In-use Emission Measurements of Snowmobiles and Snowcoaches in Yellowstone National Park

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EXECUTIVE SUMMARY

The University of Denver conducted a twelve day, winter, emissions measurement program in Yellowstone National Park that involved the collection of emissions data from in-use snowcoaches and snowmobiles between February 7 and February 18, 2005. In all more than 34 hours and 500 miles of mass emissions data were collected from nine snowcoaches and more than 960 snowmobile measurements were made. This report and all of the data sets collected are available for download from www.feat.biochem.du.edu.

- Both snowcoaches and 4-stroke snowmobiles have lower emissions per person than the 2-stroke snowmobiles. 4-stroke snowmobile emissions reductions averaged 61% for CO and greater than 96% for hydrocarbons compared to 2-strokes.

- 4-stroke snowmobiles have lower emissions per person than the measured mix of snowcoaches for CO. However, newer coaches with modern pollution controls have lower per person emissions than the current 4-stroke snowmobiles.

- The reduction in 4-stroke snowmobile hydrocarbons was significant (<96%) and readily observed. Visible exhaust plumes and odor were greatly reduced. The greater engine efficiency is reflected in an improved gas mileage by the 4-stroke snowmobiles.

- Among 4-stroke snowmobiles, the average CO emissions varied by a factor of 3 between manufacturers. The ratio of CO/NO emissions varied greatly based on the engine tuning by the manufacturer.

- The Arctic Cat and Polaris 4-stroke snowmobiles emitted roughly half as much CO and HC as the Ski Doo snowmobiles. No statistically significant difference in emissions was observed by model year.

- Higher CO and HC emissions were observed from the guide snowmobiles that had been turned off and restarted at the entrance gate.

- Snowmobile emissions were NOT observed to increase with speed on a gm/mile basis. Emissions are greatest during initial startup and idling, especially when the engine is cold.

- The mean snowmobile emissions measured in the gate area appear to provide a representative average emissions value for overall park snowmobile operations.

- The conversion vans operate often in off-cycle engine mode when much greater pollutants are emitted. The time weighted off-cycle operations for all the coaches averaged 20% of the time for the inbound trips and 29% for outbound. This is primarily caused by the high load on the engine and underpowered coaches that

causes the transmission to shift up and down. Newer vans with larger engines were found to have lower emissions.

- The Bombardier snowcoach with an uncontrolled carbureted engine had the highest CO and HC emissions and operated in this high region 98% of the time. Extremely high CO emissions were also observed at the west entrance from several additional vintage Bombardiers. Vans and coaches with efficient fuel-injected engines and catalytic converters can be nearly as clean as modern wheeled passenger vehicles.

Summary comparison of snow vehicle emissions (grams/mile/person).

Pollutant	Snowmobiles				Snowcoaches		
	Mean 1999 2-Stroke	Mean 4-Stroke	Lowest 4-Stroke	Highest 4-Stroke	Mean	Lowest Delacy	Highest B709
CO	71	28	25	60	35	0.6	74
HC	92	3.4	3.1	4.7	1.2	0.1	5.9
NO_x	---	3.4	3.3	0.3	2.8	0.2	0.9

Observations

- The snowcoach fleet needs to be modernized to reduce unnecessary CO and HC emissions. The Bombardiers should be replaced completely with either new emission controlled engines or with more efficient conversion vans.

- Current conversion vans are often operated outside the performance regions expected by the on-board engine control computer and in the process emitting more pollutants than necessary. The newer vans with the largest possible engines should be encouraged.

- Newer 4-stroke engine snowmobiles are lower polluting than the previous 2-stroke snowmobiles. Although the hydrocarbons have been reduced a lot, the amount of CO emissions still far exceeds what a late-model sedan or light duty truck emits. Even cleaner snowmobiles could be a target for the future.

- To further lower emissions and employee exposures at the entrance stations reduce the wait times as much as possible.

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INTRODUCTION

Large growth in wintertime snowmobile visits to Yellowstone National Park in the 1990's led to a series of lawsuits and environmental impact statements resulting in the adoption of a Temporary Winter Use Plans Environmental Assessment (EA).[1-4] The temporary winter use plan will be in effect for three winter seasons beginning in December of 2004. It allows motorized winter visits on snowcoaches and a limited number (up to 720/day in Yellowstone and an additional 140/day in Grand Teton) of guided snowmobiles which meet a Best Available Technology (BAT) standard.[5] Additionally the EA allows the National Park Service (NPS) the opportunity to collect additional data on the BAT approved snowmobiles and snowcoaches in use in the park.

In-use snowmobile and snowcoach emission measurements are scarce. Snowmobile emissions have been measured by the University of Denver in Yellowstone National Park in two previous studies in 1998 and 1999.[6, 7] Both studies utilized the University of Denver's on-road remote vehicle exhaust sensor to measure the tailpipe emissions of snowmobiles entering the parks west entrance. Several researchers have reported in-use and dynamometer emission measurements on 2-stroke and 4-stroke snowmobiles.[8-11] In addition there is one report of dynamometer emission measurements of a vehicle used in the winter as a snowcoach under a simulated load by Southwest Research, Inc.[12]

The two goals of this research were to repeat the gate measurements on the current crop of 4-stroke snowmobiles and to collect as much in-use emission data from snowcoaches as possible during the time frame. The snowmobile measurements would be used to directly compare and contrast with the previous data sets. The snowcoach measurements are primarily aimed in assisting with the air quality dispersion modeling. This modeling has been an integral part of the previous air quality studies in the park and have had to rely on limited emissions data.[13] Typically this type of modeling likes to have g/mi or g/sec emissions data for several vehicle-operating modes (at a minimum idle, low and high speed cruise) and time estimates for the frequency of each. The goal to instrument as many different coaches as possible is not to establish an average snowcoach emission factor but to help establish the emission and activity boundaries that coaches operate in.

SNOWMOBILES

Two previous snowmobile emission studies in 1998 and 1999 measured carbon monoxide (CO), unburned hydrocarbons (HC), carbon dioxide (CO_2) and a limited number of toluene measurements were made in the 1999 study.[6, 7] These measurements were collected on 2-stroke snowmobiles. These engines have been the preferred power plant by the industry due to their high power to weight ratio and fewer moving parts which lowers manufacturing costs. The absence of a valve train however, leads to large scavenging loses (the exhaust and intake port are open simultaneously allowing incoming fuel to enter the exhaust stream) contributing to excess HC emissions and poorer fuel economy.[14]

Since our previous studies were conducted, the Environmental Protection Agency has published new emissions limits for the snowmobile industry.[15] These emission limits are modest and will not end the use of 2-stroke engines. However, these limits along with the publicity surrounding snowmobile use in Yellowstone National Park, has prompted the industry to introduce 4-stroke engines in production snowmobiles. This fact alone should lower noise levels and dramatically reduce HC and CO emissions while improving fuel economy. For a description of the 4-stroke engine and causes of pollutants in the exhaust, see Heywood.[16]

Beginning with the winter season of 2003-2004 Yellowstone Park began restricting entries to professionally guided groups of ten or less on BAT approved snowmobiles. These snowmobiles are modern fuel injected 4-stroke powered touring snowmobiles with no exhaust after treatment manufactured by Arctic Cat, Polaris and Bombardier (Ski Doo).[5] The entrance to the park from West Yellowstone, MT (west entrance, elev. 2020m) has the highest number of snowmobile entries and was the entrance used in the two previous studies to remotely measure the tailpipe emissions of the snowmobiles entering the park.

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust and has previously been described in the literature.[17, 18] The instrument consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, and HC, and a dispersive ultraviolet (UV) spectrometer for measuring NO. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Colinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic beam splitter, which separates the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to a UV spectrometer. The UV unit is then capable of quantifying NO by measuring an absorbance band at 226.5 nm in the UV spectrum and comparing it to a calibration spectrum in the same region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor directly measures only ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. The %HC measurement is a factor of two smaller than an equivalent measurement by a flame ionization detector (FID).[19] Thus, in order to calculate mass emissions as described below, the HC values reported will first be multiplied by 2.0 as shown below, assuming that the fuel used is regular gasoline with a density of 726 g/l, a carbon fraction of 86% and 3.79 l/gallon. The measured ratios can be directly converted into mass emissions by the equations shown below.

$$\text{gm CO/gallon} = (28Q\times0.86\times726\times3.79)/((1+Q+6Q')\times12)$$
$$\text{gm HC/gallon} = (2\times44Q'\times0.86\times726\times3.79)/((1+Q+6Q')\times12)$$
$$\text{gm NO/gallon} = (30Q''\times0.86\times726\times3.79)/((1+Q+6Q')\times12)$$

These equations indicate that the relationship between ratios of emissions to mass of emissions is substantially linear, especially for CO and NO and at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from the fuel-based mass emissions.

Another useful conversion is from percent emissions to grams pollutant per kilogram (g/kg) of fuel. This conversion is achieved directly by first converting the pollutant ratio readings to moles of pollutant per mole of carbon in the exhaust using the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 6HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q+1+6Q'}$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (as above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[19]

$$gm\ CO/kg = (28Q/(1 + Q + 6Q'))/0.014$$
$$gm\ HC/kg = (2(44Q')/(1 + Q + 6Q'))/0.014$$
$$gm\ NO/kg = (30Q''/(1 + Q + 6Q'))/0.014$$

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant additional calibrations. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Scott Specialty Gases). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[20, 21] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive double blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of criteria for valid or invalid data.

The remote sensor is accompanied by a video system to record a freeze-frame image of each vehicle measured. The emissions measurements, as well as a time and date stamp, are also recorded on the video image. The images are stored on videotape, so that vehicle make information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generates a pair of infrared beams passing across the road, six feet apart and approximately two feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beams. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. Appendix B defines the database format used for the data set.

Experimental

Measurements were collected at the entrance from West Yellowstone, MT. to Yellowstone National Park (elev. 2020 m) on the mornings of Thursday Feb. 10 through Tuesday Feb. 15 and the morning of Thursday Feb. 17 between the hours of 7:00 and

12:00. Afternoon measurements were collected at the west exit Thursday Feb. 10 through Wednesday Feb. 16 between the hours of 13:30 and 17:00. Figures 1 and 2 are photographs of the entrance and exit setups. The videotapes were read for snowmobile engine type (4-stroke or 2-stroke), make, model year and to indicate snowcoaches.

Figure 1. Photograph of the remote sensor, speed sensors and camera setup at the west entrance to Yellowstone National Park.

At the entrance, the FEAT source, detector and monochromator were placed on insulating pads on top of the snow approximately 6 m beyond the park service attendant booths. The emissions were measured during mild acceleration or cruise mode. The sampling beam was angled approximately 30 degrees to the path of travel to help insure complete beam blockage. A 1-second sample of exhaust was taken after each snowmobile using the standard FEAT software used for automobiles. A video camera photographed the front of each vehicle measured and the pictures were saved on videotape. The support equipment was housed inside an unused, heated attendant booth. The FEAT instrument was calibrated according to standard operating procedures using a certified gas cylinder with 6% CO, 0.6% propane, 0.3% NO and 6% CO_2 (Scott Specialty Gases).

The successful monitoring of snowmobile emissions involves surmounting a number of physical challenges that are not encountered in measuring normal on-road vehicle emissions. The first is that the smaller displacement engines used have less exhaust

Figure 2. Photograph of a 2005 Arctic Cat snowmobile exiting Yellowstone National Park. The FEAT detector is in the upper right of the photo and opposite it is the IR/UV source. Underneath the first snowmobile is a plastic mat laid down in an attempt to eliminate excess snow spray.

volumes for sampling. Combined with the fact that Arctic Cat 4-stroke snowmobiles exhaust exits at the front allowing a longer time for it to dilute before a measurement can be made lowering signal strengths further. Over snow measurements also suffer from higher background noise levels caused by snow spray from the track and condensed exhaust water vapor on days with below zero (°F) temperatures.

Generally snow from the track impacts a spray flap and so large clumps of snow do not generally interfere with the measurement, however above about 10 mph large clouds of very fine particles are kicked up which persist for many meters behind the snowmobile. This is the main reason why we have always attempted these measurements at the park entrances where speeds are lower. New this season was the use of a 3 meter long plastic mat, originally used for indoor skiing, at the exit to try to suppress the snow spray behind the faster moving snowmobiles (see Figure 2). The mat did stop new snow from being added to the cloud, but was too short (a mat 6 to 9 meters long is probably needed) to be effective at extinguishing the snow cloud carried along with the snowmobile.

The HC emission measurement is the most difficult to make of the three species measured. Its signal to noise threshold is an order of magnitude lower than either CO or

NO. To successfully measure HC one needs to either increase the signal from the plume or lower the background noise levels. With the exception of 2-stroke snowmobiles, which have very large HC emission signals, we were unable to measure the HC emissions of the 4-stroke snowmobiles at the exit location due to the combination of low signals and high noise from the snow clouds.

