling Run Number 1: Full Run on First Driving Route

The full TOTEMS instrumentation was employed on April 1, 2009 as the first Proof-of-Concept sampling and data collection. The route used for the first sampling run included a section of rural arterial roads traveling south towards Huntington before turning north through Hinesburg to Burlington. <u>The route proved to be too long for future use in the project</u>, and was rerouted to obtain the "Final Route" used in the May 2009 sampling runs.

The first data set collected was successful in collecting data from all of the on-board instrumentation. The main objective was to achieve second-by-second data for all of the parameters collected by the TOTEMS. The percent of missing data from the particle instrumentation was only 0.98% and from the FTIR was 7.84%. A summary of the percent of data missing from the remaining instrumentation and the collection of a robust data set accounting every second was included in Table 5-3. The relatively high % missing data for the Geologger (66%) and Garmin (17%) GPS units as well as the ScanTool (12%) are noteworthy and were reduced in subsequent runs. The heated line thermocouple (Thermocouple 2) experienced severe data loss (missing 78%) due to faulty wiring connections. This problem was rectified for all subsequent runs. Similar information for all Proof-of-Concept runs is available in **Appendix D.**

Table 5-3. Percent missing data for non- emissions instruments for Run 1.

Percent of Missing Data					
	N points	Potential N points	% N points	% missing	Total
Garmin latitude	5112	6151	83.11%	16.89%	100%
Geologger latitude	2103	6151	34.19%	65.81%	100%
Garmin longitude	5112	6151	83.11%	16.89%	100%
Geologger longitude	2103	6151	34.19%	65.81%	100%
Garmin altitude (m)	5112	6151	83.11%	16.89%	100%
Total Distance (m)	5112	6151	83.11%	16.89%	100%
Distance (m)	5112	6151	83.11%	16.89%	100%
Leg Bearing	5112	6151	83.11%	16.89%	100%
Garmin Speed (km/h)	5112	6151	83.11%	16.89%	100%
Tailpipe Thermo	6151	6151	100.00%	0.00%	100%
Heated Line Thermo	1321	6151	21.48%	78.52%	100%
Accelerometer (x)	6151	6151	100.00%	0.00%	100%
Accelerometer (y)	6151	6151	100.00%	0.00%	100%
Accelerometer(z)	6151	6151	100.00%	0.00%	100%
Total Pressure	6151	6151	100.00%	0.00%	100%
Differential Pressure 1	6151	6151	100.00%	0.00%	100%
Differential Pressure 2	6151	6151	100.00%	0.00%	100%
Differential Pressure 3	6151	6151	100.00%	0.00%	100%
Differential Pressure 4	6151	6151	100.00%	0.00%	100%
Diluter pin 2	6151	6151	100.00%	0.00%	100%
Diluter pin 5	6151	6151	100.00%	0.00%	100%
Diluter pin 16	6151	6151	100.00%	0.00%	100%
Diluter pin 25	6151	6151	100.00%	0.00%	100%
Relative Humidity (in)	6151	6151	100.00%	0.00%	100%
Relative Humidity (out)	6151	6151	100.00%	0.00%	100%
Temperature (in)	6151	6151	100.00%	0.00%	100%
Temperature (out)	6151	6151	100.00%	0.00%	100%
Throttle position	5436	6151	88.38%	11.62%	100%
RPM	5248	6151	85.32%	14.68%	100%
Mass Air Flow	5430	6151	88.28%	11.72%	100%
Speed	5277	6151	85.79%	14.21%	100%

5.1.2 Sampling Run Number 1.5: Vibration Test for Particle Instruments

The TOTEMS, with the exception of the FTIR, was used to evaluate noise in both particle emissions instruments on May 12, 2009. For just this test, the inlets of both the EEPS and CPC instruments had HEPA filters such that any signal detected during the run was due solely to instrument noise. The source of instrument noise was anticipated to be higher for the EEPS instrument than for the CPC because of the differences in method of detection – electrometers used in EEPS are inherently more sensitive to road vibration and electrical interferences than the light-scattering technique used in the CPC.

5.1.3 Sampling Run Number 1.75: "Tiltmeter" Trial Run

Only the non-emissions equipment from TOTEMS was used on May 14, 2009. The purpose of this test was to evaluate the GP2X Accelerometer, borrowed from the UVM Transportation Research Center. This device is advertised as having the ability to act as a sensitive 'tilt-meter' to record instantaneous road grade. In this preliminary run, it was observed that the device is limited to a single sampling rate of 400 Hz, generating a huge quantity data that has not yet been reconciled with the other TOTEMS devices. Furthermore, the dataset obtained did not have a specific road grade parameter and there are software issues still being worked out with the manufacturer. Thus, at the time of this report, no conclusions are yet possible on the usefulness of this device.

5.1.4 Sampling Run Number 2: Full Run on Revised Driving Route (Final Route)

The full instrumentation was employed on May 17, 2009 with the exception of the Garmin GPS antenna which did not initialize properly.

5.1.5 Sampling Run Number 3: Full Run on Final Route

The full instrumentation was employed on May 21, 2009 with the exception of the CPC and the Garmin GPS antenna. The CPC malfunctioned due to the extremely high ambient air temperatures on this date (average over 33^{o}C, Table 1-1) that exceeded the CPC's ability to maintain a cool condenser temperature. This issue with the CPC is unavoidable at high ambient temperatures. The Garmin GPS issue was later resolved when the study team discovered that power must be disconnected from the device between runs in order for the GPS to seek new satellite locations.

5.1.6 Sampling Run Number 4: Full Run on Final Route

The full instrumentation was employed on May 22, 2009 to collect a full data set with all parameters from the TOTEMS on-board system.

5.2 Preliminary Results for Proof-of-Concept Runs

At the Proof-of-Concept stage, aggregate results for the data collected over the entire run are reported to demonstrate that the study team has developed the TOTEMS instrumentation package to the point that reliable vehicle operating and emissions data can be collected routinely. In future reports, data analysis will focus on more disaggregate (i.e., time-resolved) presentation and interpretation of the data.

5.2.1 Particulate Emissions: EEPS and CPC Data

Data for all runs where particle emissions were measured are combined together in Figure 5-1 (EEPS) and Figure 5-2 (CPC) so the reproducibility of data between different runs can be visually compared. It should be noted that Run 1.5 was the vibration/noise test run and data for this run represents minimum instrument detection limits. As Figure 5-1 indicates, there is a considerable noise problem with the EEPS instrument as currently configured in the TOTEMS package. We believe this high level of signal on each of the 32 EEPS channels is due to road vibration. The EEPS was positioned in the minivan using a vibration mount that was originally built for a different instrument. We suspect that the shock absorbers on this vibration mount frame were not sufficient for the weight and size of the EEPS instrument. Therefore, by mid-June 2009, (i) new shock absorbers will be ordered, (ii) a new vibration mount and EEPS suspension system will be custom-built and (iii) additional tests will be conducted to try to achieve an order of magnitude reduction in the EEPS noise level.

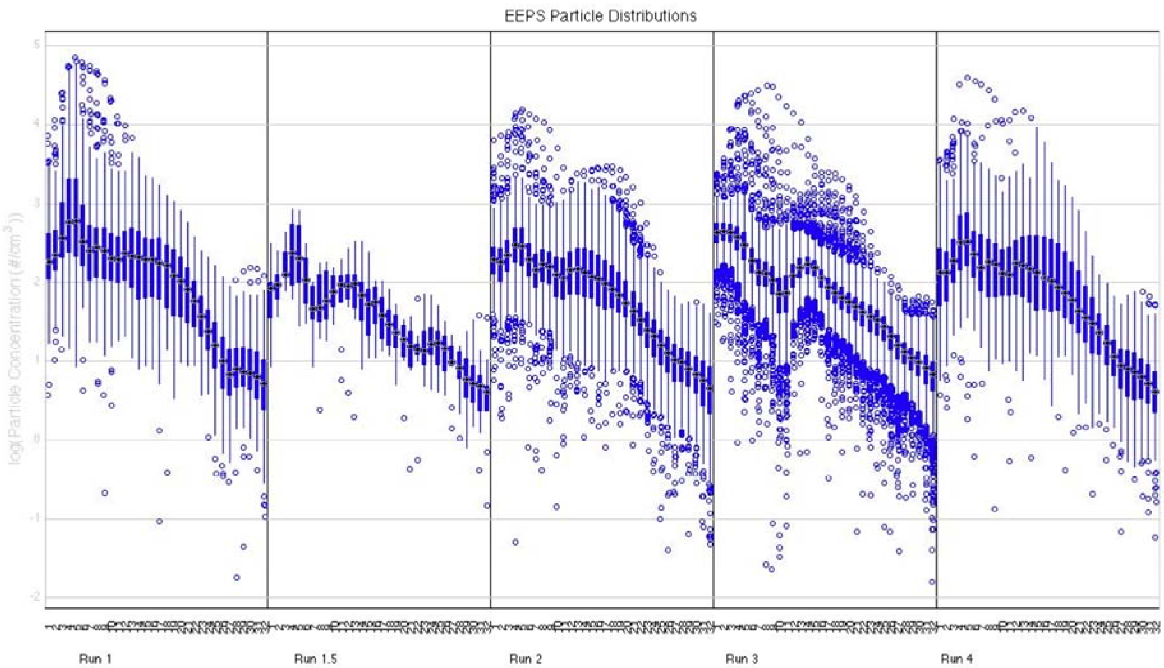

Figure 5-1. Box plots of particle number concentration (#/cm3) for each EEPS channel for individual Proof-of-Concept runs. Note that Run 1.5 had a HEPA filter on inlet of the EEPS instrument and represents instrument noise only.

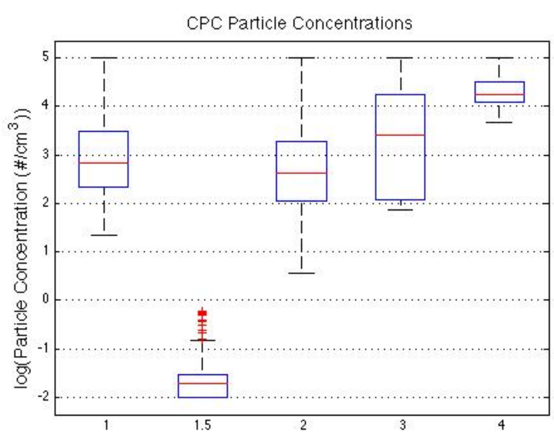

Figure 5-2. Particle concentration CPC instrument data comparing each Proof-of-Concept run. Run 1.5 was a noise quantifying run during which the CPC had a HEPA filter on the inlet, collecting only background noise.

5.2.2 Gas Emissions: FTIR Data on Criteria Pollutants, GHGs and Mobile Source Air Toxics

Figure 5-3 shows box plots of four gas emissions that are routinely quantified by other studies. These represent 3 criteria pollutant gases (CO, NO and NO_2) and one greenhouse gas (GHG) CO_2. Note that the sum NO + NO_2 = NOx, known as “oxides of nitrogen”, and that most exhaust analyzers do not have the capability to individually quantify these gases in real-time. These gas emissions data, for Runs 1-4, show good consistency between runs, even when taking into account the fact that the FTIR instrument gas cell windows were partially compromised during Runs 2, 3 and 4.

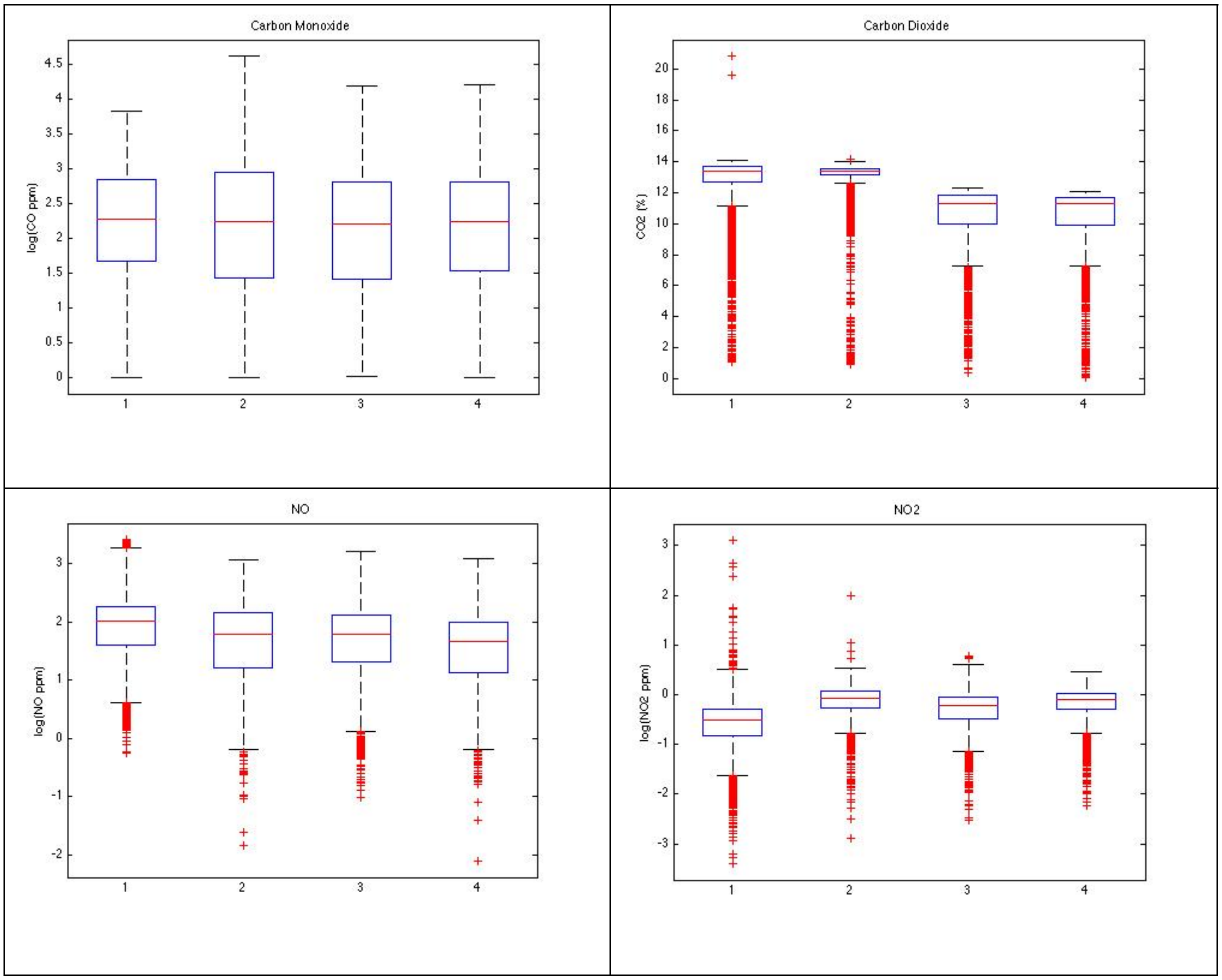

Figure 5-3. Box plots of four gaseous emissions: carbon monoxide (CO, upper left), carbon dioxide (CO_2, upper right); nitric oxide (NO, lower left); nitrogen dioxide (NO_2, lower right). Note that the CO_2 plot in upper right is linear concentration scale in percent; all others are log-scale ppm concentrations.

Results of four MSAT gas concentrations for each run are shown in the Figure 5-4 box plots. It should be noted that the difference in the formaldehyde concentration between Run 1 and Runs 2,3 and 4 is likely due to the fact that Run 1 data do not include a Warm-Up phase to the run. The Warm-Up phase was added after sampling Run 1, and allows for sufficient warm up of the vehicle's engine before sampling begins.

5.2.3 Vehicle Operating Parameters

During the Proof-of-Concept Runs the ScanTool data (Figure 5-5) indicate that the vehicle operating parameters were quite comparable between runs, but relatively variable over individual runs as is expected for real-world driving. The final driving route vehicle speed distribution compares well to the Federal Test Procedure (see Figure 5-5, lower right panel), but with higher speeds attained under the real-world driving route. The vehicle acceleration data (Figure 5-6) shows the Proof-of-Concept mean acceleration rates (mph/s) for Runs 1.5 to 4 were comparable to the FTP test.

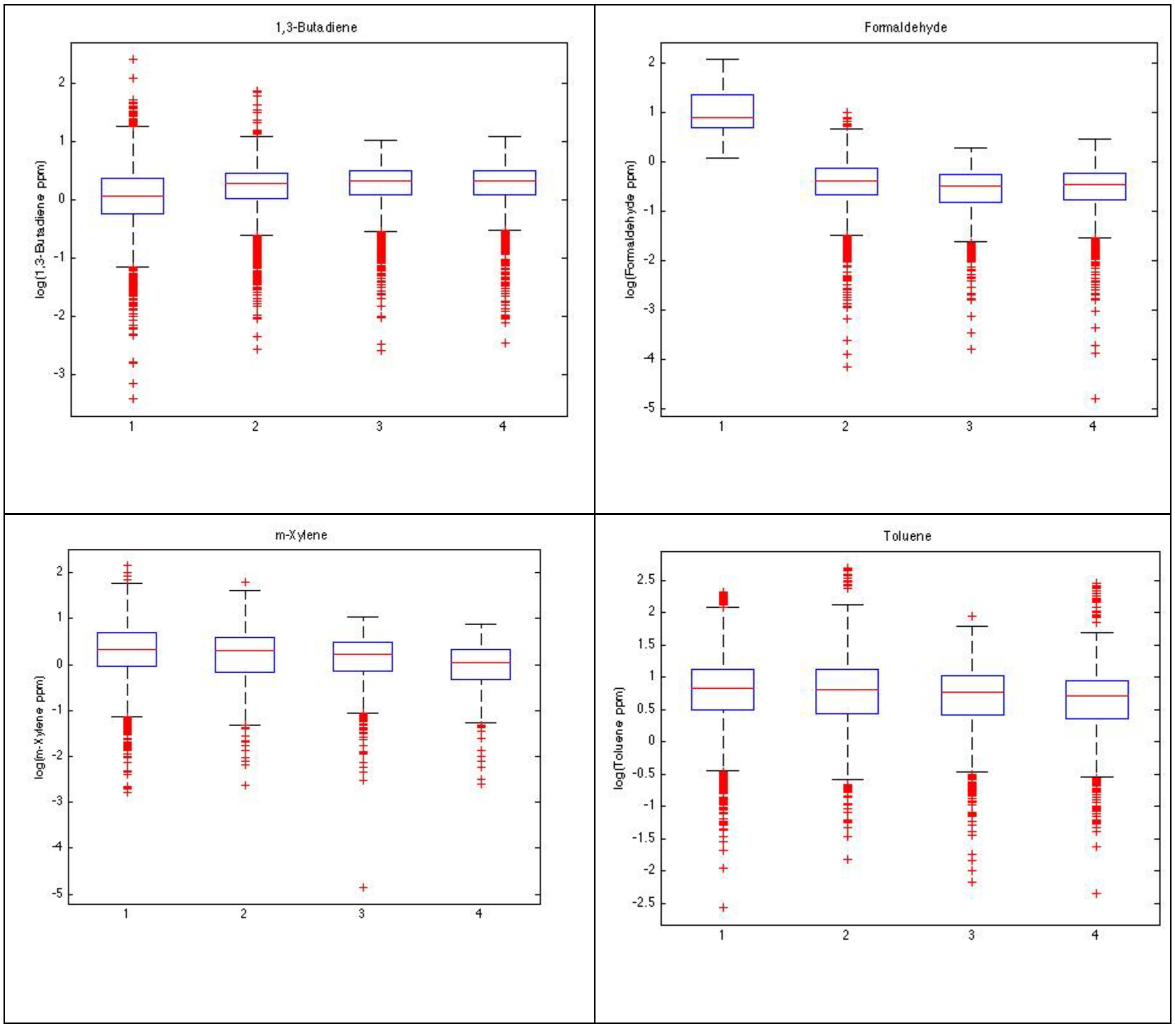

Figure 5-4. Box plots of four mobile source air toxic (MSAT) emissions: 1,3-butadiene (upper left), formaldehyde (upper right); m-xylene (lower left); toluene (lower right). Note that all four plots are log-scale ppm concentrations.

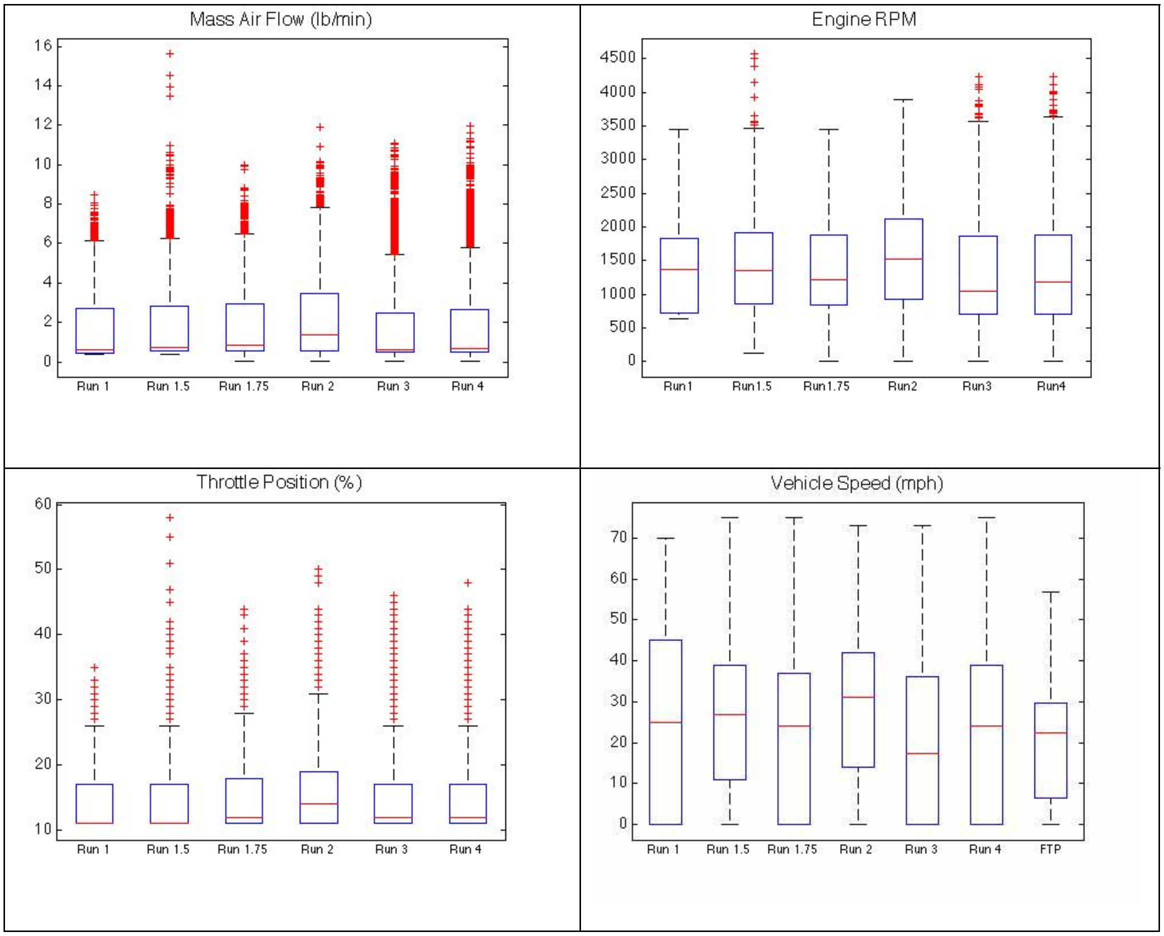

Figure 5-5. Box plots of four ScanTool parameters by Run: intake mass air flow (MAF, upper left), engine speed (in RPM, upper right); throttle position (lower left); vehicle speed (in MPH, lower right). Note that the box plot for the U.S. EPA's Federal Test Procedure (FTP) driving cycle is shown in the lower right panel for comparison.

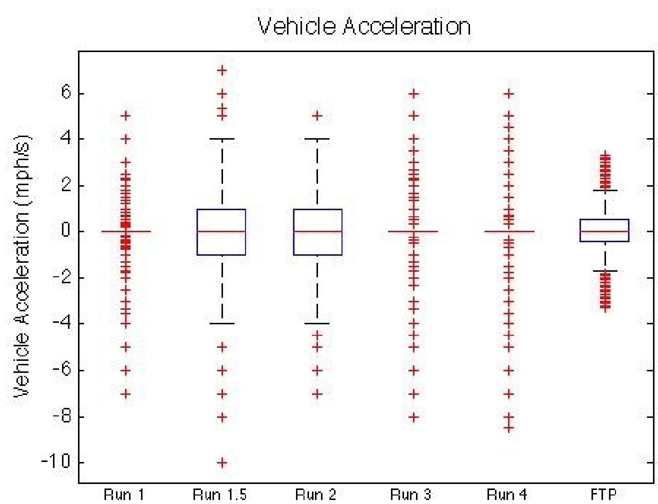

Figure 5-6. Box plots of vehicle acceleration computed from ScanTool speed data. Note that the box plot for the U.S. EPA's Federal Test Procedure (FTP) driving cycle is shown at the far right for comparison.

5.2.4 Temporal Particle Emissions Patterns

As stated above, future data analysis efforts will focus on detailed examination of the second-by-second emissions and operating data. Figure 5-7 shows a 300-sec section of the Run 1 CPC and EEPS total particle concentration data which highlights the fact that low particle number concentrations are experienced most of the time, with periodic high concentration events. The data in Figure 5.6 show (i) excellent tracking between the two particle instruments and (ii) the fact that the EEPS instrument can quantify particle concentration when the CPC upper limit is exceeded (the CPC's blue line is maxed out at ~ 280 sec, whereas the EEPS' green line is not).

Finally, future analysis will examine how vehicle operation affects the particle number <u>distributions</u>. As Figure 5-8 shows, the EEPS resolves significant changes in particle size over the driving route. These data will allow development of new models and improved understanding of particle emissions during real-world vehicle operation.

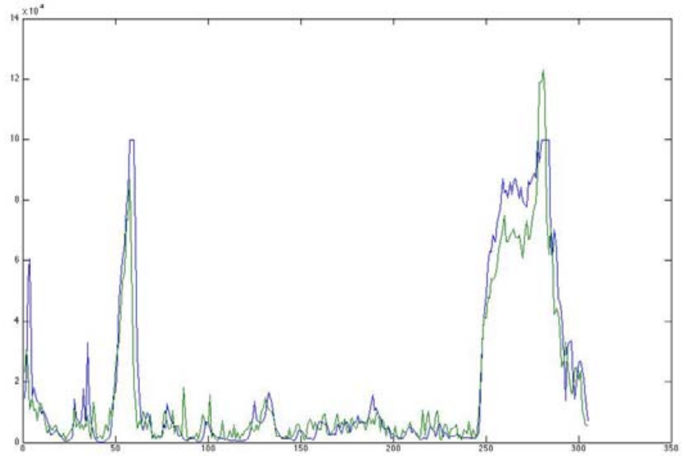

Figure 5-7. Run 1 clip of total particle concentration (y-axis is #/cm^3 x 10^4) data for EEPS and CPC. Green line is EEPS and blue line is CPC.

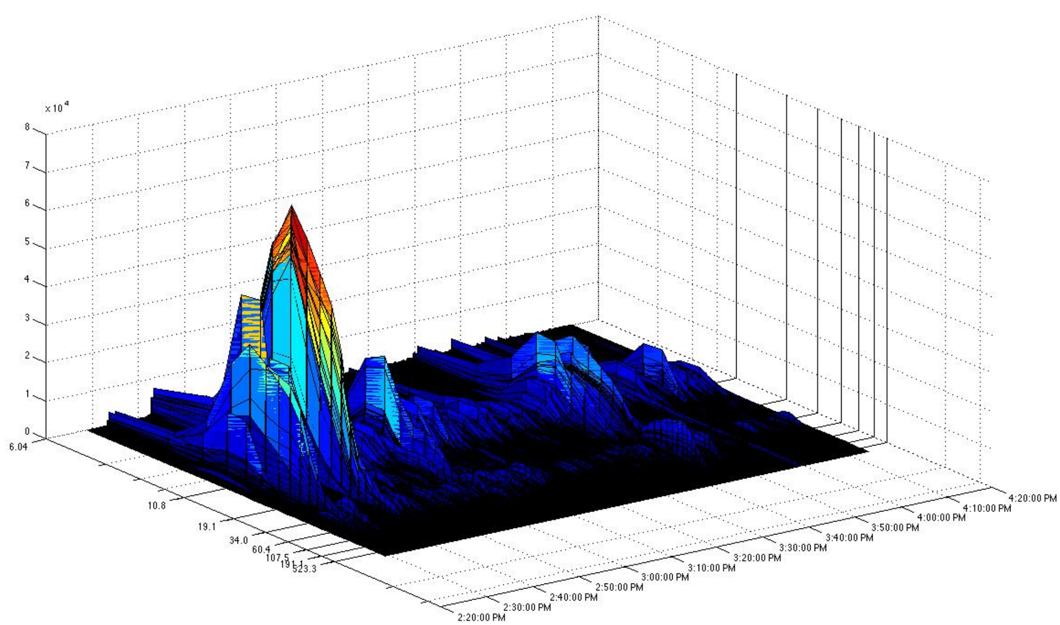

Figure 5-8. Run 1 particle distribution measured by EEPS at 1 Hz. Z-axis is particle number concentration (#/cm^3 x 10^4), Y-axis (left) is particle diameter and X-axis (right) is sampling time.

6 Laboratory Validation of Instrumentation

A number of laboratory tests were conducted to evaluate the sampling behavior of the particle instruments. The results of these tests are described here because they inform the interpretation of the on-board run results.

6.1 EEPS vs. CPC Data

Instrument Concentration Limits. Differences in the data between the EEPS and CPC are to be expected because the two particle instruments employ different measurement techniques and therefore have different lower detection limits and maximum concentration ranges. The EEPS has a significantly higher maximum concentration limit than the CPC, which results in significant differences in concentration when the CPC is "maxed out." This situation is easily identified, however, because the CPC reported values will remain at 9.99×10^4 until the particle concentration decreases below this instrument limit. Because of the significant range of total particle emissions from combustion engines, this "maxing out" cannot be addressed with increased dilution because then the lower particle concentrations (i.e., at idle operation) would not be quantifiable. The dilution factor of 125 used in the TOTEMS Proof-of-Concept runs resulted in measured particle concentrations during low emissions events of only 100 to 200 particles per cubic centimeter. Increasing the dilution factor further would make particles undetectable during these events.

Instrument Noise. Another factor that results in differences between the two particle instruments is their sensitivity to vibration. The electrometers on the EEPS, especially at lower concentrations, are very susceptible to noise. Artificial noise – such as hitting a bump in the road – results in a spike in particle concentration. Although still impacted by such events, the CPC was determined to be much less susceptible (see Run 1.5 in Figures 5-1 and 5-2). To minimize vibration interference phenomena, both instruments are seated in vibration mounts, effectively isolating the instruments from the floor of the vehicle and reducing inaccuracies that result from vibration. However, as discussed above, the Proof-of-Concept data in Figure 5-1 demonstrate that further noise reduction improvements are necessary for the EEPS instrument mount.