The morning measurements at the entrance were only compromised on the coldest mornings. Below zero degrees Fahrenheit, the water in the exhaust quickly condenses making it difficult for the optical beam to penetrate through the fog. The liquid water fog also produces a large positive interference for the HC measurements.[17] The water fog is more problematic for the 4-stroke snowmobiles because they combust the fuel more efficiently and, therefore produce more water in the exhaust. The mornings of February 11, 15 and 17 have fewer measurements due to this. We did not even attempt measurements on the morning of February 16 because of the low temperatures.

The only other interference occurs when attempting to measure NO on snowmobiles powered with 2-stroke engines. The NO measurements are carried out in the UV spectral region where raw gasoline also has a number of species with strong absorbance's. The large amount of unburned fuel emitted by the 2-stroke engines interferes with the NO absorbance bands invalidating those measurements. It was for this reason that NO measurements were not attempted in the previous studies.[6, 7]

In addition to the remote sensing measurements, we attempted to install a portable emissions analyzer on a park service 2002 Arctic Cat 4-stroke. The engine parameters were acquired using the sensor array for engine rpm (optical pickup and reflective tape on the camshaft), intake air temperature (thermistor) and intake manifold pressure (pressure transducer teed into the manifold pressure sensor). Figure 3 shows a picture of the engine compartment with the thermistor and pressure transducer clearly visible. The wire leading to the optical pickup is also visible in the upper right corner of the picture. The sensor array control module was attached to the side of the engine cowling and the analyzer was attached with bungee cords to the rear passenger seat. The GPS receiver was taped onto the rear cargo cage.

The exhaust on the Arctic Cat snowmobiles exits the engine underneath the very front of the engine cowling and on our first attempt we routed the exhaust hose underneath the engine cowling. Even at below freezing temperatures the heat under the cowling proved too much for our sampling line and it melted early in the drive. No data were obtained as a result of the sample line failure. This was eventually discovered and the lessons learned were applied the next afternoon when we routed the hose outside of the engine compartment and successfully collected some emissions data.

Figure 4 shows a picture of the snowmobile in the final configuration with the analyzer covered with improvised insulation. Power connections provided a number of problems the second afternoon along with a difficulty keeping the analyzer benches warm. Despite the problems, we were able to successfully collect some idle emissions data and 2.3 miles of a driving segment along the west entrance road. The data file for the driving segment

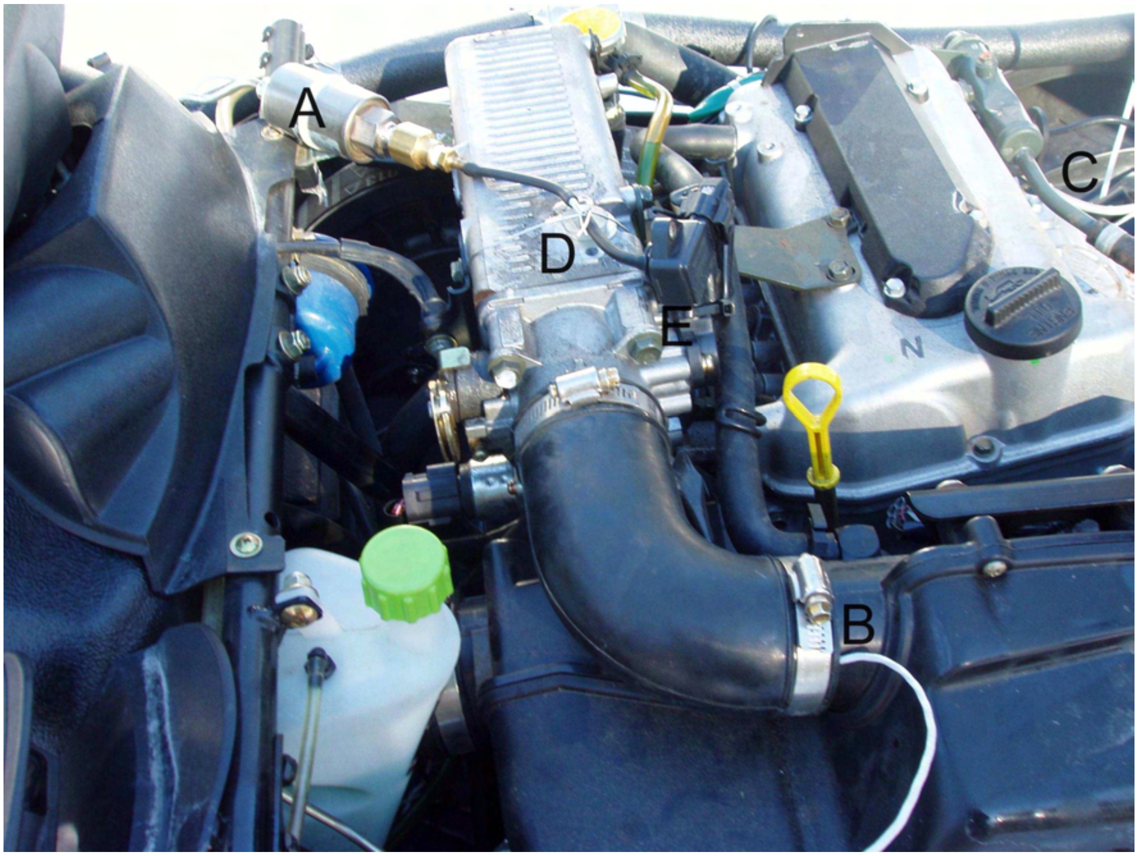

Figure 3. Arctic Cat engine showing the pressure transducer (A), thermistor (B), the top of the rpm optical pickup (C), the precision engineered rubber stopper and tee (D) for connecting the manifold pressure sensor (E) to the pressure transducer.

does not correctly record the engine rpms, truncating them at a maximum of 5000 rpms (at 35 mph the snowmobile had engine rpms around 6500). Inspection of the data confirms that this is just a recording error and that the correct rpm was used to calculate the gram/sec exhaust flows.

Results

The resulting database contains 1,008 records (965 snowmobiles and 43 snowcoach measurements) with make and model year information and valid measurements for at least CO and CO_2. Most of these records also contain valid measurements for HC, NO, speed and acceleration except during the afternoon, which, because of sampling conditions, have mostly invalid HC measurements. Invalid measurement attempts arise when the vehicle plume is highly diluted, or the reported error in the ratio of the pollutant to CO_2 exceeds a preset limit (see Appendix A). The database format is defined in Appendix B and the can be downloaded from www.feat.biochem.du.edu.

Table 1 summarizes the measured CO/CO_2, HC/CO_2, NO/CO_2 ratios and the calculated volumetric percents and grams of pollutant per gallon or per kg of fuel consumed, derived through the combustion equation for snowmobiles and snowcoaches.[17] All of the

Figure 4. Arctic Cat snowmobile with the portable emissions in the rear passenger seat.

hydrocarbon emissions are reported in units of propane. All of the snowmobile NO emission measurements are report as NO. All errors are reported as the standard error of the mean (SEM). The average speeds and accelerations for 341 snowmobiles measured at the entrance were 9.6 ± 0.1 mph and 0.37 ± 0.18 mph/sec. For 8 snowcoaches the average speeds and accelerations were 6.4 ± 0.3 mph and 0.89 ± 0.2 mph/sec. At the exit, 215 snowmobiles were measured at 15.5 ± 0.2 mph and 0.83 ± 0.15 mph/sec and 3 snowcoaches at 9.4 ± 2 mph and 0.7 ± 0.2 mph/sec.

Table 2 separates the snowmobile emission measurements by engine type. While 2-stroke snowmobiles are currently banned from the park for visitor entries, contractors and park employees are still allowed to use them. The calculations were performed utilizing the same assumptions described for Table 1.

Table 3 breaks out the 4-stroke snowmobile emission measurements by manufacturer and Table 4 summarizes the emissions of 4-stroke snowmobiles by model year. Because of the small number of the 2002 and 2003 Arctic Cat snowmobiles, they have been combined into a single model year grouping. Table 5 summarizes the emissions data collected on the 2002 Arctic Cat snowmobile using the portable emissions analyzer. All of the standard errors of the mean for the measurements reported are at least an order of magnitude less than the last significant figure. The measured fuel economy for this

Table 1. Summary of all 2005 Yellowstone National Park entrance and exit measurements.[a]

Measurement	All Snowmobiles		Snowcoaches	
	Entrance	Exit[b]	Entrance	Exit[b]
Mean CO/CO_2	0.17 ± 0.01	0.21 ± 0.01	0.19 ± 0.05	0.37 ± 0.19
Mean %CO	2.20 ± 0.06	2.60 ± 0.08	2.10 ± 0.5	3.00 ± 1.4
Mean g CO/gal[c]	680 ± 16	690 ± 21	675 ± 151	920 ± 431
Mean gCO/kg[c]	250 ± 6	250 ± 8	250 ± 55	330 ± 160
Samples	603	362	32	11
Mean HC/CO_2	0.013 ± 0.002		0.001 ± 0.001	
Mean %HC[d]	0.15 ± 0.020		0.006 ± 0.012	
Mean gHC/gal[c]	110 ± 12		4 ± 12	
Mean gHC/kg[c]	41 ± 4		1.5 ± 4.5	
Samples	489		25	
Mean NO/CO_2	0.009 ± 0.001	0.017 ± 0.001	0.002 ± 0.001	0.001 ± 0.001
Mean %NO	0.120 ± 0.004	0.220 ± 0.007	0.033 ± 0.008	0.013 ± 0.012
Mean gNO/gal[c]	42 ± 1	68 ± 2	12 ± 3	4.8 ± 4.6
Mean gNO/kg[c]	15 ± 0.5	25 ± 1	4.4 ± 1.1	1.7 ± 1.7
Samples	587	352	32	11

[a] All errors are reported as the standard error of the mean.
[b] Exit HC measurements were invalid for all but the 2-strokes that are reported below.
[c] g/gallon assumes a fuel density of 726 g/l and g/kg assumes a carbon fraction of 0.86.
[d] All percent hydrocarbon emissions are reported in units of propane.

Table 2. Summary of snowmobile emission measurements by engine type.[a]

Measurement	4-Stroke Snowmobiles		2-Stroke Snowmobiles	
	Entrance	Exit[b]	Entrance[c]	Exit[c]
Mean CO/CO_2	0.16 ± 0.01	0.19 ± 0.01	0.54 ± 0.07	0.78 ± 0.1
Mean %CO	2.08 ± 0.05	2.43 ± 0.07	5.40 ± 0.5	7.09 ± 0.6
Mean gCO/gal[d]	670 ± 16	670 ± 20	1000 ± 97	1500 ± 140
Mean gCO/kg[d]	240 ± 6	240 ± 7	370 ± 35	550 ± 50
Samples	589	362	14	9
Mean HC/CO_2	0.006 ± 0.001		0.23 ± 0.02	0.16 ± 0.01
Mean %HC[e]	0.080 ± 0.08		2.40 ± 0.26	1.50 ± 0.08
Mean gHC/gal[d]	78 ± 7		1300 ± 69	1000 ± 37
Mean gHC/kg[d]	28 ± 2		480 ± 25	370 ± 13
Samples	489		14	9
Mean NO/CO_2	0.009 ± 0.001	0.017 ± 0.001		
Mean %NO	0.119 ± 0.004	0.223 ± 0.007		
Mean gNO/gal[d]	42 ± 1	68 ± 2		
Mean gNO/kg[d]	15 ± 0.5	25 ± 1		
Samples	587	359		

[a] All errors are reported as the standard error of the mean.
[b] Exit HC measurements were invalid for all the 4-stroke engines due to snow spray.
[c] NO measurements were invalid for all the 2-stroke engines due to fuel interference's.
[d] g/gallon assumes a fuel density of 726 g/l and g/kg assumes a carbon fraction of 0.86.
[e] All percent hydrocarbon emissions are reported in units of propane.