Instrument Response Time. Despite the different measurement techniques for the CPC and EEPS, nearly identical response times to concentration changes are seen between the instruments. Lab tests were conducted using 30 to 50 nanometer sodium chloride particles. Sodium chloride was dissolved in distilled water at a concentration of 0.2 g/L and atomized using particle-free compressed air in the TSI, Inc. Atomizer. Figure 6-1 is a schematic of the setup utilized in these experiments where particle concentrations fed to the particle instruments was varied by changing the dilution factor.

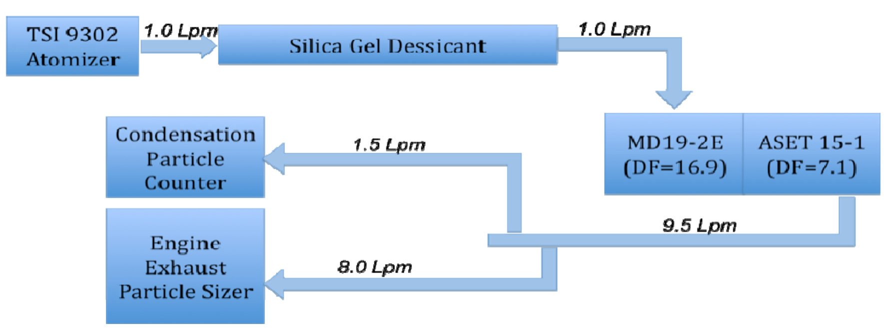

Figure 6-1. Flow of exhaust through particle emissions system for in-lab experiments.

The dilution factor (DF) for the MD19-2E was started at 16.9 and was changed periodically up to a maximum of 120. Figure 6-2 shows the response times between the EEPS and CPC. It is evident they trend up and down in a nearly identical fashion.

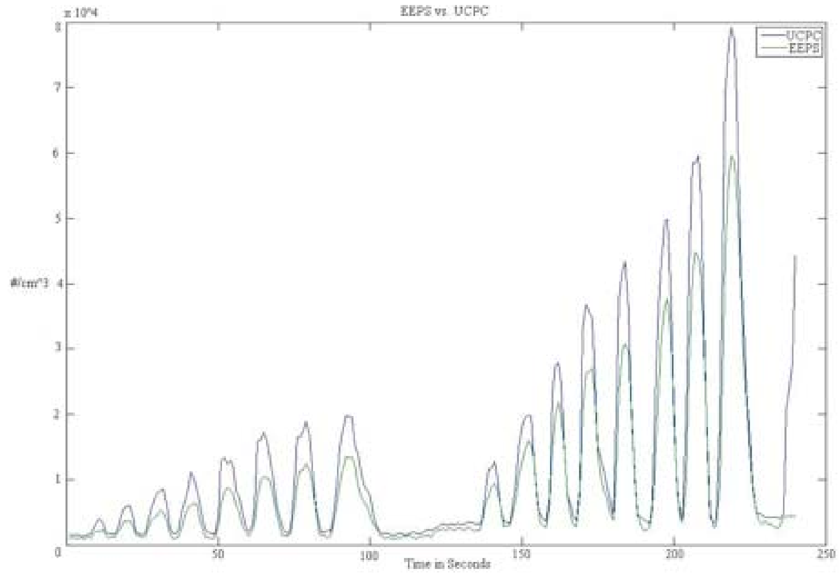

Figure 6-2. Comparison of EEPS and CPC response times to changes in the dilution factor.

Differences in particle concentration were minimal at low concentrations and increased linearly (R^2 values between 0.966 and 0.989 were routinely seen) as particle concentration increased. This nearly linear relationship between the EEPS and CPC concentrations allows application of a simple regression equation to *estimate* CPC concentrations during sampling events when the CPC maximum concentration limit is reached. The scatterplot of laboratory data (Figure 6-3) shows the regression of EEPS versus CPC particle concentrations.

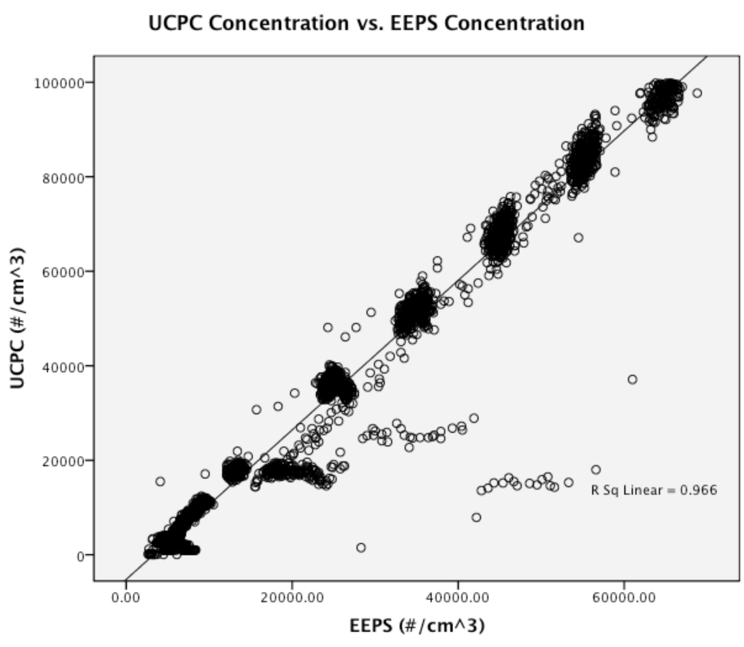

Figure 6-3. Laboratory sodium chloride total particle number concentrations collected simultaneously on EEPS and CPC instruments. The solid line is the best-fit linear regression equation: UCPC conc = 1.582 (EEPS conc) - 5213.

This linear increase in concentration differences between instruments is reasonable because of the different measurement techniques. The EEPS is more stable at higher concentration because it is affected less by electrical noise and mechanical vibrations when particle concentrations are higher. The CPC is more stable at lower concentrations (i.e., well below its maximum concentration value of 9.99 $x10^4$ $\#/cm^3$) because as concentration increases, multiple particles flow through the optic sensor at the same time. An algorithm is applied by the TSI software to account for this, but it is not as accurate as counting each particle at lower particle concentrations.

6.2 Laboratory Check of EEPS Distribution Consistency

An important consideration is how consistent the EEPS is with sizing particles from the same source. This was checked using sodium chloride particles from 20 to 70 nanometers at varying dilution factors. **Figure 6-4** shows the particle number distributions measured with the EEPS at four dilution factors. The y-axis is the time stamp, the z-axis is the particle number concentration (0 x 10^4 to 3 x 10^4 $\#/cm^3$) and the x-axis is the aerodynamic diameter of the particles on a log scale.

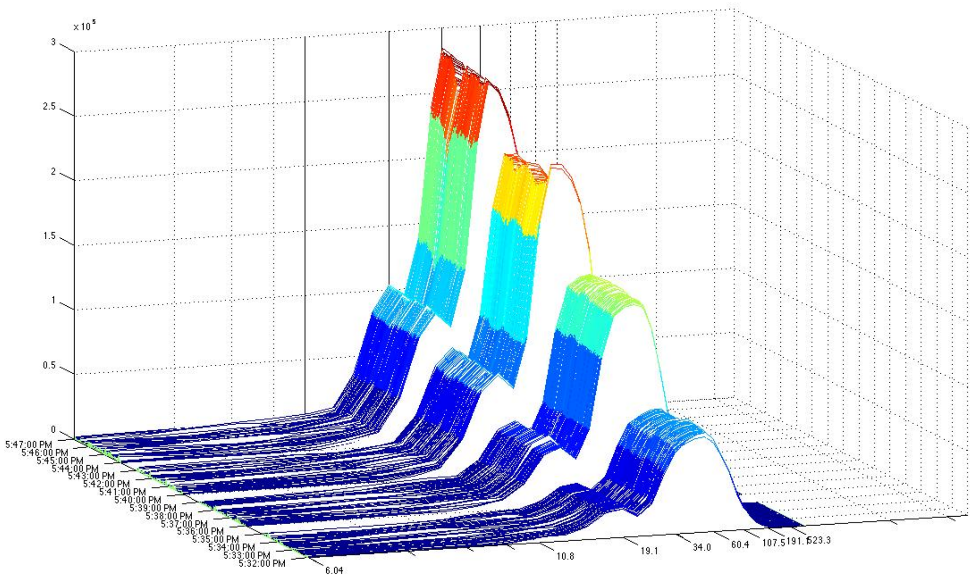

Figure 6-4. Consistency test in EEPS particle number distributions at four dilution factor settings. Note that the EEPS number distribution shapes (along x-axis, D_p) and magnitudes (z-axis, $\#/cm^3$) are quite reproducible after each of the dilution factor step changes (y-axis, time).

Figure 6-4 clearly shows the EEPS particle sizing stays extremely consistent with a bimodal distribution despite the variation in dilution factor. Lower concentrations were also tested which yielded similar results.

6.3 Laboratory Check of The Dilution System

To ensure the dilution system was accurately diluting the aerosol, laboratory tests were performed by generating sodium chloride particles (Figure 6-1). An undiluted baseline concentration was first measured with only the EEPS because the concentration exceeded the limits of the CPC. Using the same particle concentration, the aerosol was diluted by adjusting the potentiometer on the MD19-2E mini-diluter. The potentiometer setting started at 10% (high dilution) and was increased in increments of 10 to a maximum of 100% (low dilution). The concentration was then decreased back down to 10% by increments of 10, and the process was repeated a second time. Figure 6-5 shows the relationship between the calculated dilution factor (blue line) and that derived from concentrations measured by the EEPS and CPC, both referenced to the baseline.

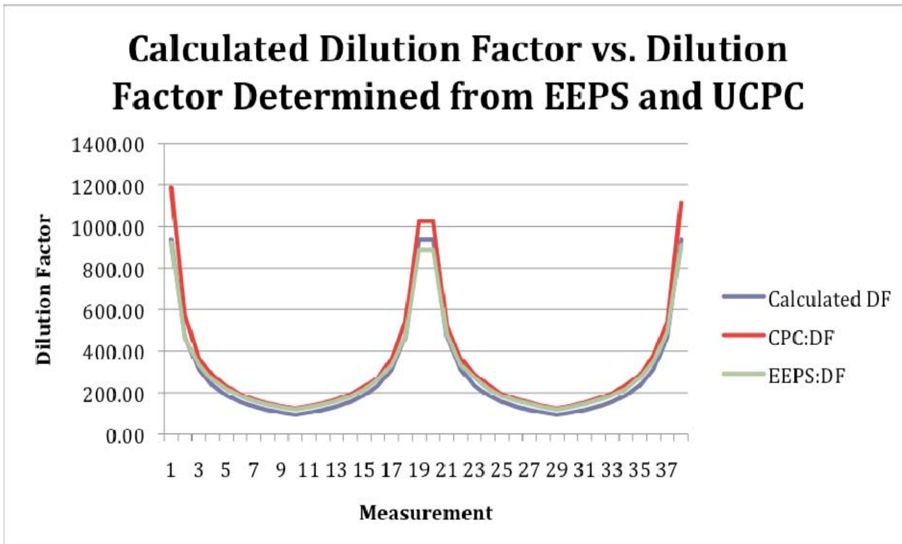

Figure 6-5. Laboratory Dilution Factor Verification Test Results.

The observed differences between the calculated dilution factors and those derived from the instruments' reported concentrations are well within the accuracy limits of both the EEPS and CPC instruments. It's also worthy to note that there seems to be a better relationship between the EEPS, CPC and calculated dilution factors when the dilution factor is below 200 (i.e., lines are closer in Figure 6-5). For Signature Project 2, a dilution factor of 120 was used for the Proof-of-Concept runs.

7 Statistical Approaches To On-Board Database Development and Data Analysis

7.1 Lags

Synchronizing the engine operating data with the emissions measurements to describe the 1:1 association between engine and tailpipe behavior is critical to enable modal emissions modeling and comparisons between vehicle types. Two temporal lags must be quantified and accounted for: (i) engine- out to tailpipe adapter probe ("engine-to-tailpipe") ; and (ii) tailpipe adapter probe to emissions instrument ("tailpipe-to-instrument"). Prior on-board studies have applied a single constant lag to all the emissions data for a run. For example, investigators at North Carolina State University used the CO spikes to mark pulses in engine RPM (Frey et al., 2001). The lags observed were considered indicative of the engine-to-tailpipe delay and were used for each run's adjustment. They observed an overall increase in lagging over the experimental period of 5 months – with a slight 'clogging' of the gas tubes causing a gradual increase in delay. Lag time increased from 3 seconds in the summer to nearly 9 seconds by December of their study year. Every run was examined individually for lag and synchronized accordingly. For future TOTEMS data, a slightly more advanced approach will be used based on the assumption that engine-to-tailpipe lag is a dynamic function of exhaust flowrate. Systematically advancing the RPMs while idling could provide a useful step function to quantify the individual engine/gas and engine/particle instrument lags. These "alignment checks" could be performed at various points during each run: one at the beginning, one at a particular stop sign along the route, and one upon returning to Burlington. Varying response correlations will be tested and the lagging with the highest correlation could be chosen, potentially resolved with a likelihood estimator.

7.2 Statistical Approaches

Experimental data sampled continuously over time, such as emissions from an automobile's tailpipe, introduce important issues that restrict us from applying many of the classical statistical techniques directly. Two common concerns deal with autocorrelation and nonstationarity. The first describes the correlation of adjacent data points in the series – for example, when a value at time t is above the series mean, the next value ($t+1$) or its previous ($t-1$), are more likely to also be above. This violates the classical parametric statistical assumption that all observations (and errors) are independent and identically distributed (iid). Data aggregation or differencing routines can help here.

For stationarity, Shumway and Stoffer (2006) state that a "strictly stationary time series is one which the probabilistic behavior of every collection of values: $\{y_{t1}, y_{t2}, \ldots, y_{tk}\}$ is identical to that of the shifted time set: $\{y_{t1+h}, y_{t2+h}, \ldots y_{tk+h}\}$". That is, the statistical properties of the series are not dependent on time. A simple way to examine this is by comparing means, variances, and autocorrelations at different intervals in the series. Most time series are not stationary and can be treated with differencing, transformations, and aggregation methods.

The specific goals of the modeling effort will be determined by the nature of each scientific question considered. The inclusion of a set of independent variables can be chosen to build two types of regression models: explanatory and predictive. These two are fundamentally different. The goal of an explanatory model is to detect the strength of association between some response (emissions) and a subset of potentially related variables (e.g. % engine load, fuel rate, engine speed, flow rate, velocity, and acceleration). Alternatively, a predictive model tries to discover variables that predict the value of a new draw of the response. We aren't as concerned if causation exists, only if the variables have predictive power. Of course, theorized causal variables will be a natural choice in any modeling effort.

There are numerous approaches for evaluating statistical regression models. Stepwise multiple regression reiteratively estimates models by the stepwise inclusion of a predetermined list of independent variables and selects the model that meets some set of criteria (often using residual sums of squares, the F-statistic, and ANOVA table). Alternatively, two model diagnostics can be used to measure goodness of fit by balancing the error of fit against the number of model variables. Most commonly, we use Akaike's Information Criterion (AIC) or Schwarz's Information Criterion (SIC) and conclude the lowest AIC or SIC value is the most efficient and parsimonious model. These are important alternatives to the inappropriate consideration of R^2 alone; a model statistic that has received unwarranted attention and emotion.

Finally, multiple regression techniques will allow us to test for significant differences in the effect of one parameter by adjusting for the effects of others. This becomes a multivariate hypothesis testing tool when univariate tests are too simplistic. Data analysis will be conducted by both UVM and RSG using a variety of analytical software tools including SAS, STATA, and R.