Table 3. Summary of measurements by make for only 4-stroke powered snowmobiles.[a]

Measurement	Entrance			Exit[b]		
	Arctic Cat	Polaris	Ski Doo	Arctic Cat	Polaris	Ski Doo
Mean CO/CO_2	0.13 ± 0.003	0.22 ± 0.02	0.39 ± 0.02	0.16 ± 0.003	0.18 ± 0.04	0.46 ± 0.02
Mean %CO	1.70 ± 0.04	2.70 ± 0.16	4.50 ± 0.16	2.10 ± 0.05	2.10 ± 0.3	5.10 ± 0.2
Mean gCO/gal[c]	550 ± 13	830 ± 44	1400 ± 49	580 ± 10	590 ± 76	1400 ± 66
Mean gCO/kg[c]	200 ± 5	300 ± 16	500 ± 18	210 ± 4	220 ± 28	520 ± 24
Samples	447	89	53	272	44	37
Mean HC/CO_2	0.005 ± 0.001	0.009 ± 0.003	0.01 ± 0.003			
Mean %HC[d]	0.071 ± 0.007	0.11 ± 0.03	0.12 ± 0.03			
Mean gHC/gal[c]	72 ± 7	91 ± 25	110 ± 27			
Mean gHC/kg[c]	26 ± 2	33 ± 9	39 ± 10			
Samples	367	67	41			
Mean NO/CO_2	0.011 ± 0.0003	0.004 ± 0.0002	0.001 ± 0.0002	0.02 ± 0.0004	0.006 ± 0.0008	0.002 ± 0.0005
Mean %NO	0.150 ± 0.004	0.049 ± 0.003	0.013 ± 0.002	0.270 ± 0.006	0.083 ± 0.01	0.024 ± 0.005
Mean gNO/gal[c]	51 ± 2	17 ± 1	4.3 ± 0.8	82 ± 2	28 ± 4	7 ± 1.5
Mean gNO/kg[c]	19 ± 0.5	6 ± 0.4	1.6 ± 0.3	30 ± 0.8	10 ± 1.4	2.6 ± 0.5
Samples	446	88	53	272	44	36

[a] All errors are reported as the standard error of the mean.
[b] Exit HC measurements were invalid for all the 4-stroke engines due to snow spray.
[c] g/gallon assumes a fuel density of 726 g/l and g/kg assumes a carbon fraction of 0.86.
[d] All percent hydrocarbon emissions are reported in units of propane.

Table 4. 4-Stroke snowmobile emissions by model year.[a]

Make / Emissions	Entrance			Exit[b]		
Samples	2002/2003	2004	2005	2003	2004	2005
Arctic Cat gCO/kg[c]	170 ± 18	210 ± 6	190 ± 7	220 ± 44	210 ± 5	220 ± 6
Samples	13	255	179	7	162	103
Arctic Cat gHC/kg[c]	39 ± 9	26 ± 3	25 ± 4			
Samples	13	207	147			
Arctic Cat gNO/kg[c]	22 ± 3.6	19 ± 0.8	18 ± 0.7	20 ± 6.2	32 ± 1	28 ± 1.1
Samples	13	254	179	7	162	103
Polaris gCO/kg[c]	180 ± 24	310 ± 19	280 ± 33	230 ± 137	210 ± 31	220 ± 60
Samples	4	73	12	4	35	5
Polaris gHC/kg[c]	2 ± 7	33 ± 10	47 ± 23			
Samples	4	54	9			
Polaris gNO/kg[c]	4.5 ± 0.8	6.3 ± 0.5	4.9 ± 0.5	1.6 ± 1	11 ± 1.6	9.4 ± 1.8
Samples	4	72	12	4	35	5
Ski Doo gCO/kg[c]	480 ± 26	530 ± 21	530 ± 34	520 ± 32	530 ± 46	540 ± 64
Samples	30	9	14	22	8	7
Ski Doo gHC/kg[c]	35 ± 14	12 ± 11	70 ± 23			
Samples	21	9	11			
Ski Doo gNO/kg[c]	1.6 ± 0.4	2.0 ± 0.8	1.3 ± 0.5	3.1 ± 0.5	2.0 ± 1.3	1.6 ± 1.8
Samples	30	9	14	21	8	7

[a] All errors are reported as the standard error of the mean.
[b] Exit HC measurements were invalid for all the 4-stroke engines due to snow spray.
[c] g/kg assumes a carbon fraction of 0.86.

Table 5. Portable emission measurement results for a 2002 Arctic Cat 4-stroke snowmobile.

Measurement	Idle	Driving
Mean CO/CO_2	0.35	0.075
Mean gCO/gal[a]	1300	390
Mean gCO/kg[a]	470	140
Mean gCO/sec	0.076	0.14
Mean gCO/mile	NA	17.0
Duration	8 min 19 sec	4 min 50 sec
Distance	0 miles	2.32 miles
Mean HC/CO_2	0.006	0.003
Mean gHC/gal[a]	65	43
Mean gHC/kg[a]	24	16
Mean gHC/sec	0.004	0.015
Mean gHC/mile	NA	1.9
Duration	8 min 19 sec	4 min 50 sec
Distance	0 miles	2.32 miles
Mean NO_x/CO_2	0.0005	0.026
Mean NO_x/gal[a]	6.6	220
Mean NO_x/kg[a]	2.4	80
Mean NO_x/sec	0.0002	0.078
Mean NO_x/mile	NA	9.7
Duration	8 min 19 sec	4 min 50 sec
Distance	0 miles	2.32 miles

[a] g/gal and g/kg results are calculated from the reported g/sec emissions and fuel consumption.

snowmobile during the driving portion was 21.9 mpg and its average speed as measured by the GPS was 28.2 ± 0.6 mph. The maximum speed was 42 mph.

Discussion

The reason for these new measurements was to compare the entrance emission measurements of the new 4-stroke snowmobiles to the data previously collected from 2-strokes. There are very noticeable qualitative differences one can only observe in person at the west entrance. There are fewer snowmobiles, the 4-stroke snowmobiles are quieter and most notably the lack of smell of lube oil. The reduction of these emissions may also be important for reasons other than just smell since a number of compounds found in lube oil have been shown to be deposited and to persist on snow.[22] Table 6 compares the emission measurements from 2-stroke snowmobiles measured at the west entrance with the two previous field studies. While the CO measurements have been shown to be temperature dependent, the small number of 2-stroke snowmobiles measured in 2005 have entrance emissions which are very similar to those measured in the past. Directly comparing these emissions with those from Table 2 of the 4-stroke snowmobiles shows

Table 6. Comparison of 2-stroke emissions measurements made at the West Entrance.[a]

Measurement	1998[b]	1999[c]	2005
Mean CO/CO_2	0.53 ± 0.01	0.69 ± 0.01	0.54 ± 0.07
Mean gCO/gal	870 ± 14	1100 ± 12	1000 ± 97
Mean gCO/kg	320 ± 5	380 ± 4	370 ± 35
Samples	888	1018	14
Mean HC/CO_2	0.26 ± 0.003	0.27 ± 0.01	0.23 ± 0.02
Mean gHC/gal	1400 ± 8	1400 ± 8	1300 ± 69
Mean gHC/kg	520 ± 3	480 ± 3	480 ± 25
Samples	888	1018	14

[a] All errors are reported as the standard error of the mean.
[b] *Environ. Sci. & Technol.* **1999**, *33*, 3924-3926.
[c] *Environ. Sci. & Technol.* **2001**, *35*, 2874-2881.

that measured entrance emissions are now factors of 3 and 38 lower for CO and HC. The mass emission rates per gallon or kilogram do not show as large a difference because they are a product of the emissions and fuel consumption rates. Since the 4-stroke snowmobiles will go almost twice as far on a gallon or kilogram of fuel as a 2-stroke snowmobile the 4-stroke snowmobiles mass per gallon emissions are further halved when comparing to the 2-strokes. Figure 5 shows a histogram comparing the 4-stroke snowmobiles measured at the west entrance to the 2-stroke snowmobiles previously measured at the same location in 1999.[7]

The snowcoach emission measurements presented in Table 1 have larger standard errors of the mean due to the smaller number of samples and the bimodal distribution of the data. The snowcoaches using the west entrance are a mix of modern conversion vans, vintage Bombardiers and upgraded Bombardiers. The modern conversion vans and upgraded Bombardiers generally have low emission readings while the vintage Bombardiers do not. For example the exit snowcoach mean %CO emissions were 10% for 3 Bombardiers and 0.3% for the remaining 8 coaches. These high CO emissions are consistent with data presented later collected from an instrumented vintage Bombardier. The entrance data is not as skewed (0.8% versus 3.5%) probably because several of the identified Bombardiers have been upgraded to a modern emissions controlled engine.

The snowmobile emissions data collected in 1999 are normally distributed.[7] The 2005 data however, tails away to higher emission levels more reminiscent of gamma distributed on-road vehicle emissions. In on-road fleets, this tail is caused by high emitting broken vehicles. We do not believe that this is the case with these snowmobile fleets. Part of the tail is because the three manufacturers have snowmobiles with differing fleet mean CO emissions as shown in Table 3. Figure 6 displays the 2005 gCO/kilogram data distributed by manufacturer. The Ski Doo snowmobiles account for most of the upper bars in the graph and are reasonably grouped for a small number (53) of measurements. The Polaris snowmobiles are only slightly shifted to higher emission

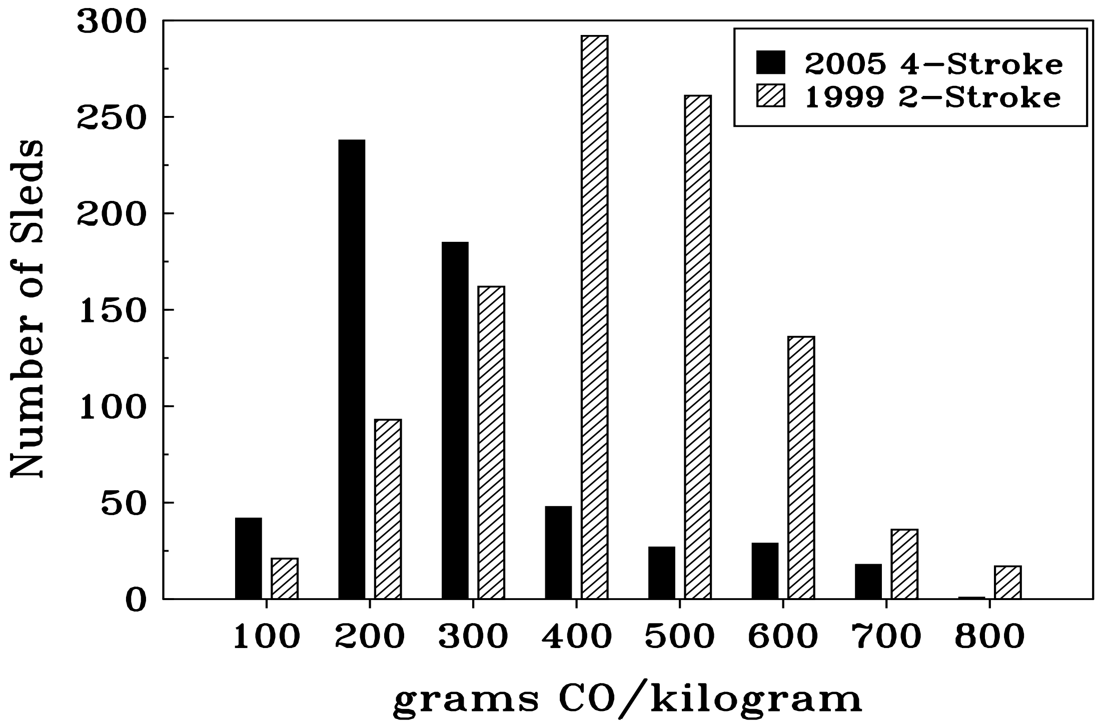

Figure 5. Comparison of gCO/kilogram of fuel emissions measured at the west entrance to Yellowstone National Park from 4-stroke snowmobiles in 2005 (588) with measurements made on 2-stroke snowmobiles in 1999 (1018).

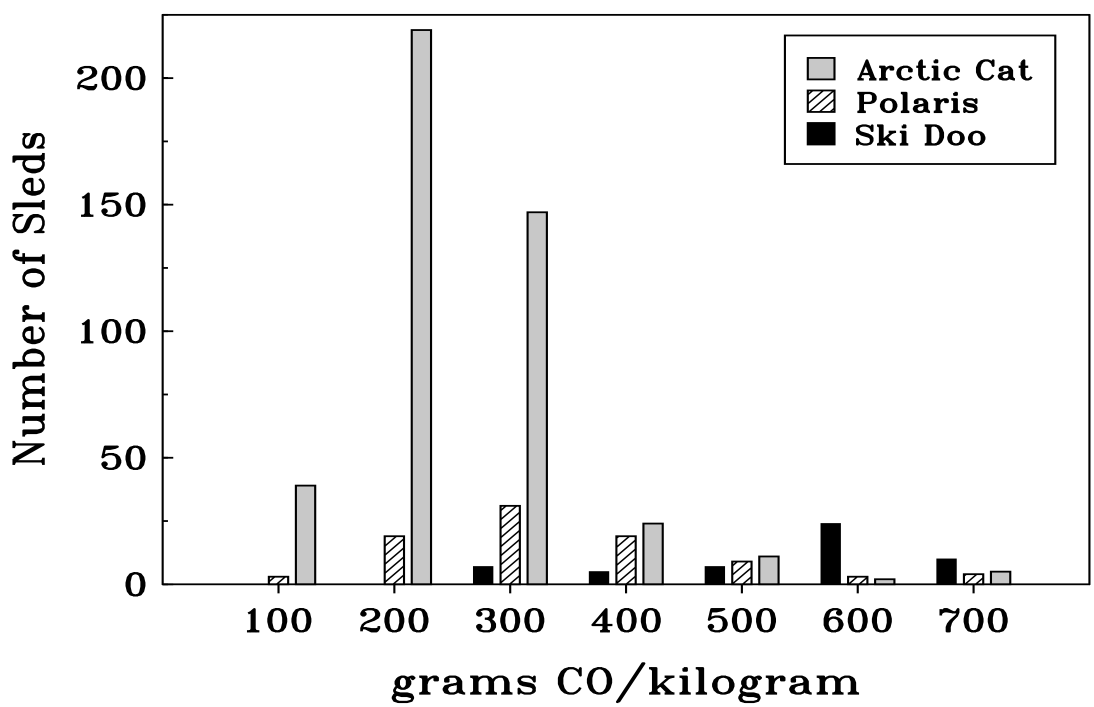

Figure 6. Comparison of gCO/kilogram of fuel emissions measured at the west entrance to Yellowstone National Park for 4-stroke snowmobiles by manufacturer. There are 447 Arctic Cat measurements, 89 Polaris measurements and 53 Ski Doo measurements.

levels when compared with the Arctic Cat snowmobiles. All but the Arctic Cat snowmobiles appear normally distributed.

So what else could be accounting for the few Arctic Cat snowmobiles that appear to have much higher emissions than the majority if it is not a maintenance issue? Ideal measurements are made on a fully warmed up vehicle. Prior to the adoption of the EA the majority of visitors, entering the park on snowmobiles did so using a prepurchased pass through an express lane. The express lane allowed a rider with a clearly visible entry pass to enter the park without stopping at the entrance gate. This helped to limit the time that snowmobiles spent in the gate area and lower the emissions that park employees were exposed to each morning. With the advent of the EA and guided groups, the Park Service has returned to requiring all snowmobiles to stop and check in at the entrance gate. Most guides and a few of their clients turned their snowmobiles off while stopped at the gate in (usually only a few minutes) an effort to reduce employee emissions exposure.[23] This results in some snowmobiles being measured very soon after starting which will often increase CO and HC emissions.

Since the guide snowmobiles are the first in line for each group, their emissions should be the most susceptible to increased emissions from starting. To test this hypothesis we identified the guide snowmobiles in the video and marked them in the database. Table 7 compares the entrance emissions between the guide and client snowmobiles by make. The CO and HC emissions for guide snowmobiles are higher for every make though many of the samples are too small for the differences to be statistically significant. It turns out that the high emitting Arctic Cat snowmobiles in the distribution in Figure 6 are guide snowmobiles and when they are removed the remaining Arctic Cat snowmobiles are normally distributed. This also highlights the fact that the entrance measurements will be slightly biased high when compared to a fully warmed up fleet measurement.

Table 7. Entrance measurement comparison between guide and client snowmobiles.[a]

Make	Guide/Client	Mean gCO/kg Samples	Mean gHC/kg Samples	Mean gNO/kg Samples
Arctic Cat	Guide	330 ± 22 47	28 ± 7 39	13 ± 1.5 46
Arctic Cat	Client	190 ± 4 400	26 ± 3 328	19 ± 0.6 400
Polaris	Guide	360 ± 56 14	53 ± 10 13	4.1 ± 0.5 14
Polaris	Client	290 ± 16 75	28 ± 11 53	6.4 ± 0.5 74
Ski Doo	Guide	530 ± 34 14	70 ± 23 11	1.3 ± 0.5 14
Ski Doo	Client	490 ± 21 39	28 ± 10 30	1.7 ± 0.4 39

[a] All errors are reported as the standard error of the mean.

Within each manufacturer there appears to be no correlation between emissions and model years. Table 4 shows that for Arctic Cat and Polaris the oldest models have slightly lower emissions, but these are very small samples and the differences seen for CO are not present during the exit measurements. It is very possible that the Arctic Cat snowmobiles lower CO emissions are a result of fewer cold start emissions since many of the 2002/2003 models were driven by NPS employees. Since the engine technology in the 4-stroke snowmobiles are essentially the same each year, the only emission differences one would expect to find from year to year would be linked to engine maintenance issues. The engine technology in use is largely borrowed from the automotive sector where many of the engine components have been designed for 100,000 mile warranties. The 2002 and 2003 snowmobiles are not old enough yet for any maintenance issues to be much of a problem.

There are emission differences by manufacturer (see Tables 3 and 4). The Ski Doo's have statistically higher CO emissions (by a factor of 2 to 3) than either the Arctic Cat or Polaris snowmobiles for both the entrance and exit measurements. The Ski Doo HC emissions are also higher but the small sample size prevents it from being statistically significant. Differences between the Arctic Cat and Polaris snowmobiles for CO and HC may be a difference in the relative number of cold starts in the Polaris fleet as the afternoon measurements for CO show no statistical difference between the two.

The Arctic Cat snowmobiles have the highest NO emissions in both the morning and the afternoon measurements. NO emissions from the Ski Doo's are expected to be lower since as CO emissions increase, the NO emissions have to correspondingly decrease. This is because rich air to fuel ratios guarantee that there is not enough oxygen available in the combustion chamber to oxidize nitrogen to NO.

To convert the mass emissions per gallon of fuel into grams per mile emission one just needs a fuel economy estimate. We obtained fuel sales records from the National Park Service for the winter of 2004-2005 that list gallons sold and odometer readings.[24] Many of the records contain obvious errors that include more gallons sold than can possibly fit into a single tank and incorrect or omitted odometer readings. With these caveats the data produces an average fuel economy of 17 ± 3 mpg. The 2002 Arctic Cat snowmobile that we instrumented with the portable emissions analyzer was measured at 21.9 mpg during the high speed driving portion of our test. An industry representative felt that a conservative fuel economy range for Yellowstone driving conditions would be between 16 and 20 mpg.[25] Table 8 is compiled using the emissions measurements from Tables 2 and 3 and assuming a 4-stroke fuel economy of 18 mpg and a 2-stroke fuel economy of 13 mpg.[7]

With the use of the Clean Air Technologies portable emissions monitor (fully described in the next section) it was possible to collect some in-use data covering the entire park operating range of a 2002 Arctic Cat snowmobile.[26, 27] Figure 7 displays second by second data collected during a 2.3 mile drive along the west entrance road. Because of

Table 8. Estimated snowmobile gram/mile emissions from grams/gallon measurements.

Fleet	Estimate	4-Strokes[a]		2-Strokes[b]	
		Entrance	Exit	Entrance	Exit
All	Mean gCO/mile	37	37	78	120
All	Mean gHC/mile	4.3	NA	100	78
All	Mean gNO/mile	2.3	3.8	NA	NA
Arctic Cat	Mean gCO/mile	31	32		
Arctic Cat	Mean gHC/mile	4	NA		
Arctic Cat	Mean gNO/mile	2.8	4.6		
Polaris	Mean gCO/mile	46	33		
Polaris	Mean gHC/mile	5.1	NA		
Polaris	Mean gNO/mile	1	1.6		
Ski Doo	Mean gCO/mile	77	80		
Ski Doo	Mean gHC/mile	6	NA		
Ski Doo	Mean gNO/mile	0.24	0.39		

[a] Assumes a fuel economy of 18mpg.
[b] Assumes a fuel economy of 13mpg.

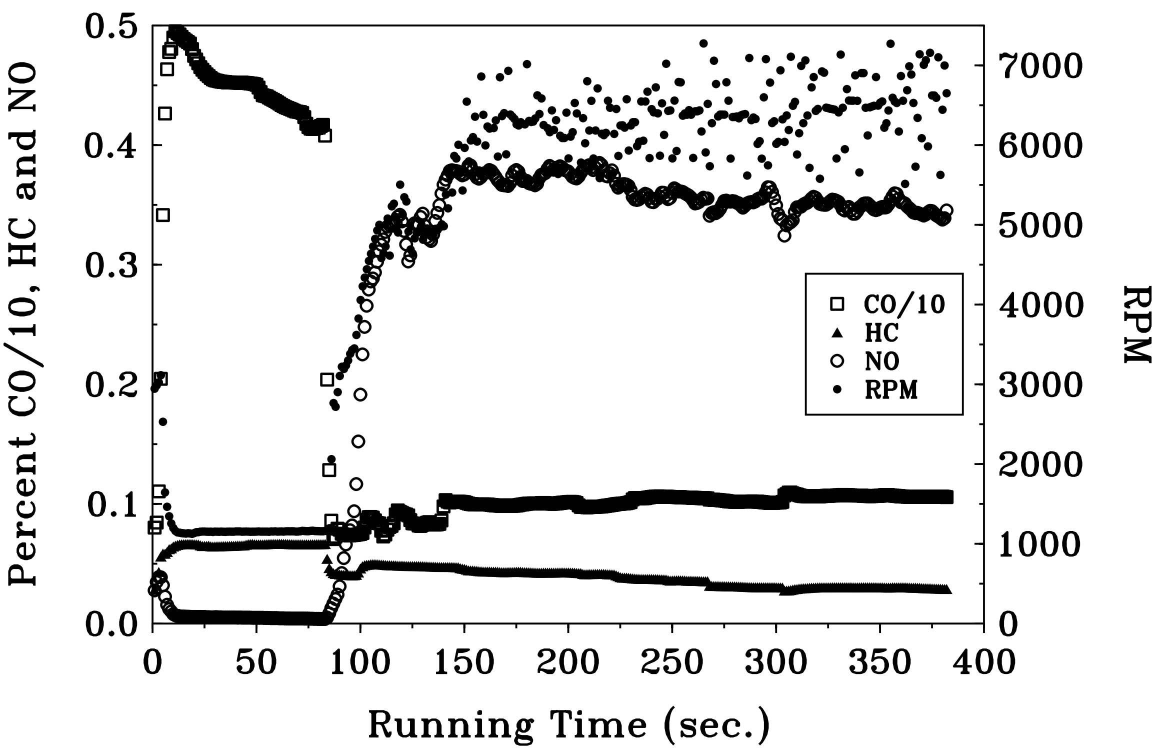

Figure 7. Second by second emission data collected from a 2002 Arctic Cat 4-stroke snowmobile on a 2.3 mile drive along the west entrance road. The rpm data is a composite of measured and estimated values. The percent CO data are divided by 10 for display purposes.

the rpm recording problem described previously, the displayed rpm's are a mix of the recorded values and those estimated from the GPS speed data. The recorded percent CO data has been divided by ten to facilitate displaying all of the emissions on the same graph. The drive consisted of a warm start and 85 seconds of idling followed by the snowmobile being accelerated up to cruising speed (35 to 40 mph) and then maintaining that speed until the data collection ended.

The obvious emission differences are between idle and cruise with the snowmobile operating with a richer air to fuel mixture during the idle portion. This is most likely an operational decision by the manufacturer to help the engine start and idle better at the normally low operational temperatures that will be expected. During the cruise portion, the snowmobile has very consistent emission levels throughout all of the operating speeds as would be expected from a closed-loop computer-controlled engine. This is in contrast to data reported by Southwest Research showing a large speed dependence of CO emissions.[11] Figure 8 shows a comparison between the measured grams/mile emissions as a function of speed and estimated gram per mile emissions that Southwest Research reported for a similar pre-production Arctic Cat snowmobile. The two data sets show similar downward trends with speed for NO and HC, however the dynamometer CO emissions increased rapidly with increasing speed. Our data did not show this behavior. This is an important observation because the previous emissions modeling included this large CO speed dependence in its emissions profiles.[13] Possible explanations for the observed differences are that the intake air temperatures for our measurements are significantly lower than those used in the lab (13 °C versus 26 – 30 °C). The higher intake air temperature in the lab could cause the snowmobile to enrich the air/fuel mixture to keep the engine cooler during the test. This would result in the large increase in the CO emissions. Since Southwest's testing was performed on a pre-production Arctic Cat snowmobile it is also possible that this behavior was fixed in the production model.[28]

One last issue to discuss is how representative the FEAT measurements collected at the entrance and exit are for the snowmobile operations in the rest of the park. Most of the snowmobile fuel expended within the park is used at speeds of 25 to 40mph. This is higher than those observed in the gate area (10 to 15mph). The data collected from the 2002 Arctic Cat with the portable emissions analyzer at higher speeds compares favorably with the Arctic Cat measurements collected at the entrance and exit. Table 9 shows that the remote measurements collected at the gate area are spanned by the idle and cruise measurements collected from the instrumented 2002 Arctic Cat. The instrumented snowmobile cruise emissions should be viewed as a lower limit. When deceleration and idle operations are added in, the overall emissions number will increase. Those increases will result in an average number that is similar to the fleet measurements collected in the gate area by the remote sensor.