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9 Appendix A. FTIR Gas Quantification Information

Table A-1. MKS MultiGas Measured Detection Limits & Manufacturer Calibration Gas Concentrations Compared to AutoLogic 5-Gas Analyzer Ranges.

	Compound	On-Board Detection Limit* (ppm or %)	Lowest Calibration Std (ppm or %)	Highest Calibration Std (ppm or %)	Range (ppm or %)	Autologic AutoGas Analyzer
"Criteria"	Carbon Monoxide	3.01	99.6	5000	4997	
	Carbon Monoxide (%)	0.02	3.19	7.99	8	0-15
	Nitric Oxide	1.47	279	2795	2794	0-5,000 (as NO_x)
	Nitrogen Dioxide	0.54	358	488	487	
	Ammonia	0.42	12.73	2995	2995	
	Sulfur Dioxide	1.00	19.6	964.5	963	
Hydrocarbons	Ethane	2.09	100.4	1004	1002	0-2,000 (as HC, propane surrogate)
	Octane	1.64	20	1000	998	
	IsoOctane	1.66	20	1000	998	
	1,2,4-Trimethylbenzene	3.49	20	1000	997	
	1,3,5-Trimethylbenzene	1.77	100	1000	998	
	Ethylene	1.51	9.74	3000	2998	
	Propylene	4.76	89.8	194	189	
	1,2-Propadiene	1.11	306	1020	1019	
	2-Methylpropene	1.82	150	500	498	
	2-Methyl-2-Butene	11.08	19.57	19.57	8	
	Ethanol	3.28	20	1000	997	
	Methanol	1.35	18.63	931.74	930	
	Acetylene	1.77	101.6	1016	1014	
	Propyne	4.43	50	500	496	
"MSAT"	Formaldehyde	1.16	4.2	69	68	
	1,3-Butadiene	3.18	8.3	83.4	80	
	Toluene	22.55	18.63	931.74	909	
	m-Xylene	5.56	93.17	931.74	926	
GHG	Carbon Dioxide (%)	0.15	4.6	23	23	0-20
	Methane	3.64	414	3143	3139	
	Nitrous Oxide	0.77	146.9	200.1	199	
	Water (%)	1.17	17.87	20.57	19	

* Detection Limit computed from on-board tunnel blank data as mean + 3(standard deviation)

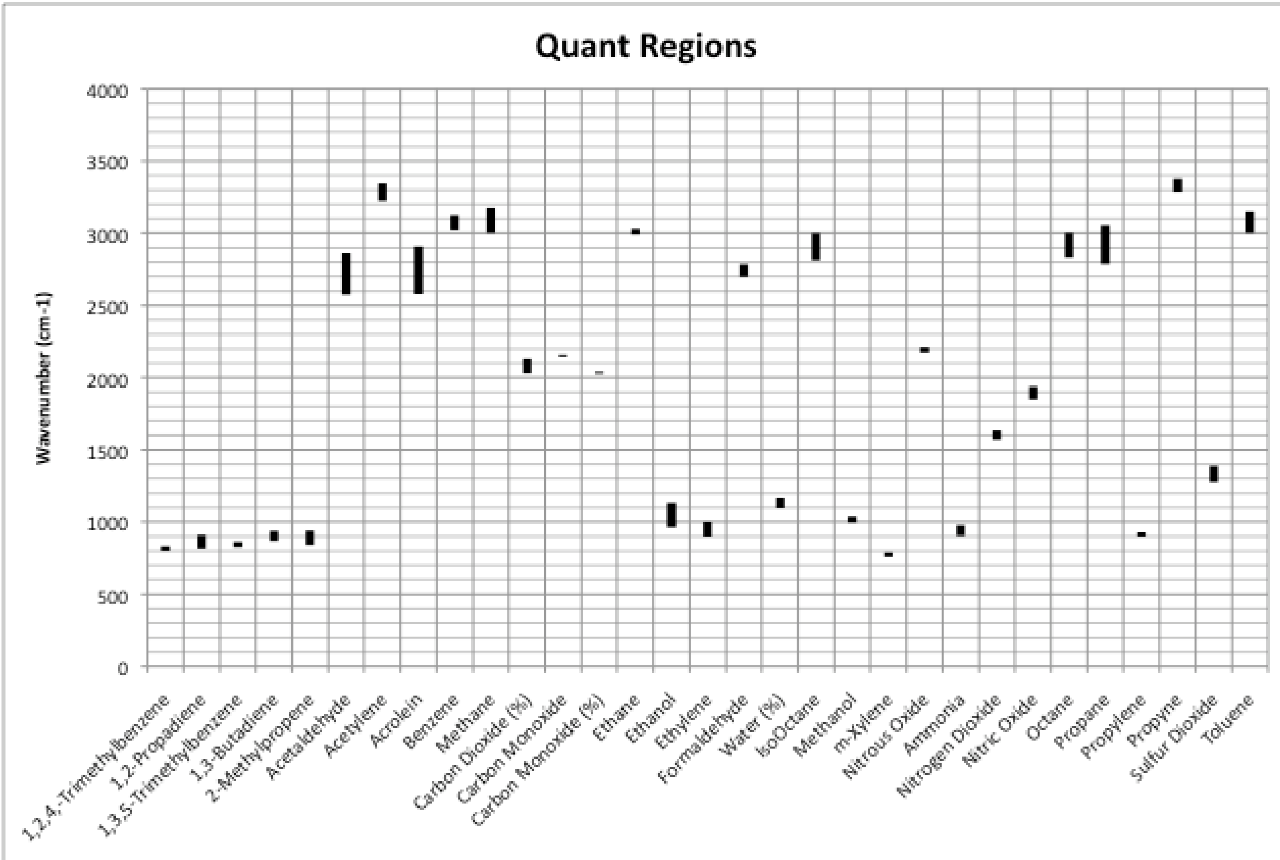


Figure A-1. Regions in IR spectrum used to quantify each of the gas compounds measured using the MKS MultiGas.

10 Appendix B. EEPS Instrument Specifications & Results By Channel

Table B-1. Particle Diameters Associated with EEPS Channels.

Channel	Lower Limit (nm)	Upper Limit (nm)	Midpoint (nm)
1	5.6234	6.4938	6.04
2	6.4938	7.4989	6.98
3	7.4989	8.6596	8.06
4	8.6596	10.0000	9.31
5	10.0000	11.5478	10.75
6	11.5478	13.3352	12.41
7	13.3352	15.3993	14.33
8	15.3993	17.7828	16.55
9	17.7828	20.5353	19.11
10	20.5353	23.7137	22.07
11	23.7137	27.3842	25.48
12	27.3842	31.6228	29.43
13	31.6228	36.5174	33.98
14	36.5174	42.1697	39.24
15	42.1697	48.6968	45.32
16	48.6968	56.2341	52.33
17	56.2341	64.9382	60.43
18	64.9382	74.9894	69.78
19	74.9894	86.5964	80.58
20	86.5964	100.0000	93.06
21	100.0000	115.4782	107.46
22	115.4782	133.3521	124.09
23	133.3521	153.9927	143.30
24	153.9927	177.8279	165.48
25	177.8279	205.3525	191.10
26	205.3525	237.1374	220.67
27	237.1374	273.8420	254.83
28	273.8420	316.2278	294.27
29	316.2278	365.1741	339.82
30	365.1741	421.6965	392.42
31	421.6965	486.9675	453.16
32	486.9675	562.3413	523.30

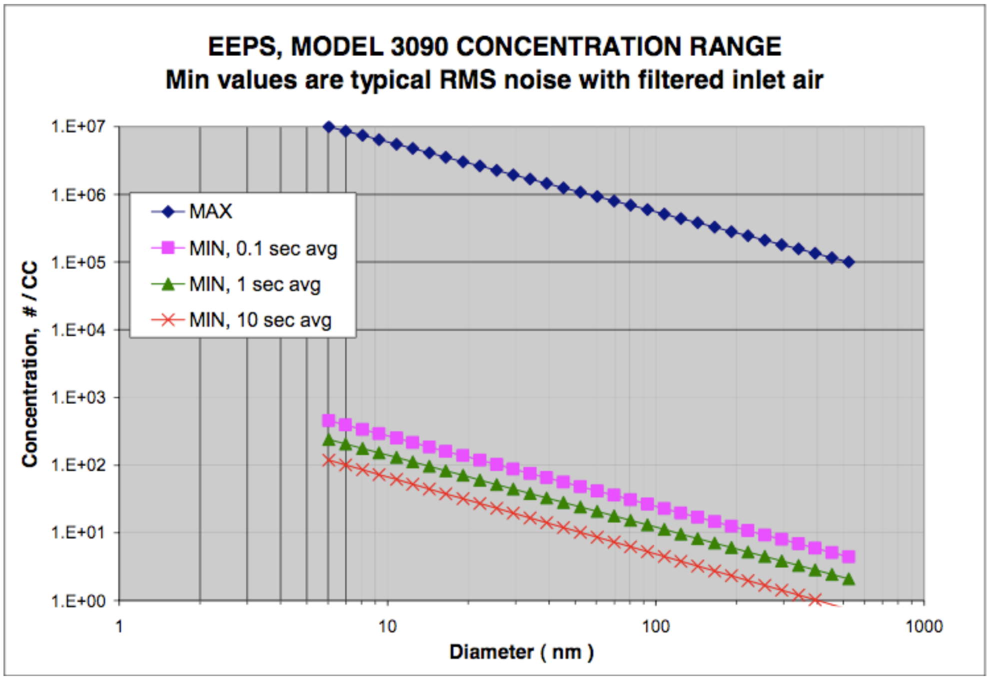


Figure B-1. Manufacturer's minimum and maximum concentration limits for EEPS.

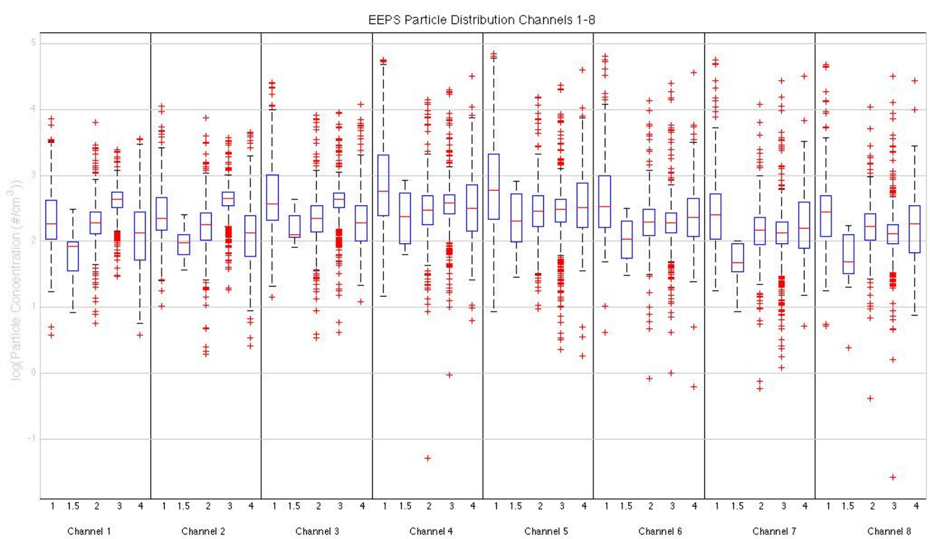


Figure B-2. EEPS particle concentrations for channels 1 to 8 compared over sampling runs.

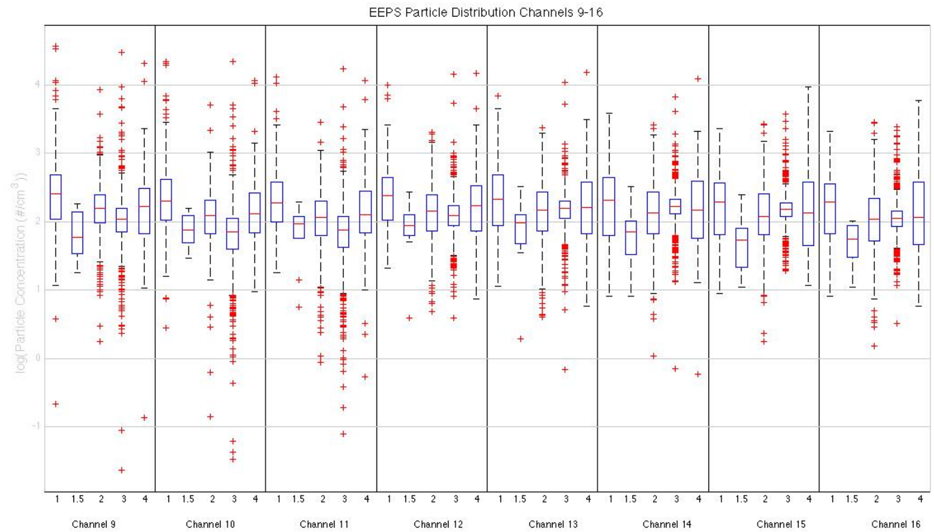


Figure B-3. EEPS particle concentrations for channels 9 - 16 compared over sampling runs.

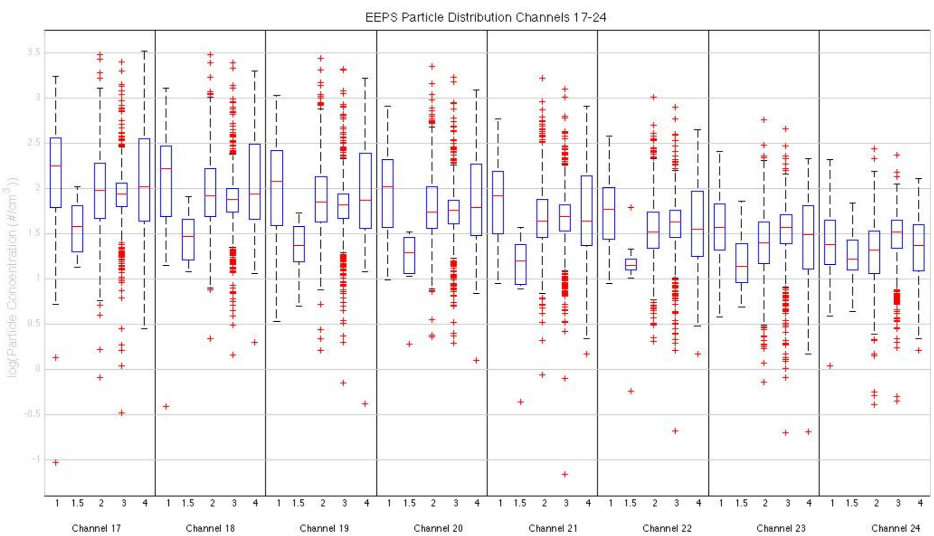


Figure B-4. EEPS particle concentrations for channels 17 - 24 compared over sampling runs.

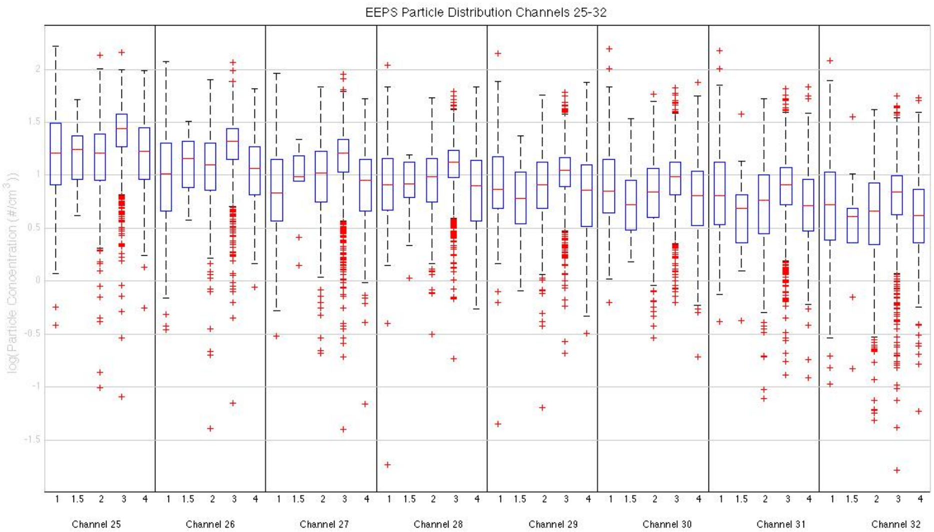


Figure B-5. EEPS particle concentrations for channels 25 - 32 compared over sampling runs.