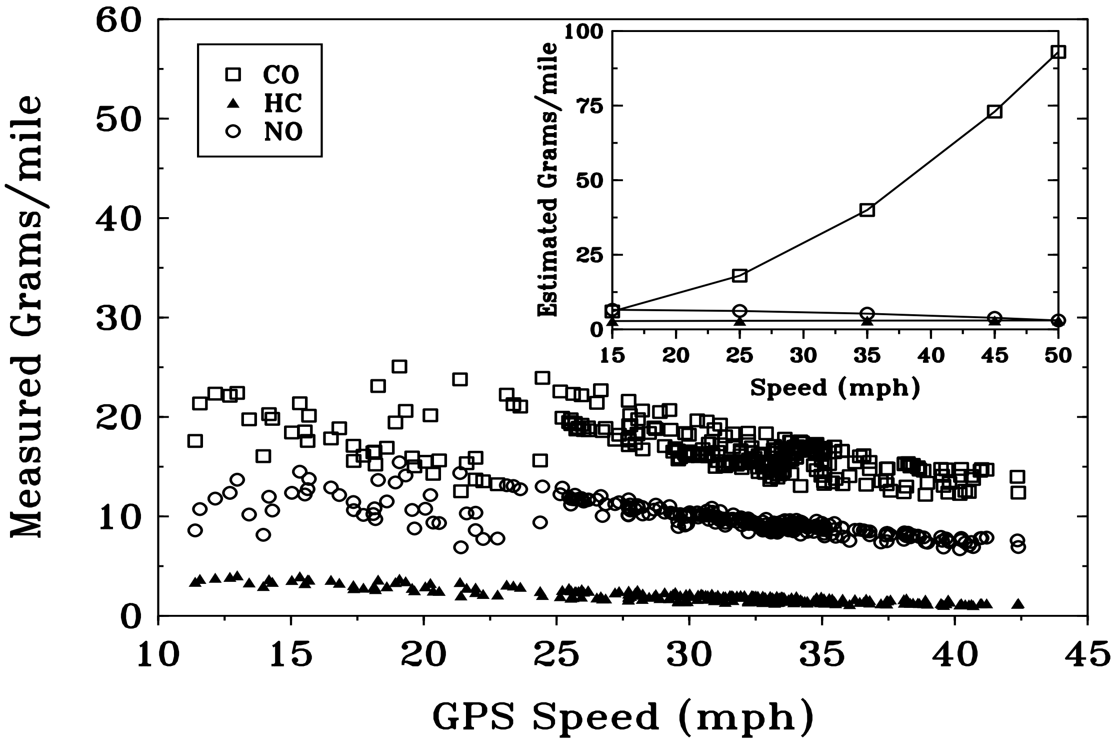

Figure 8. Measured CO, HC and NO grams/mile emissions as a function of speed from a 2002 Arctic Cat 4-stroke snowmobile on a 2.3 mile drive along the west entrance road. The inset graph is reproduced from dynamometer data reported by Southwest Research on a pre-production Arctic Cat 4-stroke snowmobile.[11]

Table 9. In-use emissions comparison between the Arctic Cat fleet, excluding the tour guide snowmobiles, and the 2002 Arctic Cat instrumented with the portable emissions analyzer.

Measurement	2002 Arctic Cat Instrumented[a]		Arctic Cat In-use Fleet[b,c]	
	Idle	Cruise	Entrance	Exit
CO/CO_2	0.35	0.08	0.11	0.16
gCO/kg	470	140	190	210
HC/CO_2	0.006	0.003	0.005	NA
gHC/kg	24	16	26	NA
NO_x/CO_2	0.0005	0.026	0.011	0.02
gNO_x/kg	2.4	80	29	46

[a] g/kg results are calculated from the reported g/sec emissions and fuel consumption.
[b] g/kg calculations assumes a carbon fraction of 0.86.
[c] Snowmobile NO emissions have been converted to NO_2 emissions for comparison.

SNOWCOACHES

Joseph-Armand Bombardier has the distinction of being a founding father of both the snowcoach and the Ski-Doo snowmobile.[29] The historical snowcoaches best known now as Bombardiers, or Bombs for short, began serving Yellowstone National Park in the mid 1950's and were manufactured until 1981. A number of these coaches are still operated by the park's concessionaire and private operators. They consist of a rear-mounted engine that drives a twin track from a forward mounted drive axle. Twin skis are used to steer and a metal cabin holds around 10 passengers. Today these are supplemented by an assortment of modern wheeled vehicles that have been converted to over-the-snow use by adapting various track/ski systems as wheel replacements.

Modern vehicles sold in the United States are required by the Federal Government to meet stringent laboratory emissions standards. The improving national air quality is a strong testament to the fact that these standards have worked to make large reductions in vehicle emissions.[30, 31] Many recent studies have demonstrated that not only do new vehicles have very low initial emissions, but they now maintain these low levels many years longer than previous models.[32] However, there are circumstances under which vehicles can be operated outside of the laboratory parameters causing tailpipe emission levels to increase. Snowcoaches in use in Yellowstone National Park are potentially just those types of vehicles and operation modes. The coaches in use in the park experience extremes of temperature, load and fuel consumption that fall well outside of all of the original emission design goals and testing parameters.

Assortments of vehicles have been converted to snowcoach use in the park by the park's concessionaire Xanterra and a number of private concessionaires. Xanterra has one of the largest collections of coaches that are operated from Mammoth, WY and Old Faithful. The Mammoth coaches serve Old Faithful and Canyon on daily trips, while the coaches based at Old Faithful serve the south and west entrances. Private operators provide coach trips into the park from the east, south and west entrances with the west entrances having the largest number of entries. During the winter 2004-2005 season 2,021 coach trips were reported in the park transporting 17,218 passengers.[33] This was a 27% increase in coach trips and a 38% increase in passengers from the 2003-2004 season.

Experimental

On-board emission measurements were made on nine snowcoaches from February 7–18, 2005. One goal of this project was to try to measure as many different snowcoaches as possible during this eleven-day period. Measurements were made with a commercially available Clean Air Technologies International, Inc. Universal Montana portable on-board emissions monitoring system (see Figure 9).[26] The universal unit is capable of testing electronically controlled sparked ignition vehicles and compression ignition vehicles that utilize heavy-duty engine controls. The system measures, in real-time, the gaseous species using twinned analyzer benches. Each bench includes an NDIR analyzer to measure CO, CO_2 and HC, measured and reported as propane. Electrochemical cells are used on each bench to measure oxygen (O_2) and NO (see Appendix C for the

Figure 9. Photograph of the Montana system ready for sampling in a coach. Pictured are the video screen at left, compact flash card top center, GPS receiver connector top right and the exhaust lines exiting the cabin through the side window.

Montana's accuracy, repeatability and noise specifications). Both benches measure the same exhaust sample and the resulting concentrations are averaged between the two analyzers except during zeroing. The benches alternate zero checks so that one analyzer is always on-line at all times. On compression ignition engines, the HC measurements are not considered accurate because, without a heated sample line, it is believed that only a fraction of the heavier hydrocarbons reach the sample cell in gaseous form.[26] The HC data are therefore not reported for the diesel snowcoach. Particulate matter (PM) emissions are measured on compression ignition engines using a real-time laser light scattering monitor. The system contains both light and heavy-duty engine computer scanners, and a GPS receiver. The data are stored on a second by second basis to a compact flash memory card. The analyzer was calibrated with a certified gas cylinder containing 12.0 % CO_2, 8.02 % CO, 3220 ppm propane, and 3010 ppm NO (Messer, Morrisville, PA).

Tailpipe concentration data including CO_2 directly measure mass emissions per gallon of fuel. To convert into mass emissions per mile, a measure of the vehicle exhaust flow is needed. The Montana system indirectly measures the exhaust flow by calculating the intake air mass flow and using mass balance equations to obtain the exhaust flow. On late model vehicles, the Montana's engine scanners allow the intake air mass flow to be obtained from the engine intake mass airflow sensor via the engine control unit on-board diagnostic (OBD) port. On older vehicles this parameter is determined from engine design (displacement and compression ratio) and operating parameters collected through a set of three temporarily mounted sensors using a speed-density method.[27] The three sensors collect engine rpm (inductive or optical pickup), engine intake air temperature (thermistor) and the absolute intake manifold pressure (pressure transducer). The use of the Montana system to record gram/mile emission factors for the gaseous species measured has been shown to correlate well with laboratory grade equipment.[26] The laser light scattering particulate measurement has been successfully compared to both gravimetric filter methods and a real-time TEOM-1105 particulate monitor with good results.[26]

The Montana system labels the second-by-second data as valid when engine data are available and the analyzer benches are reporting satisfactory operating parameters. However, we learned with use that the software does not require any exhaust gas to be present for it to report valid gram/sec emissions data. These episodes are easy noted by large oxygen concentration measurements and the absence of the other exhaust gases. Also flow restrictions caused by water freezing in either the intake or exhaust lines sometimes produced large positive or negative emissions values that were not marked as invalid by the software. These events were often noted by the operator in the field notebook.

Therefore the database contains two fields (*Org_validity* and *Valid_g_s*) that addresses data validity (see Appendix D). *Org_validity* is the flag originally produced by the Montana system and signifies valid data by a "YES" when engine data are available and the analyzer benches are reporting satisfactory operating parameters. The additional field *Valid_g_s* has been added to denote the data that we have included in our analysis. Appendix E contains a listing by coach as to the sections of data that we have invalidated for this analysis and the reasons for this designation. All of the data will be available for download from www.feat.biochem.du.edu and using the *Org_validity* flag data can be selected using any criteria desired.

Sampling in-use emissions means having to deal with the differences between vehicles, the in-use environments and routines that the vehicles experience on a daily basis. In our case that meant different engine types, track configurations, freezing temperatures with lots of snow and ice and daily schedules to be kept to transport paying customers. We sampled one diesel and eight gasoline powered snowcoaches with 3 different track configurations. Since gasoline powered engines have about 12% water vapor in their exhaust, major steps had to be taken to try and prevent (not always successfully) water from freezing in the lines. The coach's schedule each day was to warm-up from 7 – 8 am, depart the park entrance around 8:30 am and arrive at the destination for lunch around noon. After an hour and a half break, the coaches are warmed upped and the return trip starts at 1:30 pm and arrive back at the entrance between 5 and 6 pm. We generally needed 2 to 3 hours of time with each coach to install and calibrate the analyzer. Of the nine coaches that were sampled, only two were garaged indoor's overnight, the National

Park Service diesel van and the Alpen Guides Bombardier. All of the Xanterra coaches located at the north entrance were parked in a wooded area at the end of the plowed road. Typically, we would install and calibrate the analyzer on a coach the night before its use. The analyzer and sampling lines were then removed to store them at room temperature overnight and arrive early the next morning to reinstall and allow the analyzer to warm-up along with the coach. A round trip ticket was purchased each day and an operator accompanied the analyzer during the trip. On the afternoon of February 11 and the morning of February 13, the analyzer was unattended and no data were collected.

There were three basic types of vehicles and track arrangements sampled during this study. Figures 10 - 12 show the National Park Service diesel van outfitted with "Mat-Trax" treads, a vintage Bombardier coach with elevated exhaust and an early 90's van conversion with a "Snowbuster" twin track/ski combination. Table 10 provides a summary of each vehicle along with the testing schedule and the roundtrip route information. In all, three 2000 model year and newer Mat-trax equipped vans were sampled, two vintage Bombardiers (one a traditional carbureted engine, the second converted to a modern fuel injected emissions controlled engine) and four early 90's Snowbuster van conversions. They included eight gasoline and one diesel engine.

Installation of the analyzer required routing the gas sampling and exhaust lines in and out of the vehicle and installing the power, OBD or sensor array cables and the GPS receiver. The exhaust tail pipes of the coaches were typically located behind and above the track of the vehicle. Snow was constantly kicked up into this area and an L-shaped extension was fabricated to attach to the end of the tailpipe to distance the opening from the track and

Figure 10. National Park Service 2000 Ford E350 Diesel snowcoach with Mat-trax conversion also showing the insulated exhaust sampling lines.

Figure 11. Vintage Bombardier 709 that utilizes a rear engine, forwards driven twin track and twin steering ski arrangement. This engine has an elevated exhaust system and the sample and data lines enter the cabin through a rear roof hatch.

Figure 12. Xanterra 164 is a 1992 Chevrolet Van with a rear driven Snowbuster track/ski conversion.

Table 10. Snowcoach sampling dates, vehicle information and route summary.

Vehicle Date Sampled	Year Make Type	Vin Engine Fuel Type	Track Type Entrance	Load In / Out	Destination Distance
NPS 2/7 – 2/8/05	2000 Ford E350 Van	1FBSS31F3YHB26376 DI 7.3L V-8 Turbo Diesel	Mat-Trax North	5 / 5	Loop of Park 145 miles
Xanterra 163 2/15/05	1992 Chevrolet Van	2GAGG39K0N4165176 TBI 5.7L V-8 Gasoline	Snowbuster North	11 / ?	RT Old Faithful 103 miles
Xanterra 164 2/9/05	1992 Chevrolet Van	2GAGG39K1N4142358 TBI 5.7L V-8 Gasoline	Snowbuster North	8 / ?	RT Old Faithful 103 miles
Xanterra 165 2/12/05	1991 Chevrolet Van	2GJGG39K3M4515530 TBI 5.7L V-8 Gasoline	Snowbuster North	9 / 2	RT Old Faithful 103 miles
Xanterra 166 2/13/05	1991 Chevrolet Van	2GJGG39K8M4513787 TBI 5.7L V-8 Gasoline	Snowbuster North	- / 5	One Way Old Faithful 52 miles
Xanterra 416 2/14/05	2001 Chevrolet Van	1GAHG39R111132819 CPI 5.7L V-8 Gasoline	Mat-Trax North	10 / -	One Way Old Faithful 52 miles
Xanterra 419 2/11/05	2001 Chevrolet Van	1GAHG39G811211760 MFI 8.1L V-8 Gasoline	Mat-Trax North	8 / -	One Way Old Faithful 52 miles
Xanterra 709 2/10/05	2001 Engine Bombardier	Carbureted 5.7L V-8 Gasoline	Twin Track North	6 / 6	RT Canyon 70 miles
Alpen Guides DeLacy 2/18/05	2002 Engine Bombardier	ZGCEC19T021214428 MFI 5.3L V-8 Gasoline	Twin Track West	3 / 3	RT Old Faithful 63 miles

protect the sampling probe. The probe and sample line was wrapped in oversized foam pipe insulation and routed the shortest distance possible through a window into the cabin. The extra space in the opened window was plugged with foam rubber. Once inside the cabin, a plastic tee was installed into the end of the foam insulation and the sample line was threaded straight through to the analyzer. Because of power limitations, we could not electrically heat the sampling line. We instead relied on a 12-volt rechargeable motorcycle battery powered fan to continuously draw warm air out of the cabin and pass it through the plastic tee into and down the oversized pipe insulation to warm the line. Fiberglass, aluminum insulating tape and/or Mylar coated bubble wrap were used at the probe-hose interface for extra insulation and protection. Figure 13 shows a rear view of a coach with the tailpipe extension, insulated sample line and the rear window sealed with the foam rubber.

Figure 13. Rear view of a Snowbuster coach showing the tailpipe extension, insulated sample line and the temporary foam insulation installed to seal the rear window.

The Montana portable system was usually placed in the seat behind the driver. The exhaust lines, power and GPS receiver lines were routed out of the window next to the analyzer. Power was taken either from the 12V cigarette lighter outlet, or from a power cable run from the battery in the engine compartment. All of the externally mounted lines and wires were held in place by right angle brackets held to the vehicle by strong magnets. The magnet/bracket assemblies were coated with electrical tape to keep the lines in place without scratching the vehicle. For the modern vehicles the OBD data line was duct taped along the floor to the dash area and connected to the data port. In the Bombardiers, the lines were routed via a rear roof hatch. The Montana system also records location and altitude from an integrated GPS receiver. The GPS antenna was mounted to the roof of the vehicle by a permanent magnet.

The integrated GPS receiver proved to be more valuable than originally envisioned. We were interested in knowing the location of the coaches during monitoring so we could factor terrain into the analysis if desired. What we had not thought through is the fact that the drive wheels used in the track systems change the speed/odometer calibration. The integrated GPS receiver proved a more accurate measurement of speed and distance traveled. The only caveat when summing the GPS distances is recognizing that the GPS receiver we used had a stationary variation of approximately a half a meter. In calculating distance traveled, any change in location that is less than or equal to 0.5 meters was summed as 0 meters.

In comparing the GPS data with the engine reported odometer data it was also learned that the Mat-Trax conversions slip, over reporting distance travel by 5 to 10%. This was found from comparing the distance traveled calculations on the NPS diesel van during a short drive on pavement. The over snow engine reported distances always ended up 5 to 10% higher than the GPS summed distance, except for the trip over pavement that agreed to better than 1%. When this was investigated further by graphing engine reported speeds versus GPS measured speed the Mat-Trax equipped vehicles had larger engine reported speed variations at the higher speeds than the Snowbuster track system. This again indicated that the longer Snowbuster track does not slip during over the snow travel.

Results

Nine days of sampling in Yellowstone National Park resulted in the collection of 51.9 hours of second-by-second data (186,845 records) with 34.6 hours of valid gram per second data for CO, HC, and NO and an additional 6.3 hours of valid PM data from the park services diesel powered coach. The entire valid gram per second data includes at least engine rpm, intake air temperature and absolute intake manifold pressure. Additionally recorded from some of the engines were speed, acceleration, percent throttle, torque, coolant temperature and fuel economy. The GPS receiver reported its fix status, number of satellites visible, time, longitude, latitude and altitude. The database format is defined in Appendix D and is available for download from www.feat.biochem.du.edu.

Table 11 details the valid data collected for each of the nine coaches instrumented during this study. The snowcoach NO data is measured as NO but is reported by the Montana unit as NO_2 (NO_x) for all of the g/mi, g/gal and g/kg snowcoach emission values. These data include a significant amount of idling that arose from the analyzers need for a consistent power source. Absent our presence, the coaches extended idling is generally restricted to the early morning and after lunch warm-up periods. Appendix F has a map for each day that the nine coaches were sampled, plotting the location of valid gram per second data along Yellowstone National Park roadways. For the roundtrips (see Table 10) some points will overlap and areas not sampled inbound may have been sampled on the return trip.

The National Park Service diesel van was the only vehicle tested on more than one day and they are combined in a single entry in Table 11. The test on February 7 was a short roundtrip from the maintenance garage to the Mammoth Post Office and on February 8 we traveled on the longest trip of a grand loop around the park. Three roundtrips turned into one way sampling trips. Our roundtrip seat was used to ferry an NPS researcher to Old Faithful for an overnight visit resulting in two coach segments where the analyzer package was unattended and did not collect data. On February 11 (Xanterra 419) data collection was only attempted on the inbound trip and on February 13 (Xanterra 166) only on the return trip to the North entrance. On Monday, February 14 in Xanterra 416

Table 11. Summary of all the valid second by second data collected for each coach.

Vehicle	Sampled		Mean Speed	Fuel Use	Gram/mile Emissions			
	Hours	Miles	(mph)	(mpg)	CO	HC[a]	NO_x	PM[a]
NPS Van	6.3	107.0	17.0	3.0	7.2	NA	49	0.12
Xanterra 163	6.0	83.6	14.1	2.9	600	7.2	26	NA
Xanterra 164	5.9	78.0	13.2	3.1	460	5.8	19	NA
Xanterra 165	4.0	69.6	17.5	5.0	310	5.5	16	NA
Xanterra 166	3.6	42.8	11.9	2.9	600	34	25	NA
Xanterra 416	2.9	32.9	11.4	2.5	84	0.93	26	NA
Xanterra 419	0.6	6.0	10.5	3.5	9.3	1.4	16	NA
Alpen Guides	3.5	60.9	17.5	6.8	5.3	0.97	1.4	NA
Xanterra 709	1.8	22.7	12.2	3.6	630	50	7.7	NA
Totals and Time-Weighted Means	34.6	503.5	14.6	3.7	300	10	24	0.12

[a] HC data are not considered valid for the diesel vehicle (NPS Van) and PM data were only collected from this vehicle.

because of a coach breakdown, we were asked to give up our seat and the return trip was with the luggage coach and no data was collected.

Other reasons for reduced sampling times in Table 11 can be attributed to either line freezing problems or equipment malfunctions (see Appendix E). Xanterra 709 had line-freezing problems early in its trip and the data collected on the return trip were lost when the computer failed to save the emissions data to the flash card. Xanterra 419 had major line freezing problems that occurred shortly after departure and were never resolved. These problems continued the next day with Xanterra 165 when a cracked fitting was discovered and temporarily repaired. The entire line was replaced for the next day's trip and we had fewer line problems with the remaining coaches.

For the purposes of the dispersion emissions modeling Table 12 breaks out the measurement time, distance and average speed for three self-defined operation modes of idle, low speed and cruise. Note that some data are lost between Tables 11 and 12 due to the additional requirement in Table 12 that the GPS receiver must have a valid fix. Idle has been defined by restricting the GPS measured distances change between readings of less than or equal to 0.5 meter. The low speed driving mode was defined as the GPS measured speed being greater than idle and less than or equal to 15 mph. Cruise mode was selected for GPS measured speeds of greater than 15 mph. Table 13 is the companion table and gives the measured mass emission rates for the three modes defined in Table 12.

Discussion

The goals of this research project seem on the surface to be very simple and straightforward. Instrument and measure the tailpipe emissions of an in-use snowcoach during normal operations. There are reasons though for why these data have never before

Table 12. Valid data distributed for three GPS defined driving modes.

Vehicle	Hours Sampled (Miles Traveled)			Mean Low Speed 0 < GPS Speed ≤ 15 mph	Mean Cruise Speed GPS Speed > 15 mph
	Idle	Low Speed	Cruise		
NPS Van	1.9 (0)	0.8 (7.1)	3.6 (99.9)	8.2	27.9
Xanterra 163	1.8 (0)	1.2 (9.3)	3 (74.3)	7.7	25.1
Xanterra 164	2.0 (0)	1 (8.0)	2.9 (70.0)	8.2	24.5
Xanterra 165	0.8 (0)	0.7 (5.7)	2.5 (63.9)	8.1	25.8
Xanterra 166	1.4 (0)	0.3 (2.5)	1.5 (40.3)	8.6	26.5
Xanterra 416	1.2 (0)	0.4 (3.9)	1.2 (29)	9.2	23.3
Xanterra 419	0.3 (0)	0.01 (0.1)	0.2 (5.9)	7.1	27.0
Alpen Guides	0.5 (0)	0.9 (7.7)	2.1 (53.2)	8.4	25.8
Xanterra 709	0.7 (0)	0.2 (2.8)	0.6 (17)	8.2	27.6
Totals and Weighted Means	10.6 (0)	5.5 (47.1)	17.6 (453.5)	8.2	25.9

been collected in this manner. The first is that there are not many snowcoaches used around the world and those that are used are generally in places where exhaust emissions are not considered important. The second and perhaps more important factor is the environmental conditions that necessitate the use of snowcoaches mean that collecting warm wet exhaust emissions will be much easier in a laboratory setting than an in-use one. However, the environmental conditions that these vehicles operate in are apparently an important parameter that is almost impossible to reproduce in a laboratory setting.

The collection of almost 35 hours of valid emissions and engine data is a major accomplishment in spite of the difficulties. Keeping the collection and exhaust lines from freezing was a difficult task some days. One of the intake sampling lines was especially troublesome and after its replacement beginning on Sunday February 13th we had far less trouble. The battery powered fan which forced cabin air down the outside of the intake line was very successful and any future work should add a second fan to blow air over the exit lines which had icing problems as well.

The vehicles that we have measured can be segregated into three distinct engine/emissions control groupings. 1) The NPS diesel van with a direct injection

Table 13. Mass emissions data for the three driving modes defined in Table 12.[a]

Vehicle Measured	Species	Idle			Low Speed			Cruise		
		mg/s	g/gal	g/kg	g/mi	g/gal	g/kg	g/mi	g/gal	g/kg
NPS Van	CO	6.8	53	19	8.9	32	12	6.2	17	6.1
NPS Van	NO_x	16	130	46	42	150	55	47	130	46
NPS Van	PM	0.07	0.6	0.2	0.1	0.4	0.1	0.1	0.3	0.1
Xanterra 163	CO	17	110	40	88	230	84	660	2000	730
Xanterra 163	HC	9.1	59	21	7.0	18	6.7	6.4	19	7.0
Xanterra 163	NO_x	2.6	17	6.0	38	100	36	24	72	22
Xanterra 164	CO	29	170	61	64	140	53	490	1700	620
Xanterra 164	HC	6.7	38	14	5.9	13	4.9	4.9	17	6.3
Xanterra 164	NO_x	0.9	5.0	1.8	27	62	23	17	60	22
Xanterra 165	CO	150	1200	420	65	260	95	330	1700	620
Xanterra 165	HC	14	110	41	6.3	25	9.2	4.8	25	9.1
Xanterra 165	NO_x	0.8	6.5	2.4	21	83	30	15	79	29
Xanterra 166	CO	130	850	310	360	920	330	510	1800	650
Xanterra 166	HC	15	100	36	22	57	21	30	100	38
Xanterra 166	NO_x	0.3	1.8	0.7	28	73	26	22	78	28
Xanterra 416	CO	4.8	34	12	5.8	14	5.1	94	250	91
Xanterra 416	HC	1.1	8.0	2.9	0.9	2.2	0.8	0.8	2.0	0.7
Xanterra 416	NO_x	0.4	3.0	1.1	21	50	18	27	72	26
Xanterra 419	CO	16	120	44	35	77	28	5.8	22	8.0
Xanterra 419	HC	4.2	33	12	3.3	7.2	2.6	0.4	1.7	0.6
Xanterra 419	NO_x	0.07	0.5	0.2	10	22	8.0	16	61	22
Alpen Guides	CO	3.7	28	10	7.5	44	16	4.9	35	13
Alpen Guides	HC	1.3	10	3.7	1.4	8.5	3.1	0.8	6.0	2.2
Alpen Guides	NO_x	0.03	0.2	0.1	1.4	8.2	3.0	1.4	9.6	3.5
Xanterra 709	CO	260	1600	590	580	2000	740	580	2300	850
Xanterra 709	HC	13	80	29	15	57	21	51	210	75
Xanterra 709	NO_x	0.3	1.8	0.7	9.4	33	12	7.0	28	10
Time-Weighted Means	CO	56	380	140	76	240	87	300	1100	410
Time-Weighted Means	HC	8.5	56	20	6.0	19	6.9	9.2	34	16
Time-Weighted Means	NO_x	3.6	27	9.9	25	75	27	23	73	27
Time-Weighted Means	PM	0.07		0.2	0.1	0.4	0.1	0.1	0.3	0.1