11 Appendix C. Driving Route Details

Table C-1. Driving route directions with directions indicated by L – left, R – right, and C – continue straight.

Direction	Facility Name
L	Colchester Avenue
R	North Prospect Street
R	Riverside Avenue
R	Cumberland Farms Gulf Station
R	Riverside Avenue
R	Colchester Avenue
C	Pearl Street
L	Battery Street
L	Maple Street
L	South Prospect Street
R	Main Street
C	Williston Road
R	I-89 South
R	Exit 11 – Richmond
R	West Main Street Rte. 2
C	East Main Street Rte. 2
R	Cochran Road
C	Huntington Road
R	Hinesburg Road
C	East Hill Road
R	South Road
R	Oak Hill Road
L	Route 2
R	Patchen Road
C	Grove Street
L	Barrett Street
L	Colchester Avenue
C	Pearl Street
R	North Prospect Street
R	Riverside Avenue
L	Cumberland Farms Gulf Station
L	Riverside Avenue
L	North Prospect Street
L	Pearl Street
C	Colchester Avenue
R	Votey Hall Parking Lot

12 Appendix D. Descriptive Statistics Tables for Sampling Runs

12.1 Sampling Run 1 Descriptive Statistics

EEPS/CPC Concentrations

	N	Range	Minimum	Maximum	Mean	Std. Deviation
CPC Concentration	6091	99878.00	22.00	99900.00	4035.27	12217.44
EEPS Concentration	6091	417000.00	.00	417000.00	6766.02	18541.37
c1	6091	7361.92	.00	7361.92	176.95	358.95
c2	6091	11459.40	.00	11459.40	219.50	498.61
c3	6091	25888.80	.00	25888.80	418.71	1343.30
c4	6091	58785.40	.00	58785.40	1016.63	3248.42
c5	6091	70963.80	.00	70963.80	1055.39	3658.36
c6	6091	63695.60	.00	63695.60	527.50	2692.55
c7	6091	56334.10	.00	56334.10	337.16	2159.65
c8	6091	48879.30	.00	48879.30	331.58	1803.70
c9	6091	37025.60	.00	37025.60	283.52	1348.00
c10	6091	22074.70	.00	22074.70	209.04	776.88
c11	6091	13020.80	.00	13020.80	160.26	443.94
c12	6091	9864.04	.00	9864.04	228.94	447.43
c13	6091	8132.25	.00	8132.25	291.77	523.29
c14	6091	8388.29	.00	8388.29	290.99	524.77
c15	6091	9061.31	.00	9061.31	254.39	465.67
c16	6091	9565.45	.00	9565.45	198.69	390.08
c17	6091	9994.81	.00	9994.81	170.39	369.72
c18	6091	10349.40	.00	10349.40	130.97	346.98
c19	6091	9720.71	.00	9720.71	112.83	318.76
c20	6091	8108.75	.00	8108.75	88.36	259.28
c21	6091	6142.65	.00	6142.65	67.12	193.95
c22	6091	3822.40	.00	3822.40	46.06	121.33
c23	6091	2117.27	.00	2117.27	31.03	70.03
c24	6091	1027.26	.00	1027.26	20.30	39.23
c25	6091	364.96	.00	364.96	14.35	24.12
c26	6091	206.48	.00	206.48	11.31	18.80
c27	6091	229.04	.00	229.04	8.37	14.50
c28	6091	264.14	.00	264.14	8.21	16.25
c29	6091	400.02	.00	400.02	11.77	26.39
c30	6091	596.88	.00	596.88	15.29	35.56
c31	6091	633.66	.00	633.66	15.67	36.70
c32	6091	496.36	.00	496.36	12.60	29.38
Valid N (listwise)	6091					

GPS Recievers

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Garmin latitude	5112	.2010117	44.287878	44.488890	44.407352	.061163
Geologger latitude	2103	.20078	44.288070	44.488850	44.386361	.058888
Garmin longitude	5112	.2819616	-73.219018	-72.937057	-73.096172	.090131
Geologger longitude	2103	.26894	72.950080	73.219020	73.079770	.085908
Garmin altitude (m)	5112	190.4	42.8	233.2	128.068	40.6582
Valid N (listwise)	2103					

Garmin Additional Parameters

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Total Distance (m)	5112	93855.8	.0	93855.8	46726.607	31034.3903
Distance (m)	5112	1033.2	.0	1033.2	18.359	37.6766
Leg Bearing	5112	359.7	.0	359.7	215.276	102.1263
Garmin Speed (km/h)	5112	112.2	.0	112.2	57.473	28.4290
Valid N (listwise)	5112					

Labview Device 1

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Tailpipe Thermo	6151	311.90	64.18	376.08	206.1088	72.69955
Heated Line Thermo	1321	70.92	38.61	109.53	62.0850	4.20855
Accelerometer (x)	6151	.57	2.17	2.74	2.4902	.06333
Accelerometer (y)	6151	1.12	2.10	3.22	2.4920	.06948
Accelerometer(z)	6151	1.16	.99	2.15	1.4877	.05820
Total Pressure	6151	.20	.87	1.07	1.0156	.00787
Valid N (listwise)	1321					

Labview Device 2

	N	Minimum	Maximum	Mean	Std. Deviation
Differential Pressure 1	6151	.00	7.04	.5093	.91394
Differential Pressure 2	6151	.05	10.00	2.8060	3.41121
Differential Pressure 3	6151	.01	10.00	5.3607	4.32965
Differential Pressure 4	6151	5.52	10.00	9.3318	1.05717
Diluter pin 2	6151	2.31	3.95	2.8791	.03423
Diluter pin 5	6151	-10	-10	-10.00	.009
Diluter pin 16	6151	9.95	10.00	9.9926	.00890
Diluter pin 25	6151	5.00	5.00	5.0000	.00000
Valid N (listwise)	6151				

Relative Humidity and Temperature

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Relative Humidity (in)	6151	17.898	35.322	53.220	41.07861	4.178519
Relative Humidity (out)	6151	13.442	42.587	56.029	48.86657	2.031804
Temperature (in)	6151	3.908	10.932	14.840	13.77583	.820320
Temperature (out)	6151	3.523	8.866	12.389	9.66568	.883415
Valid N (listwise)	6151					

ScanTool

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Throttle position	5436	24.00	11.00	35.00	15.0653	4.48290
RPM	5248	2819.00	633.00	3452.00	1511.3035	572.08950
Mass Air Flow	5430	8.09	.40	8.49	2.0518	1.74793
Speed	5277	70.00	.00	70.00	32.0648	19.80613
Valid N (listwise)	5248					

FTIR POC Run 1

	N	Range	Minimum	Maximum	Mean	Std. Deviation
124Trimethylbenzene	5669	311.19	-127.74	183.45	-.08	6.92
12Propadiene	5669	71.59	-64.65	6.94	-.16	1.53
135Trimethylbenzene	5669	253.89	-55.31	198.58	-.04	3.37
13Butadiene	5669	315.00	-50.33	264.67	2.09	6.19
2methyl2butene	5669	363.10	-165.50	197.59	7.83	20.91
2Methylpropene	5669	130.88	-101.66	29.22	2.42	5.40
Acetylene	5669	186.22	-98.86	87.36	4.78	16.15
CH4	5669	183.15	1.66	184.81	35.50	24.95
COppm	5669	6820.23	-.62	6819.61	722.14	1314.34
CO	5669	.62	.00	.62	.06	.12
CO2	5669	20.42	.43	20.85	12.74	2.01
Ethane	5669	54.55	-8.14	46.41	5.04	6.77
Ethanol	5669	541.82	-211.46	330.37	7.71	18.40
Ethylene	5669	602.29	-312.40	289.89	14.24	42.69
Formaldehyde	5669	115.42	1.17	116.59	14.86	16.06
H2O	5669	81.52	4.97	86.50	10.45	6.34
IsoOctane	5669	137.31	-6.07	131.24	8.48	23.43
mXylene	5669	2275.43	-2129.44	145.98	2.08	30.48
MeOH	5669	171.51	-17.52	153.98	2.09	3.81
N2O	5669	252.43	-2.16	250.27	10.90	20.29
NH3	5669	307.28	-31.89	275.39	12.45	15.96
NO	5669	2587.99	-8.14	2579.86	172.54	293.38
NO2	5649	2298.79	-1008.39	1290.40	.42	23.66
Octane	5669	140.40	-13.61	126.79	8.32	22.52
Propylene	5669	410.03	-12.33	397.70	6.37	18.27
Propyne	5669	616.69	-598.43	18.26	.55	10.08
SO2	5669	445.08	-107.03	338.06	.96	6.72
Toluene	5669	2418.25	-2213.34	204.91	7.16	49.40
Valid N (listwise)	5649					

Run 1 Blanks: Descriptive Statistics for EEPS and CPC

	N	Minimum	Maximum	Mean	Std. Deviation
CPC_pre_instrument_C	600	0.00	0.00	0.00	0.00
EEPS_pre_inst_C	600	4.84	4020.00	477.63	304.60
CPC_pre_tunnel_C	600	18.00	39.90	26.29	5.54
EEPS_pre_tunnelC	600	19.50	3140.00	521.01	347.86
CPC_post_tunnel_C	600	82.00	279.00	169.79	40.65
EEPS_post_tunnel_C	21	28600.00	31300.00	29785.71	915.03
CPC_post_instrument_C	600	0.00	0.03	0.01	0.01
EEPS_post_inst_C	600	0.00	3000.00	339.28	271.37
Valid N (listwise)	21				

Run 1 Blanks: Percent of Missing data for EEPS and CPC

	N points	Potential N points	% N points	% missing	Total
CPC pre ins.	600	600	100%	0%	100%
EEPS pre ins.	600	600	100%	0%	100%
CPC pre tunnel	600	600	100%	0%	100%
EEPS pre tunnel	600	600	100%	0%	100%
CPC post tunnel	600	600	100%	0%	100%
EEPS post tunnel	21	600	3.5%	96.5%	100%
CPC post ins	600	600	100%	0%	100%
EEPS post ins	600	600	100%	0%	100%

EEPS Pre-run Instrument Blank Descriptive Statistics of Size Distribution

	N	Minimum	Maximum	Mean	Std. Deviation
c1	600	.00	226.88	21.31	31.10
c2	600	.00	228.91	42.48	47.95
c3	600	.00	284.92	52.17	57.57
c4	600	.00	1225.04	63.75	86.72
c5	600	.00	1263.41	58.63	85.48
c6	600	.00	350.05	30.23	39.11
c7	600	.00	161.63	21.64	28.70
c8	600	.00	177.80	20.49	25.90
c9	600	.00	208.41	19.86	25.52
c10	600	.00	144.84	19.40	26.30
c11	600	.00	148.06	19.07	27.10
c12	600	.00	114.28	16.25	21.97
c13	600	.00	121.99	14.58	20.74
c14	600	.00	129.60	11.82	17.92
c15	600	.00	106.42	9.74	15.56
c16	600	.00	83.33	7.82	13.86
c17	600	.00	73.38	6.93	12.25
c18	600	.00	65.53	4.96	8.98
c19	600	.00	65.92	4.94	8.64
c20	600	.00	56.52	5.52	8.14
c21	600	.00	41.64	5.81	7.47
c22	600	.00	28.47	4.92	6.00
c23	600	.00	26.38	4.12	5.11
c24	600	.00	24.70	2.71	3.90
c25	600	.00	20.69	2.00	3.28
c26	600	.00	16.33	1.39	2.45
c27	600	.00	11.51	1.03	1.91
c28	600	.00	6.94	.71	1.31
c29	600	.00	6.69	.74	1.33
c30	600	.00	9.07	.85	1.51
c31	600	.00	10.20	.92	1.61
c32	600	.00	9.64	.85	1.44
Valid N (listwise)	600				

EEPS Pre-run Tunnel Blank Descriptive Statistics of Size Distribution

	N	Minimum	Maximum	Mean	Std. Deviation
p1	600	.00	247.58	23.31	32.71
p2	600	.00	223.91	40.06	47.82
p3	600	.00	331.36	50.55	59.24
p4	600	.00	957.92	66.59	88.94
p5	600	.00	960.98	63.58	87.35
p6	600	.00	323.47	36.92	40.75
p7	600	.00	160.76	26.52	29.36
p8	600	.00	121.49	23.27	26.70
p9	600	.00	139.03	20.18	25.57
p10	600	.00	126.12	18.77	24.22
p11	600	.00	116.16	18.26	24.04
p12	600	.00	446.44	17.63	28.46
p13	600	.00	564.30	17.42	33.04
p14	600	.00	384.93	13.86	26.12
p15	600	.00	369.00	11.89	23.22
p16	600	.00	516.51	11.78	26.81
p17	600	.00	428.06	11.18	23.08
p18	600	.00	103.66	7.75	11.76
p19	600	.00	50.37	6.62	10.02
p20	600	.00	39.02	6.19	8.81
p21	600	.00	40.19	6.02	7.65
p22	600	.00	34.24	5.35	6.09
p23	600	.00	32.58	4.48	5.43
p24	600	.00	23.45	2.83	4.13
p25	600	.00	18.36	2.06	3.31
p26	600	.00	13.99	1.48	2.51
p27	600	.00	12.43	1.17	2.03
p28	600	.00	9.90	.90	1.52
p29	600	.00	18.95	1.01	1.79
p30	600	.00	33.00	1.16	2.32
p31	600	.00	37.05	1.21	2.47
p32	600	.00	31.08	1.08	2.09
Valid N (listwise)	600				

EEPS Post-run Tunnel Blank Descriptive Statistics of Size Distribution

Channel Number	N	Minimum	Maximum	Mean	Std. Deviation
1	21	1039.37	1312.70	1179.26	85.50
2	21	1403.37	1865.38	1624.79	123.24
3	21	2938.64	3382.78	3129.04	145.06
4	21	5344.44	6255.25	5692.02	238.05
5	21	5488.40	6451.86	5817.25	236.55
6	21	3297.48	3707.36	3504.73	120.63
7	21	1894.13	2250.76	2019.89	99.53
8	21	1242.59	1626.31	1362.73	97.49
9	21	674.64	1033.68	816.41	87.38
10	21	241.01	553.27	380.93	67.86
11	21	76.09	331.73	213.19	56.35
12	21	220.54	442.08	313.20	43.49
13	21	320.83	511.73	388.38	44.07
14	21	367.97	540.71	438.74	43.75
15	21	418.78	558.68	486.53	42.27
16	21	456.98	591.75	531.76	37.40
17	21	433.02	577.43	511.61	34.04
18	21	346.88	480.26	426.08	29.36
19	21	267.64	373.95	331.26	24.89
20	21	195.29	258.80	227.13	19.29
21	21	114.77	181.81	149.86	16.95
22	21	65.68	127.54	99.42	13.96
23	21	34.58	84.90	62.36	11.85
24	21	21.48	54.30	38.69	8.69
25	21	8.69	34.17	21.57	6.96
26	21	1.26	21.46	11.00	5.36
27	21	.00	12.45	4.83	4.08
28	21	.00	6.82	2.56	2.50
29	21	.00	5.05	1.43	1.87
30	21	.00	4.51	1.27	1.65
31	21	.00	4.09	1.13	1.54
32	21	.00	3.80	.98	1.34
Valid N (listwise)	21				

EEPS Post-run Instrument Blank Descriptive Statistics of Size Distribution

Channel Number	N	Minimum	Maximum	Mean	Std. Deviation
1	600	.00	242.47	4.91	17.37
2	600	.00	208.28	30.86	44.24
3	600	.00	402.07	48.11	58.96
4	600	.00	1117.25	50.80	75.35
5	600	.00	1086.00	42.62	69.82
6	600	.00	308.32	19.25	31.54
7	600	.00	105.77	11.24	20.82
8	600	.00	105.90	10.58	19.15
9	600	.00	122.78	12.67	21.10
10	600	.00	149.64	17.85	24.24
11	600	.00	174.92	19.60	25.89
12	600	.00	134.41	15.56	22.66
13	600	.00	169.53	13.15	22.48
14	600	.00	177.46	9.45	19.36
15	600	.00	137.19	5.94	13.86
16	600	.00	48.73	3.11	7.95
17	600	.00	55.82	2.75	7.31
18	600	.00	43.03	1.78	5.34
19	600	.00	32.35	1.81	4.93
20	600	.00	36.10	2.65	6.07
21	600	.00	41.81	3.19	6.75
22	600	.00	42.17	3.10	6.14
23	600	.00	40.44	2.66	5.50
24	600	.00	38.57	1.66	4.02
25	600	.00	28.40	1.30	3.20
26	600	.00	11.58	.78	2.03
27	600	.00	10.66	.49	1.42
28	600	.00	4.79	.19	.70
29	600	.00	5.07	.18	.61
30	600	.00	7.15	.27	.76
31	600	.00	7.91	.38	.94
32	600	.00	7.19	.38	.90
Valid N (listwise)	600				

Run 1 pre-purge descriptive statistics for FTIR

	N	Minimum	Maximum	Mean	Std. Deviation
124Trimethylbenzene	74	-3.54	3.98	-0.23	1.38
12Propadiene	74	-1.06	0.54	-0.13	0.40
135Trimethylbenzene	74	-1.05	1.23	0.09	0.51
13Butadiene	74	-1.92	1.77	-0.11	0.87
2methyl2butene	74	-7.64	9.49	0.82	2.85
2Methylpropene	74	-1.01	1.34	0.04	0.47
Acetylene	74	-0.94	0.86	0.00	0.38
CH4	74	-0.54	0.48	-0.04	0.21
Coppm	74	-0.95	1.26	0.01	0.45
CO	74	0.00	0.00	0.00	0.00
CO2	74	-0.04	0.03	0.00	0.02
Ethane	74	-1.32	1.09	-0.01	0.60
Ethanol	74	-3.08	2.28	-0.16	0.82
Ethylene	74	-0.48	0.72	0.09	0.23
Formaldehyde	74	-0.80	0.64	-0.02	0.30
H2O	74	-0.03	0.04	0.00	0.01
IsoOctane	74	-0.81	1.94	-0.04	0.36
mXylene	74	-5.02	3.35	-0.11	1.80
MeOH	74	-0.70	1.02	0.10	0.38
N2O	74	-0.14	0.22	0.03	0.08
NH3	74	-0.26	0.25	-0.01	0.11
NO	74	-1.02	0.71	-0.04	0.32
NO2	74	-0.35	0.31	-0.03	0.12
Octane	74	-0.72	0.84	-0.01	0.37
Propylene	74	-3.75	3.42	-0.33	1.54
Propyne	74	-2.21	2.37	0.31	1.07
SO2	74	-0.66	0.51	-0.10	0.29
Toluene	74	-9.92	15.83	-0.32	4.97
TempC	74	189.01	191.25	190.30	0.52
PressureAtm	74	1.00	1.00	1.00	0.00
IgramDC	74	0.00	0.34	0.26	0.05
IgramPP	74	0.00	0.14	0.12	0.02
phaseAngle	74	0.00	0.25	0.21	0.04
laserPP	74	0.00	0.21	0.16	0.03
laserDC	74	0.00	0.65	0.57	0.10
BadScancounter	74	0.00	0.21	0.18	0.03
CenterburstLocation	74	0.00	0.21	0.19	0.03
LinearizerCheck	74	0.00	0.34	0.29	0.05
SNR2500	74	0.00	0.47	0.33	0.07
sBeam@2500	74	0.00	0.00	0.00	0.00
Valid N (listwise)	74				

Run 1 post-purge descriptive statistics for FTIR

	N	Minimum	Maximum	Mean	Std. Deviation
124Trimethylbenzene	539	-8.31	7.24	-1.03	2.41
12Propadiene	539	-2.96	3.20	0.23	0.87
135Trimethylbenzene	539	-3.76	4.27	0.26	1.15
13Butadiene	539	-6.63	4.92	-0.85	2.03
2methyl2butene	539	-20.44	21.79	1.28	6.95
2Methylpropene	539	-2.50	4.23	1.17	1.09
Acetylene	539	-7.15	6.52	0.07	2.07
CH4	539	-3.96	3.85	-0.17	1.24
Coppm	539	-7.15	5.30	0.06	2.02
CO	539	0.00	0.00	0.00	0.00
CO2	539	-0.21	0.23	-0.01	0.08
Ethane	539	-7.16	8.55	0.33	2.82
Ethanol	539	-14.01	3.71	-3.22	2.31
Ethylene	539	-1.46	1.69	0.09	0.55
Formaldehyde	539	-4.25	4.17	0.20	1.46
H2O	539	0.17	1.09	0.49	0.20
IsoOctane	539	-4.35	2.92	-0.80	1.34
mXylene	539	-7.20	11.03	0.82	3.25
MeOH	539	-2.70	2.61	-0.03	0.94
N2O	539	-1.08	1.13	0.00	0.36
NH3	539	-0.09	1.94	0.62	0.28
NO	539	-4.04	4.45	0.02	1.29
NO2	539	-1.56	1.59	-0.03	0.45
Octane	539	-8.66	4.70	0.20	1.64
Propylene	539	-10.34	9.33	0.15	3.19
Propyne	539	-25.21	19.88	-0.96	6.99
SO2	539	-3.89	1.81	-0.83	0.90
Toluene	539	-107.93	76.02	1.52	23.90
TempC	539	190.23	190.64	190.45	0.06
PressureAtm	539	0.99	0.99	0.99	0.00
IgramDC	539	0.42	0.68	0.54	0.04
IgramPP	539	0.21	0.33	0.28	0.02
phaseAngle	539	0.35	0.55	0.46	0.03
laserPP	539	0.25	0.51	0.36	0.04
laserDC	539	1.15	1.52	1.32	0.07
BadScancounter	539	0.36	0.48	0.42	0.02
CenterburstLocation	539	0.87	1.20	1.02	0.05
LinearizerCheck	539	1.19	1.82	1.52	0.10
SNR2500	539	0.85	2.14	1.45	0.22
sBeam@2500	539	0.00	0.00	0.00	0.00
Valid N (listwise)	539				

Run 1 FTIR percent of missing data for pre and post-purge

	N points	Potential N points	% N points	% missing	Total
FTIR pre-purge	74	600	12.33%	87.67%	100.00%
FTIR post-purge	539	600	89.83%	10.17%	100.00%

Run 1 EEPS and CPC concentration descriptive statistics over entire run

	N	Minimum	Maximum	Mean	Std. Deviation
CPC Concentration	6091	22.00	99900.00	4035.27	12217.44
EEPS Concentration	6091	.00	417000.00	6766.02	18541.37
c1	6091	.00	7361.92	176.95	358.95
c2	6091	.00	11459.40	219.50	498.61
c3	6091	.00	25888.80	418.71	1343.30
c4	6091	.00	58785.40	1016.63	3248.42
c5	6091	.00	70963.80	1055.39	3658.36
c6	6091	.00	63695.60	527.50	2692.55
c7	6091	.00	56334.10	337.16	2159.65
c8	6091	.00	48879.30	331.58	1803.70
c9	6091	.00	37025.60	283.52	1348.00
c10	6091	.00	22074.70	209.04	776.88
c11	6091	.00	13020.80	160.26	443.94
c12	6091	.00	9864.04	228.94	447.43
c13	6091	.00	8132.25	291.77	523.29
c14	6091	.00	8388.29	290.99	524.77
c15	6091	.00	9061.31	254.39	465.67
c16	6091	.00	9565.45	198.69	390.08
c17	6091	.00	9994.81	170.39	369.72
c18	6091	.00	10349.40	130.97	346.98
c19	6091	.00	9720.71	112.83	318.76
c20	6091	.00	8108.75	88.36	259.28
c21	6091	.00	6142.65	67.12	193.95
c22	6091	.00	3822.40	46.06	121.33
c23	6091	.00	2117.27	31.03	70.03
c24	6091	.00	1027.26	20.30	39.23
c25	6091	.00	364.96	14.35	24.12
c26	6091	.00	206.48	11.31	18.80
c27	6091	.00	229.04	8.37	14.50
c28	6091	.00	264.14	8.21	16.25
c29	6091	.00	400.02	11.77	26.39
c30	6091	.00	596.88	15.29	35.56
c31	6091	.00	633.66	15.67	36.70
c32	6091	.00	496.36	12.60	29.38
Valid N (listwise)	6091				

Run 1 GPS receivers descriptive statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Garmin latitude	5112	44.287878	44.488890	44.407352	.061163
Geologger latitude	2103	44.288070	44.488850	44.386361	.058888
Garmin longitude	5112	-73.219018	-72.937057	-73.096172	.090131
Geologger longitude	2103	-73.219020	-72.950080	73.079770	.085908
Garmin altitude (m)	5112	42.8	233.2	128.068	40.6582
Valid N (listwise)	2103				

Run 1 descriptive statistics for Labview device 1 parameters

	N	Minimum	Maximum	Mean	Std. Deviation
Tailpipe Thermo	6151	64.18	376.08	206.1088	72.69955
Heated Line Thermo	1321	38.61	109.53	62.0850	4.20855
Accelerometer (x)	6151	2.17	2.74	2.4902	.06333
Accelerometer (y)	6151	2.10	3.22	2.4920	.06948
Accelerometer(z)	6151	.99	2.15	1.4877	.05820
Total Pressure	6151	.87	1.07	1.0156	.00787
Valid N (listwise)	1321				

Run 1 descriptive statistics for Labview device 2 parameters

	N	Minimum	Maximum	Mean	Std. Deviation
Differential Pressure 1	6151	.00	7.04	.5093	.91394
Differential Pressure 2	6151	.05	10.00	2.8060	3.41121
Differential Pressure 3	6151	.01	10.00	5.3607	4.32965
Differential Pressure 4	6151	5.52	10.00	9.3318	1.05717
Diluter pin 2	6151	2.31	3.95	2.8791	.03423
Diluter pin 5	6151	-10	-10	-10.00	.009
Diluter pin 16	6151	9.95	10.00	9.9926	.00890
Diluter pin 25	6151	5.00	5.00	5.0000	.00000
Valid N (listwise)	6151				

Run 1 descriptive statistics for ScanTool

	N	Minimum	Maximum	Mean	Std. Deviation
Throttle position	5436	11.00	35.00	15.0653	4.48290
RPM	5248	633.00	3452.00	1511.3035	572.08950
Mass Air Flow	5430	.40	8.49	2.0518	1.74793
Speed	5277	.00	70.00	32.0648	19.80613
Valid N (listwise)	5248				

Run 1 EEPS and CPC percent of missing data

	N points	Potential N points	% N points	% missing	Total
CPC Concentration	6091	6151	99.02%	0.98%	100%
EEPS Concentration	6091	6151	99.02%	0.98%	100%
c1	6091	6151	99.02%	0.98%	100%
c2	6091	6151	99.02%	0.98%	100%
c3	6091	6151	99.02%	0.98%	100%
c4	6091	6151	99.02%	0.98%	100%
c5	6091	6151	99.02%	0.98%	100%
c6	6091	6151	99.02%	0.98%	100%
c7	6091	6151	99.02%	0.98%	100%
c8	6091	6151	99.02%	0.98%	100%
c9	6091	6151	99.02%	0.98%	100%
c10	6091	6151	99.02%	0.98%	100%
c11	6091	6151	99.02%	0.98%	100%
c12	6091	6151	99.02%	0.98%	100%
c13	6091	6151	99.02%	0.98%	100%
c14	6091	6151	99.02%	0.98%	100%
c15	6091	6151	99.02%	0.98%	100%
c16	6091	6151	99.02%	0.98%	100%
c17	6091	6151	99.02%	0.98%	100%
c18	6091	6151	99.02%	0.98%	100%
c19	6091	6151	99.02%	0.98%	100%
c20	6091	6151	99.02%	0.98%	100%
c21	6091	6151	99.02%	0.98%	100%
c22	6091	6151	99.02%	0.98%	100%
c23	6091	6151	99.02%	0.98%	100%
c24	6091	6151	99.02%	0.98%	100%
c25	6091	6151	99.02%	0.98%	100%
c26	6091	6151	99.02%	0.98%	100%
c27	6091	6151	99.02%	0.98%	100%
c28	6091	6151	99.02%	0.98%	100%
c29	6091	6151	99.02%	0.98%	100%
c30	6091	6151	99.02%	0.98%	100%
c31	6091	6151	99.02%	0.98%	100%
c32	6091	6151	99.02%	0.98%	100%

Run 1 percent of missing data for all operational parameters

	N points	Potential N points	% N points	% missing	Total
Garmin latitude	5112	6151	83.11%	16.89%	100%
Geologger latitude	2103	6151	34.19%	65.81%	100%
Garmin longitude	5112	6151	83.11%	16.89%	100%
Geologger longitude	2103	6151	34.19%	65.81%	100%
Garmin altitude (m)	5112	6151	83.11%	16.89%	100%
Total Distance (m)	5112	6151	83.11%	16.89%	100%
Distance (m)	5112	6151	83.11%	16.89%	100%
Leg Bearing	5112	6151	83.11%	16.89%	100%
Garmin Speed (km/h)	5112	6151	83.11%	16.89%	100%
Tailpipe Thermo	6151	6151	100.00%	0.00%	100%
Heated Line Thermo	1321	6151	21.48%	78.52%	100%
Accelerometer (x)	6151	6151	100.00%	0.00%	100%
Accelerometer (y)	6151	6151	100.00%	0.00%	100%
Accelerometer(z)	6151	6151	100.00%	0.00%	100%
Total Pressure	6151	6151	100.00%	0.00%	100%
Differential Pressure 1	6151	6151	100.00%	0.00%	100%
Differential Pressure 2	6151	6151	100.00%	0.00%	100%
Differential Pressure 3	6151	6151	100.00%	0.00%	100%
Differential Pressure 4	6151	6151	100.00%	0.00%	100%
Diluter pin 2	6151	6151	100.00%	0.00%	100%
Diluter pin 5	6151	6151	100.00%	0.00%	100%
Diluter pin 16	6151	6151	100.00%	0.00%	100%
Diluter pin 25	6151	6151	100.00%	0.00%	100%
Relative Humidity (in)	6151	6151	100.00%	0.00%	100%
Relative Humidity (out)	6151	6151	100.00%	0.00%	100%
Temperature (in)	6151	6151	100.00%	0.00%	100%
Temperature (out)	6151	6151	100.00%	0.00%	100%
Throttle position	5436	6151	88.38%	11.62%	100%
RPM	5248	6151	85.32%	14.68%	100%
Mass Air Flow	5430	6151	88.28%	11.72%	100%
Speed	5277	6151	85.79%	14.21%	100%