[a] g/gal and g/kg results are calculated from the reported g/sec emissions and fuel consumption.

turbocharged compression ignition engine and no aftertreatment, 2) Xanterra van conversions and the Alpen Guides Bombardier all with modern gasoline spark ignition closed-loop, computer controlled, fuel injected engines with 3-way catalytic converters and 3) Xanterra Bombardier with a carbureted gasoline engine with no aftertreatment. There are engine (Xanterra vans 164-166 are throttle body injected and vans 416 and 419 are port injected) and transmission (vans 164-166 have had the original transmissions replaced with a heavy-duty version) differences in the second group, however the certification emission standards and certification tests are not very different. The park service's diesel van is the easiest to first discuss. Low CO and HC emissions are typical for compression ignition engines and while we did not measure the HC emissions, it is expected that they mirror the low CO emissions we did measure. For the loads produced by the tracks, it is also not a surprise that the NO_x emissions are the highest for any of the vehicles that we measured. We do not know of any fuels or current after treatments that could be economically employed to reduce these emissions. The PM emissions are very good at 120 milligrams per mile when one considers the very high loads the vehicle experiences. The only negative comment one can make on the use of diesel powered vehicles in these conditions is that the low temperatures experienced will require the vehicle to be garaged or block heated overnight and some may object to the fuel odor.

The modern gasoline powered vehicles present a more complicated emissions picture when one reviews the data from the various driving modes. All of these drive trains were originally certified to very low on-road tailpipe emission limits. The fact that all of these vehicles exhibited low idle emissions suggests that the engines still meet those original standards. Yet, many of the vehicles had very high over-snow emissions. There are many terms used when talking about computer controlled, close-loop gasoline engines. The "closed-loop" referred to is the link between the fuel management computer and the oxygen sensor or sensors in the vehicles exhaust stream. The oxygen sensors help the fuel management system keep the air to fuel ratio as close to stoichiometry as possible for the conditions. When this feedback system is operational, the vehicle is referred to as operating in "closed-loop mode". The fuel management computer has the capability to operate the engine without this feedback mechanism, for example, if the oxygen sensor fails to function properly. The vehicle calibration provides the fuel management computer with an engine map (effectively an air to fuel ratio cheat sheet) that allows it to make an informed decision about how much fuel to put into the engine for the current conditions. This situation is often referred to as "open-loop operation." A vehicle can operate in either closed or open-loop modes and still maintain its low emissions certification levels. However, it is also common that higher emission levels are associated with open-loop operation and thus many references link high emission levels with open-loop operation. Southwest research used this term in their report.[12]

A second term that more often is linked with excessive vehicle emissions is off-cycle emissions. All of these vehicles are certified to a series of tests conducted on a laboratory chassis dynamometer where the vehicle is driven over a flat (no hills in lab tests) cycle with predefined accelerations, decelerations, idle and cruise segments. These cycles contain a matrix of loads and speeds over which the manufacturer is required to meet a certain average emissions performance. When in-use conditions force the vehicle into an operating mode that is outside the laboratory conditions, the vehicle is referred to as operating "off-cycle." Again, there are many off-cycle conditions in which these vehicles do not exceed the government-mandated tailpipe limits. However, for a properly maintained vehicle, excessive tailpipe emissions only occur during off-cycle driving and we will use this term when discussing a vehicle's high emissions.

The difference in load is probably the single biggest determining factor in the emissions performance of these vehicles. This difference alone insures that these coaches are never operated in an on-cycle situation. For example, on-road fuel economy for these vans is around 15 mpg. Under the best snow conditions, these vans get 3 to 5 mpg and for heavy wet snow conditions 1 to 2 mpg has been reported by some of the drivers. NO emissions are produced in gasoline engines during lean (low CO) conditions under high temperature and high load conditions. This is the reason for the high NO emissions measured from most of these coaches, however the large amount of CO being produced would seem on the surface to preclude large NO emissions.

In order to explain this apparently unlikely observation, Figure 14 displays a fourteen-minute segment (4.6 miles) of second by second emissions data from Xanterra 164 (see Table 10 and Figure 12). Xanterra 164 is a snowbuster conversion van, measured as it nears the Old Faithful area. The vehicle is initially operating in a lean combustion region with low CO and HC emissions and high NO emissions as it travels along a short downgrade. At a constant speed and engine rpm, the grade changes, the throttle is increased and forces the engine into a rich combustion region with very high CO emissions, increased HC emissions and low NO emissions. At about 11:32:20 the driver rapidly decelerates and as the CO emissions drop, a large HC emissions spike is recorded. The HC puff is due to this older model engine's throttle body fuel injector not being able to shut the fuel off as fast as it shuts the air off. The term "manifold flash" is often used. This phenomenon results in the catalyst having no available oxygen to oxidize the puff of unburned fuel. For this 4.6 mile segment the gram per mile emissions are 330, 4.1 and 19 grams/mile respectively for CO, HC and NO_x.

Figure 14 illustrates how we achieved high averaged levels of CO and NO concurrently (see Tables 11 and 12). There exists a load point about which the coach alternates between on-cycle (lean combustion) operation and off-cycle (rich combustion) operation. Peak power in a gasoline engine is usually achieved at around a 4% CO level. The high levels of CO (> 10%) would only make sense if the vehicle is trying to protect the engine and catalyst from over heating and catalyst destruction. All of the drive trains and emissions systems were designed for wheeled traveled. Because of the track conversion, the engine computer believes the coach is traveling in excess of 70 mph. The only on-road situation that might have been anticipated with this combination of load and perceived high speed is an extreme mountain, trailer towing situation where overheating would be a real concern. Excess fuel causes high CO levels but lowers combustion temperatures and completely precludes any catalytic activity thus lowering engine and valve temperatures and keeping the catalytic converter, safe from burning itself up.

A similar fourteen-minute segment (5.6 miles) of second by second emissions data is graphed in Figure 15 from Xanterra 416 (see Table 10). Xanterra 416 is a Mat-trax conversion van, shown again as it approaches Old Faithful. Again, the vehicle alternates about a load point between regions of rich and lean engine operation due to an apparent lack of power. The rapid increases and decreases in the engine rpm's shown in the middle graph of Figure 15 highlight this vehicle's struggle to maintain speed with frequent shifting between second (high rpm's) and third gear (low rpm's). Each time this vehicle

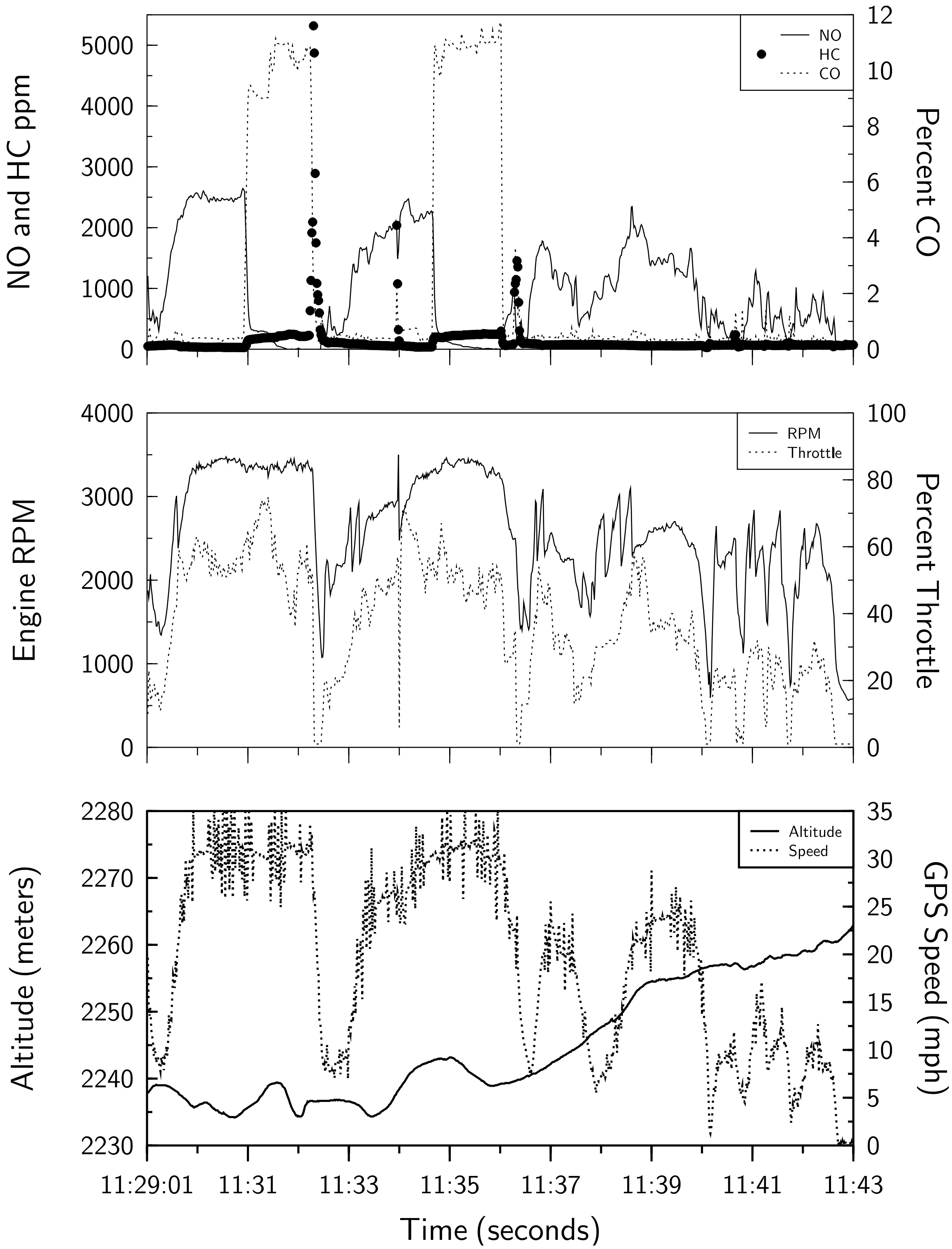

Figure 14. Second by second emissions, engine and vehicle data collected during a fourteen-minute segment (4.6 miles) from Xanterra 164 as it nears Old Faithful. For this segment the CO, HC and NO_x emissions were 330, 4.1, and 19 grams/mile.