Run 1 FTIR monitoring parameters descriptive statistics

TempC	5669	187.99	191.55	190.09	0.74
PressureAtm	5669	0.94	0.99	0.98	0.01
IgramDC	5669	0.35	90.55	0.73	1.42
IgramPP	5669	0.11	55.97	0.19	0.76
phaseAngle	5669	0.20	84.76	0.41	1.25
laserPP	5669	0.10	64.07	0.22	0.86
laserDC	5669	0.62	241.74	1.18	3.47
BadScancounter	5669	0.18	81.86	0.32	1.12
CenterburstLocation	5669	0.33	51.09	0.56	0.84
LinearizerCheck	5669	0.34	45.60	0.68	0.72
SNR2500	5669	0.27	143.20	7.34	12.47
sBeam@2500	5669	0.00	0.08	0.00	0.00
Valid N (listwise)	5669				

Run 1 descriptive statistics for FTIR

	N	Minimum	Maximum	Mean	Std. Deviation
124Trimethylbenzene	5669	-127.74	183.45	-.08	6.92
12Propadiene	5669	-64.65	6.94	-.16	1.53
135Trimethylbenzene	5669	-55.31	198.58	-.04	3.37
13Butadiene	5669	-50.33	264.67	2.09	6.19
2methyl2butene	5669	-165.50	197.59	7.83	20.91
2Methylpropene	5669	-101.66	29.22	2.42	5.40
Acetylene	5669	-98.86	87.36	4.78	16.15
CH4	5669	1.66	184.81	35.50	24.95
COppm	5669	-.62	6819.61	722.14	1314.34
CO	5669	.00	.62	.06	.12
CO2	5669	.43	20.85	12.74	2.01
Ethane	5669	-8.14	46.41	5.04	6.77
Ethanol	5669	-211.46	330.37	7.71	18.40
Ethylene	5669	-312.40	289.89	14.24	42.69
Formaldehyde	5669	1.17	116.59	14.86	16.06
H2O	5669	4.97	86.50	10.45	6.34
IsoOctane	5669	-6.07	131.24	8.48	23.43
mXylene	5669	-2129.44	145.98	2.08	30.48
MeOH	5669	-17.52	153.98	2.09	3.81
N2O	5669	-2.16	250.27	10.90	20.29
NH3	5669	-31.89	275.39	12.45	15.96
NO	5669	-8.14	2579.86	172.54	293.38
NO2	5649	-1008.39	1290.40	.42	23.66
Octane	5669	-13.61	126.79	8.32	22.52
Propylene	5669	-12.33	397.70	6.37	18.27
Propyne	5669	-598.43	18.26	.55	10.08
SO2	5669	-107.03	338.06	.96	6.72
Toluene	5669	-2213.34	204.91	7.16	49.40
Valid N (listwise)	5649				

Run 1 percent of missing data for FTIR

	N points	Potential N points	% N points	% missing	Total
124Trimethylbenzene	5669	6151	92.16%	7.84%	100.00%
12Propadiene	5669	6151	92.16%	7.84%	100.00%
135Trimethylbenzene	5669	6151	92.16%	7.84%	100.00%
13Butadiene	5669	6151	92.16%	7.84%	100.00%
2methyl2butene	5669	6151	92.16%	7.84%	100.00%
2Methylpropene	5669	6151	92.16%	7.84%	100.00%
Acetylene	5669	6151	92.16%	7.84%	100.00%
CH4	5669	6151	92.16%	7.84%	100.00%
COppm	5669	6151	92.16%	7.84%	100.00%
CO	5669	6151	92.16%	7.84%	100.00%
CO2	5669	6151	92.16%	7.84%	100.00%
Ethane	5669	6151	92.16%	7.84%	100.00%
Ethanol	5669	6151	92.16%	7.84%	100.00%
Ethylene	5669	6151	92.16%	7.84%	100.00%
Formaldehyde	5669	6151	92.16%	7.84%	100.00%
H2O	5669	6151	92.16%	7.84%	100.00%
IsoOctane	5669	6151	92.16%	7.84%	100.00%
mXylene	5669	6151	92.16%	7.84%	100.00%
MeOH	5669	6151	92.16%	7.84%	100.00%
N2O	5669	6151	92.16%	7.84%	100.00%
NH3	5669	6151	92.16%	7.84%	100.00%
NO	5669	6151	92.16%	7.84%	100.00%
NO2	5649	6151	91.84%	8.16%	100.00%
Octane	5669	6151	92.16%	7.84%	100.00%
Propylene	5669	6151	92.16%	7.84%	100.00%
Propyne	5669	6151	92.16%	7.84%	100.00%
SO2	5669	6151	92.16%	7.84%	100.00%
Toluene	5669	6151	92.16%	7.84%	100.00%

12.2 Sampling Run 1.5 Descriptive Statistics (Vibration Noise Run)

Run 1.5: EEPS and CPC Concentrations

	N	Minimum	Maximum	Mean	Std. Deviation
CPC_Total_C	5403	.00	.59	.0471	.10831
EEPS_Total_C	5343	.46	11600.00	1252.4686	1109.82315
c6.04	5343	.00	755.50	48.9447	86.31308
c6.98	5343	.00	867.43	41.8921	74.06277
c8.06	5343	.00	1069.65	60.9666	105.10780
c9.31	5343	.00	3109.29	155.6164	275.98544
c10.80	5343	.00	3062.62	163.0781	282.72392
c12.40	5343	.00	1313.13	81.5097	129.16027
c14.30	5343	.00	1067.03	57.2156	92.37425
c16.50	5343	.00	1408.87	52.2975	92.17771
c19.10	5343	.00	1385.31	52.1589	92.47902
c22.10	5343	.00	793.43	48.1123	79.52154
c25.50	5343	.00	833.37	50.5720	81.23957
c29.40	5343	.00	1005.89	53.0997	84.37050
c34.00	5343	.00	1353.61	56.1070	88.42782
c39.20	5343	.00	1292.57	52.1271	80.76983
c45.30	5343	.00	1039.69	44.1922	67.71462
c52.30	5343	.00	688.94	32.5347	49.58618
c60.40	5343	.00	697.40	27.2788	40.79377
c69.80	5343	.00	287.99	19.9164	25.30617
c80.60	5343	.00	139.31	17.6857	20.94934
c93.10	5343	.00	137.16	14.8163	17.51386
c107.50	5343	.00	158.34	13.0066	15.69321
c124.10	5343	.00	165.16	11.6609	15.14323
c143.30	5343	.00	169.51	12.2198	16.53718
c165.50	5343	.00	182.67	13.8220	18.43812
c191.10	5343	.00	187.42	13.8690	18.70930
c220.70	5343	.00	173.45	12.0830	16.63523
c254.80	5343	.00	131.03	9.7740	13.23066
c294.30	5343	.00	121.06	7.1526	9.46155
c339.80	5343	.00	120.82	6.9669	10.40375
c392.40	5343	.00	149.85	7.6725	12.67899
c453.20	5343	.00	155.71	7.6524	13.18047
c523.30	5343	.00	126.17	6.4363	11.13584
EEPS_Column_Pressure_mbar	5343	964.80	992.50	983.5980	4.62650
EEPS_sample_Temp_Celsius	5343	25.40	27.70	26.4732	.68058
Valid N (listwise)	5343				

Run 1.5: GPS Recievers

	N	Minimum	Maximum	Mean	Std. Deviation
Latitude	5091	44.38079	44.49333	44.45224	.03486
Longitude	5091	-73.21904	-72.93698	-73.12308	.08809
GEO_Latitude	4142	44.38077	44.49332	44.44477	.03508
GEO_Longitude	4142	-73.21900	-72.93702	73.10559	.08939
Valid N (listwise)	4142				

Run 1.5: Labview Device 1

	N	Minimum	Maximum	Mean	Std. Deviation
Tailpipe_Temp	5403	61.96	373.28	201.1231	68.08923
Total_Pressure	5403	.83	2.95	1.0152	.02827
Accel_x	5403	2.10	2.86	2.5359	.07850
Accel_y	5403	2.06	3.09	2.5502	.07842
Accel_z	5403	1.04	2.06	1.5036	.06164
Valid N (listwise)	5403				

Run 1.5 Labview Device 2

	N	Minimum	Maximum	Mean	Std. Deviation
DiffP1	5403	.00	10.00	.5412	1.16899
DiffP2	5403	.03	10.00	2.5474	3.51494
DiffP3	5403	.00	10.00	4.5038	4.27287
DiffP4	5403	5.11	10.00	9.3310	.97642
Valid N (listwise)	5403				

Run 1.5: ScanTool

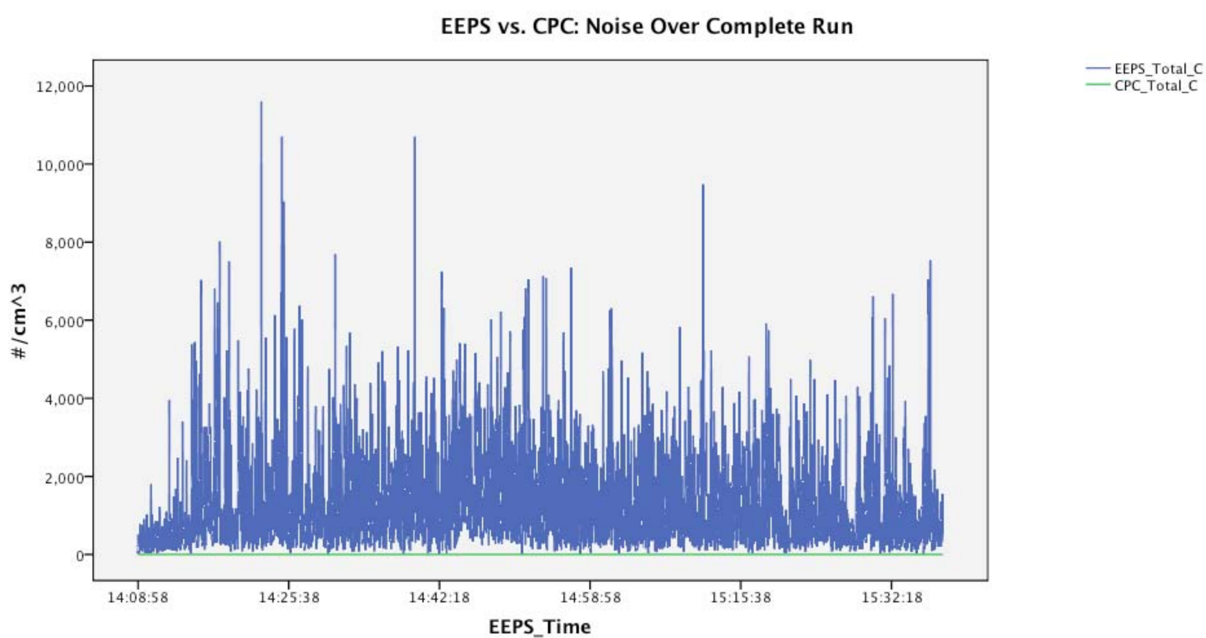
	N	Minimum	Maximum	Mean	Std. Deviation
Mass_air_flow	5346	.41	15.63	1.8973	1.90736
SCN_Speed	5364		75	27.28	19.883
RPM	5367	114	4578	1451.21	649.978
Throttle_position	5371	11	58	14.63	5.084
Valid N (listwise)	5346				

Percent of Missing Data: Particle Instruments

	N points	Potential N points	% N points	% missing	Total
CPC Concentration	5403	5403	100.00%	0.00%	100%
EEPS Concentration	5343	5403	98.89%	1.11%	100%
c1	5343	5403	98.89%	1.11%	100%
c2	5343	5403	98.89%	1.11%	100%
c3	5343	5403	98.89%	1.11%	100%
c4	5343	5403	98.89%	1.11%	100%
c5	5343	5403	98.89%	1.11%	100%
c6	5343	5403	98.89%	1.11%	100%
c7	5343	5403	98.89%	1.11%	100%
c8	5343	5403	98.89%	1.11%	100%
c9	5343	5403	98.89%	1.11%	100%
c10	5343	5403	98.89%	1.11%	100%
c11	5343	5403	98.89%	1.11%	100%
c12	5343	5403	98.89%	1.11%	100%
c13	5343	5403	98.89%	1.11%	100%
c14	5343	5403	98.89%	1.11%	100%
c15	5343	5403	98.89%	1.11%	100%
c16	5343	5403	98.89%	1.11%	100%
c17	5343	5403	98.89%	1.11%	100%
c18	5343	5403	98.89%	1.11%	100%
c19	5343	5403	98.89%	1.11%	100%
c20	5343	5403	98.89%	1.11%	100%
c21	5343	5403	98.89%	1.11%	100%
c22	5343	5403	98.89%	1.11%	100%
c23	5343	5403	98.89%	1.11%	100%
c24	5343	5403	98.89%	1.11%	100%
c25	5343	5403	98.89%	1.11%	100%
c26	5343	5403	98.89%	1.11%	100%
c27	5343	5403	98.89%	1.11%	100%
c28	5343	5403	98.89%	1.11%	100%
c29	5343	5403	98.89%	1.11%	100%
c30	5343	5403	98.89%	1.11%	100%
c31	5343	5403	98.89%	1.11%	100%
c32	5343	5403	98.89%	1.11%	100%
EEPS_Column_Pressure_mbar	5343	5403	98.89%	1.11%	100%
EEPS_sample_Temp_Celsius	5343	5403	98.89%	1.11%	100%

Percent of Missing Data: Operational Parameters					
	N points	Potential N points	% N points	% missing	Total
Garmin Latitude	5091	5403	94.23%	5.77%	100%
Garmin Longitude	5091	5403	94.23%	5.77%	100%
GEO_Latitude	4142	5403	76.66%	23.34%	100%
GEO_Longitude	4142	5403	76.66%	23.34%	100%
Tailpipe_Temp	5403	5403	100.00%	0.00%	100%
Total_Pressure	5403	5403	100.00%	0.00%	100%
Accel_x	5403	5403	100.00%	0.00%	100%
Accel_y	5403	5403	100.00%	0.00%	100%
Accel_z	5403	5403	100.00%	0.00%	100%
DiffP1	5403	5403	100.00%	0.00%	100%
DiffP2	5403	5403	100.00%	0.00%	100%
DiffP3	5403	5403	100.00%	0.00%	100%
DiffP4	5403	5403	100.00%	0.00%	100%
Mass_air_flow	5346	5403	98.95%	1.05%	100%
SCN_Speed	5364	5403	99.28%	0.72%	100%
RPM	5367	5403	99.33%	0.67%	100%
Throttle_position	5371	5403	99.41%	0.59%	100%

FIGURE C-1. RUN 1.5 PLOT OF NOISE ON EEPS AND CPC:



12.3 Sampling Run 1.75 Descriptive Statistics (Tiltmeter)

Run 1.75: Labview Device 2

	N	Minimum	Maximum	Mean	Std. Deviation
DiffP1	5369	.00	10.00	.5970	1.10459
DiffP2	5369	.07	10.00	2.8134	3.61761
DiffP3	5369	.06	10.00	4.9846	4.36710
DiffP4	5369	6.05	10.00	9.3586	.91816
Valid N (listwise)	5369				

Run 1.75: Labview Device 1

	N	Minimum	Maximum	Mean	Std. Deviation
Tailpipe_Temp	5369	82.74	374.88	227.1176	54.55964
Total_Pressure	5369	.64	2.58	1.0150	.03513
Accel_x	5369	1.96	2.89	2.5339	.08685
Accel_y	5369	1.44	3.38	2.5343	.08121
Accel_z	5369	1.05	2.14	1.4971	.06295
Valid N (listwise)	5369				

Run 1.75: GPS Recievers

	N	Minimum	Maximum	Mean	Std. Deviation
Latitude	3952	44.38077	44.48889	44.45575	.03530
Longitude	3952	-73.21903	-72.93705	-73.13491	.09160
GEO_latitude	4410	44.38075	44.48903	44.44519	.03453
GEO_Longitude	4410	-73.21902	-72.93708	73.11018	.08869
Valid N (listwise)	3952				

Run 1.75: ScanTool

	N	Minimum	Maximum	Mean	Std. Deviation
Mass_air_flow	5168	.41	9.98	2.0884	1.92430
SCN_Speed	5223	0.00	75	27.56	20.116
RPM	5175	628	3448	1492.20	659.176
Throttle_position	5220	11	44	15.11	4.961
Valid N (listwise)	5223				

Percent of Missing Data

	N points	Potential N points	% N points	% missing	Total
DiffP1	5369	5369	100.00%	0.00%	100%
DiffP2	5369	5369	100.00%	0.00%	100%
DiffP3	5369	5369	100.00%	0.00%	100%
DiffP4	5369	5369	100.00%	0.00%	100%
Tailpipe_Temp	5369	5369	100.00%	0.00%	100%
Total_Pressure	5369	5369	100.00%	0.00%	100%
Accel_x	5369	5369	100.00%	0.00%	100%
Accel_y	5369	5369	100.00%	0.00%	100%
Accel_z	5369	5369	100.00%	0.00%	100%
Garmin Latitude	3952	5369	73.61%	26.39%	100%
Garmin Longitude	3952	5369	73.61%	26.39%	100%
GEO_latitude	4410	5369	82.14%	17.86%	100%
GEO_Longitude	4410	5369	82.14%	17.86%	100%
Mass_air_flow	5168	5369	96.26%	3.74%	100%
SCN_Speed	5223	5369	97.28%	2.72%	100%
RPM	5175	5369	96.39%	3.61%	100%
Throttle_position	5220	5369	97.22%	2.78%	100%

12.4 Sampling Run 2 Descriptive Statistics

Run 2: EEPS and CPC Concentrations

	N	Range	Minimum	Maximum	Mean	Std. Deviation
EEPS Concentration	4278	93743.10	56.90	93800.00	3876.24	6568.22
CPC Concentration	4218	99894.89	5.11	99900.00	3168.70	9627.69
c6.04	4218	7827.09	.00	7827.09	174.41	246.93
c6.98	4218	7619.40	.00	7619.40	160.39	236.00
c8.06	4218	6738.45	.00	6738.45	187.24	248.62
c9.31	4218	6869.59	.00	6869.59	296.17	376.46
c10.8	4218	6158.22	.00	6158.22	293.10	369.42
c12.4	4218	3420.05	.00	3420.05	176.51	206.81
c14.3	4218	2230.15	.00	2230.15	145.26	179.51
c16.5	4218	2820.57	.00	2820.57	163.43	218.45
c19.1	4218	2763.97	.00	2763.97	157.24	212.08
c22.1	4218	1959.78	.00	1959.78	122.10	151.81
c25.5	4218	2543.46	.00	2543.46	120.98	172.62
c29.4	4218	4447.03	.00	4447.03	151.60	281.81
c34	4218	5986.54	.00	5986.54	176.47	374.76
c39.2	4218	7162.00	.00	7162.00	187.69	444.15
c45.3	4218	8082.87	.00	8082.87	189.24	500.96
c52.3	4218	8770.28	.00	8770.28	182.76	544.93
c60.4	4218	9281.70	.00	9281.70	182.21	591.71
c69.8	4218	9498.90	.00	9498.90	182.54	641.72
c80.6	4218	8920.21	.00	8920.21	168.31	606.87
c93.1	4218	7297.99	.00	7297.99	136.28	486.06
c107.5	4218	5389.05	.00	5389.05	102.54	354.09
c124.1	4218	3234.70	.00	3234.70	67.07	210.17
c143.3	4218	1690.00	.00	1690.00	42.06	108.50
c165.5	4218	754.94	.00	754.94	27.10	49.59
c191.1	4218	191.22	.00	191.22	17.84	21.18
c220.7	4218	147.43	.00	147.43	13.80	16.78
c254.8	4218	124.66	.00	124.66	10.99	13.67
c294.3	4218	115.61	.00	115.61	8.45	10.04
c339.8	4218	101.69	.00	101.69	8.14	10.76
c392.4	4218	121.34	.00	121.34	8.71	13.06
c453.2	4218	123.54	.00	123.54	8.54	13.52
c523.3	4218	104.97	.00	104.97	7.13	11.38
EEPS Column Pressure (mBar)	4218	27.60	945.70	973.30	963.54	4.71
EEPS Sample Temp (Celsius)	4218	5.10	24.30	29.40	27.77	1.27
Valid N (listwise)	4218					

Run 2: GPS Recievers

	N	Range	Minimum	Maximum	Mean	Std. Deviation
GEO_latitude	3812	.10752	44.38078	44.48830	44.4424038	.03322396
GEO_longitude	3812	.28194	72.93708	73.21902	73.1029232	.08871895
Valid N (listwise)	3812					

Run 2: Labview Device 1

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Tailpipe_Temp	4218	368.90	39.19	408.09	248.9049	60.10884
HL_Temp	4218	19.73	77.34	97.07	88.8078	3.93669
Total_pressure	4218	.10	.98	1.08	1.0144	.00964
accel_x	4218	.72	2.18	2.90	2.5241	.08337
accel_y	4218	1.27	1.82	3.09	2.5232	.08275
accel_z	4218	1.02	.97	1.99	1.4859	.06935
Valid N (listwise)	4218					

Run 2: Labview Device 2

	N	Range	Minimum	Maximum	Mean	Std. Deviation
DiffP1	4218	10.00	.00	10.00	.8371	1.49344
DiffP2	4218	9.98	.02	10.00	3.4629	3.86815
DiffP3	4218	10.00	.00	10.00	5.6959	4.30808
DiffP4	4218	4.88	5.12	10.00	9.5277	.89208
Diluter Pin 2	4218	.56	2.68	3.24	2.7915	.02918
Diluter Pin 5	4218	.69	-10.00	-9.31	-9.9928	.03739
Diluter Pin 16	4218	.05	9.95	10.00	9.9920	.00935
Diluter Pin 25	4218	1.25	1.66	2.91	2.3635	.18913
Valid N (listwise)	4218					

Run 2: Relative Humidity and Temperature Loggers

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Temp_RHT_IN	4218	2.380	18.509	20.889	19.72463	.953782
RH_IN	4218	5.586	23.347	28.933	26.05428	1.348728
Temp_RHT_OUT	4218	4.187	16.749	20.936	19.25231	1.301225
RH_OUT	4218	9.353	23.743	33.096	27.27115	1.937017
Valid N (listwise)	4218					

Run 2: ScanTool

	N	Range	Minimum	Maximum	Mean	Std. Deviation
Mass_air_flow	4367	11.88	.03	11.91	2.3687	2.12866
Speed	4384	73		73	33.19	19.405
RPM	4407	3891		3891	1639.71	670.824
Throttle_position	4424	39	11	50	15.86	5.611
Valid N (listwise)	4367					

	N	Range	Minimum	Maximum	Mean	Std. Deviation
124Trimethylbenzene	3854	997.06	-808.94	188.12	-3.48	15.81
12Propadiene	3854	515.47	-120.92	394.55	-.86	6.78
135Trimethylbenzene	3854	378.40	-78.31	300.09	-1.72	6.98
13Butadiene	3854	1214.14	-396.81	817.34	1.99	15.63
2methyl2butene	3854	1301.75	-275.67	1026.08	-.60	20.95
2Methylpropene	3854	225.48	-181.16	44.31	1.47	4.35
Acetylene	3853	6074.13	-6.38	6067.75	3.07	98.61
CH4	3853	775.11	-.47	774.65	30.90	51.21
Coppm	3853	41918.75	-1.11	41917.64	1104.29	3692.20
CO	3853	4.27	-.01	4.26	.10	.38
CO2	3853	14.20	.01	14.21	12.90	2.05
Ethane	3854	979.94	-774.42	205.52	4.04	16.56
Ethanol	3854	216.44	-153.91	62.53	5.06	3.79
Ethylene	3854	1453.68	-738.56	715.12	5.09	38.64
Formaldehyde	3853	44.04	-2.93	41.11	.38	1.17
H2O	3854	66.03	1.81	67.83	11.19	2.69
IsoOctane	3854	5116.67	-15.40	5101.27	3.99	83.87
mXylene	3854	1357.22	-380.59	976.64	-2.67	23.60
MeOH	3854	274.45	-169.24	105.20	1.07	3.48
N2O	3854	206.86	-4.47	202.39	7.64	16.46
NH3	3854	353.43	-32.14	321.29	32.78	21.59
NO	3853	1411.31	-279.48	1131.84	118.11	156.83
NO2	3845	339.99	-90.41	249.59	.84	4.63
Octane	3854	6255.06	-86.01	6169.05	3.72	99.88
Propylene	3854	7568.44	-5997.61	1570.83	.07	100.39
Propyne	3852	2806.86	-2755.97	50.90	-1.34	44.71
SO2	3853	1133.18	-826.14	307.04	-.02	17.47
Toluene	3854	21037.16	-20438.27	598.88	-8.19	330.89
Valid N (listwise)	3845					

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
TempC	3854	187.99	191.55	190.57	.67
PressureAtm	3854	.93	1.00	.97	.01
IgramDC	3854	-15.69	-10.19	-12.92	1.41
IgramPP	3854	.11	6.16	2.76	1.76
phaseAngle	3854	88.24	88.94	88.76	.31
laserPP	3854	4.39	4.82	4.63	.09
laserDC	3854	-7.06	-6.75	-6.95	.04
BadScancounter	3854	2.00	3.00	2.02	.15
CenterburstLocation	3854	1140.18	7282.59	1142.82	98.93
LinearizerCheck	3854	.00	.09	.00	.00
SNR2500	3854	.11	1404.25	479.40	279.10
sBeam@2500	3854	.00	1.21	.72	.47
Valid N (listwise)	3854				

Missing Data: EEPS and CPC					
	N points	Potential N points	% N points	% missing	Total
EEPS Concentration	4218	4218	100.00%	0.00%	100%
CPC Concentration	4158	4218	98.58%	1.42%	100%
c6.04	4158	4218	98.58%	1.42%	100%
c6.98	4158	4218	98.58%	1.42%	100%
c8.06	4158	4218	98.58%	1.42%	100%
c9.31	4158	4218	98.58%	1.42%	100%
c10.8	4158	4218	98.58%	1.42%	100%
c12.4	4158	4218	98.58%	1.42%	100%
c14.3	4158	4218	98.58%	1.42%	100%
c16.5	4158	4218	98.58%	1.42%	100%
c19.1	4158	4218	98.58%	1.42%	100%
c22.1	4158	4218	98.58%	1.42%	100%
c25.5	4158	4218	98.58%	1.42%	100%
c29.4	4158	4218	98.58%	1.42%	100%
c34	4158	4218	98.58%	1.42%	100%
c39.2	4158	4218	98.58%	1.42%	100%
c45.3	4158	4218	98.58%	1.42%	100%
c52.3	4158	4218	98.58%	1.42%	100%
c60.4	4158	4218	98.58%	1.42%	100%
c69.8	4158	4218	98.58%	1.42%	100%
c80.6	4158	4218	98.58%	1.42%	100%
c93.1	4158	4218	98.58%	1.42%	100%
c107.5	4158	4218	98.58%	1.42%	100%
c124.1	4158	4218	98.58%	1.42%	100%
c143.3	4158	4218	98.58%	1.42%	100%
c165.5	4158	4218	98.58%	1.42%	100%
c191.1	4158	4218	98.58%	1.42%	100%
c220.7	4158	4218	98.58%	1.42%	100%
c254.8	4158	4218	98.58%	1.42%	100%
c294.3	4158	4218	98.58%	1.42%	100%
c339.8	4158	4218	98.58%	1.42%	100%
c392.4	4158	4218	98.58%	1.42%	100%
c453.2	4158	4218	98.58%	1.42%	100%
c523.3	4158	4218	98.58%	1.42%	100%
EEPS Column Pressure (mBar)	4158	4218	98.58%	1.42%	100%
EEPS Sample Temp (Celsius)	4158				

Missing Data: Operational Parameters					
	N points	Potential N points	% N points	% missing	Total
GEO_latitude	3812	4218	90.37%	9.63%	100%
GEO_longitude	3812	4218	90.37%	9.63%	100%
Tailpipe_Temp	4218	4218	100.00%	0.00%	100%
HL_Temp	4218	4218	100.00%	0.00%	100%
Total_pressure	4218	4218	100.00%	0.00%	100%
accel_x	4218	4218	100.00%	0.00%	100%
accel_y	4218	4218	100.00%	0.00%	100%
accel_z	4218	4218	100.00%	0.00%	100%
DiffP1	4218	4218	100.00%	0.00%	100%
DiffP2	4218	4218	100.00%	0.00%	100%
DiffP3	4218	4218	100.00%	0.00%	100%
DiffP4	4218	4218	100.00%	0.00%	100%
Dil2	4218	4218	100.00%	0.00%	100%
Dil16	4218	4218	100.00%	0.00%	100%
Dil5	4218	4218	100.00%	0.00%	100%
Dil25	4218	4218	100.00%	0.00%	100%
Temp_RHT_IN	4218	4218	100.00%	0.00%	100%
RH_IN	4218	4218	100.00%	0.00%	100%
Temp_RHT_OUT	4218	4218	100.00%	0.00%	100%
RH_OUT	4218	4218	100.00%	0.00%	100%
Mass_air_flow	4001	4218	94.86%	5.14%	100%
Speed	3969	4218	94.10%	5.90%	100%
RPM	4091	4218	96.99%	3.01%	100%
Throttle_position	3954	4218	93.74%	6.26%	100%

Missing Data: FTIR					
	N points	Potential N points	% N points	% missing	Total
124Trimethylbenzene	3854	4218	91.37%	8.63%	100.00%
12Propadiene	3854	4218	91.37%	8.63%	100.00%
135Trimethylbenzene	3854	4218	91.37%	8.63%	100.00%
13Butadiene	3854	4218	91.37%	8.63%	100.00%
2methyl2butene	3854	4218	91.37%	8.63%	100.00%
2Methylpropene	3854	4218	91.37%	8.63%	100.00%
Acetylene	3853	4218	91.35%	8.65%	100.00%
CH4	3853	4218	91.35%	8.65%	100.00%
Coppm	3853	4218	91.35%	8.65%	100.00%
CO	3853	4218	91.35%	8.65%	100.00%
CO2	3853	4218	91.35%	8.65%	100.00%
Ethane	3854	4218	91.37%	8.63%	100.00%
Ethanol	3854	4218	91.37%	8.63%	100.00%
Ethylene	3854	4218	91.37%	8.63%	100.00%
Formaldehyde	3853	4218	91.35%	8.65%	100.00%
H2O	3854	4218	91.37%	8.63%	100.00%
IsoOctane	3854	4218	91.37%	8.63%	100.00%
mXylene	3854	4218	91.37%	8.63%	100.00%
MeOH	3854	4218	91.37%	8.63%	100.00%
N2O	3854	4218	91.37%	8.63%	100.00%
NH3	3854	4218	91.37%	8.63%	100.00%
NO	3853	4218	91.35%	8.65%	100.00%
NO2	3845	4218	91.16%	8.84%	100.00%
Octane	3854	4218	91.37%	8.63%	100.00%
Propylene	3854	4218	91.37%	8.63%	100.00%
Propyne	3852	4218	91.32%	8.68%	100.00%
SO2	3853	4218	91.35%	8.65%	100.00%
Toluene	3854	4218	91.37%	8.63%	100.00%