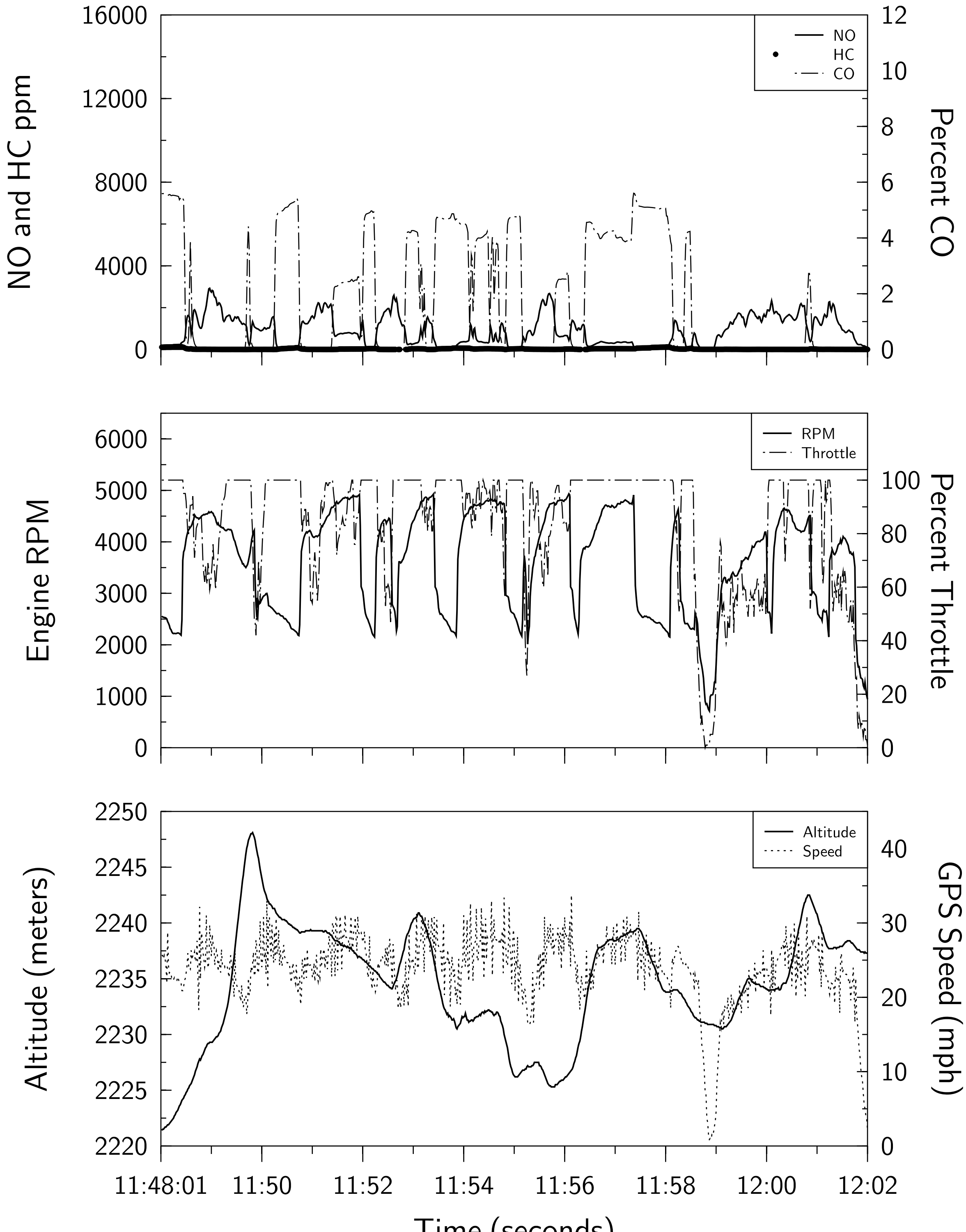

Figure 15. Second by second emissions, engine and vehicle data collected during a fourteen-minute segment (5.6 miles) from Xanterra 416 as it nears Old Faithful. For this segment the CO, HC and NO_x emissions were 310, 1.2, and 28 grams/mile.

shifts into third, it does not have enough power to maintain speed and the engine rpm's begin to lag. The driver gives it full throttle and the extra fuel sent to the engine as a power enrichment command causes the CO emissions to increase. However, the power is inadequate and eventually the vehicle downshifts back to second and reenters the lean combustion region and high NO emissions and the cycle repeats itself. Just before 11:51 and at 11:57, power enrichment is also apparent even when the vehicle is in second gear. The lower power to weight ratio of this vehicle directly results in higher CO and HC emissions and poorer fuel economy.

Figure 16 details this section of driving by plotting the vehicles GPS speed divided by its engine rpm, which groups similar gear ratios. This again shows that this coach is unable to spend very much time in third gear. Simply increasing the engine size of this vehicle will likely be enough to eliminate most of the power enrichment excursions experienced by Xanterra 416 for these snow conditions. Xanterra 419 is an identical coach to Xanterra 416 except that it is equipped with a larger 8.1L engine. Unfortunately we were unsuccessful in collecting either emissions or engine data during this same stretch of roadway for comparison. We have anecdotal information from Xanterra that the coach with the larger engine gets better fuel economy (limited data from Table 2 also reflects this). This otherwise counterintuitive conclusion would be consistent with the coach having fewer excursions into the power enrichment mode experienced by coach 416.

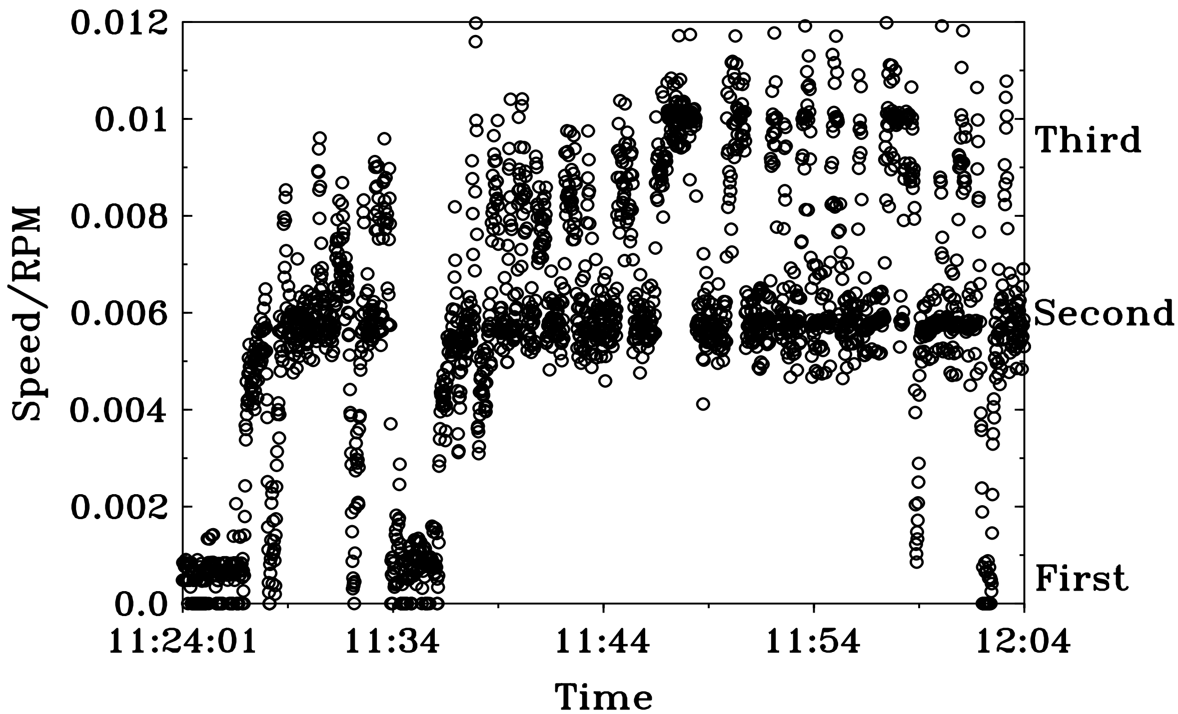

Figure 16. Graph of speed/rpm versus time for Xanterra 416. Gear groupings are noted along the right hand axis.

All of the coaches utilizing the modern closed-loop computer controlled engines that we tested have a load point that, when exceeded, resulted in the engine control system going from lean or stoichiometric to rich operation. Depending on the power to weight ratio and snow conditions this load point will change from day to day and coach to coach. Even the Alpen Guides Bombardier equipped with the modern engine, which was measured with the lowest overall emissions, briefly went into power enrichment during an aggressive acceleration. One, perhaps unexpected, conclusion is that gasoline powered coaches need to be purchased with the largest engine possible to meet the power demands of over snow operation.

The final vehicle group is represented by Xanterra 709, which is a vintage Bombardier operating with a carbureted V-8 engine and no emissions aftertreatment. Figure 17 details a fourteen-minute segment (5.7 miles) from this coach as it traverses a downgrade in the Canyon area with 490, 74, and 4.9 grams/mile for CO, HC and NO_x. Since this coach was not computer equipped there is no throttle position data and the rpm data are nosier due to it being measured with an inductive pickup clamped to a spark plug wire. The two noticeable operating characteristics of this engine during this segment is that there really are no lean operating conditions and the HC emissions are so high that cylinder misfires must be occurring during the decelerations. The HC emissions are so high (they are beginning to approach two-stroke snowmobile territory) they are inadvertently helping to lower the CO emissions since a large portion of the fuel is not being combusted. The downgrade is increasing the HC emissions, however as shown in Table 11 this vehicle still has very high HC emissions overall. It should be pointed out that simply adding emissions after treatment, like an oxidation catalyst, would do nothing to reduce the emissions of this vehicle. The Park Service would do well to discourage carbureted vehicles at any time of year.

If we arbitrarily define off-cycle operation as anytime a vehicles tailpipe CO levels exceeds 3% we can calculate the percent of off-cycle operation for each of the coaches. The choice of 2, 3 or 4% CO does not change the off-cycle operations percentages very much since most of the coaches greatly exceeded this value during actual operation. Table 14 breaks out all of the non-idle operations by coach, inbound or outbound route segment and the percent of time that the tailpipe emissions exceeded 3% CO defining off-cycle operation. Keep in mind that coaches were operated on different routes and even those that were operated on the same routes have data that may not overlap. As will be discussed later the coaches are driven harder on the homebound leg and this is reflected in the higher percentage of off-cycle operation in the outbound segment. The diesel powered NPS Van and all of the newer gasoline powered coaches spent the least amount of time in off-cycle operation. The early 90's conversion vans spend almost half their operation time off-cycle in the afternoon while the morning is much lower due to lower speed operation. The vintage Bombardier as shown before is high emitting all of the time. The time weighted averages are 20% off-cycle operation for inbound trips and 29% for outbound.

The coaches that serve the north entrance have two different activity patterns. Generally,

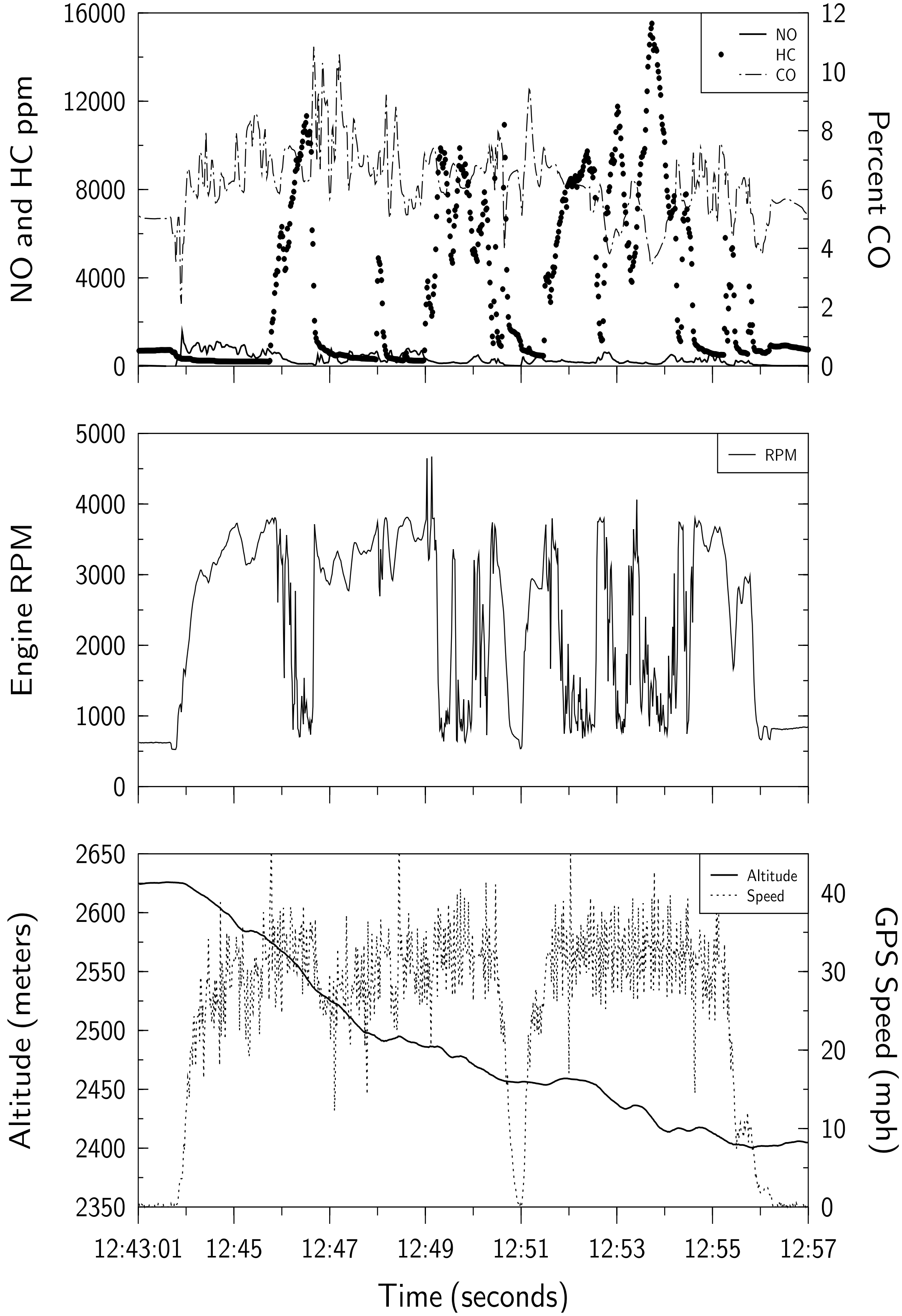

Figure 17. Second by second emissions, engine and vehicle data collected during a fourteen-minute segment (5.7 miles) from Xanterra 709 in the Canyon area. For this segment the CO, HC and NO_x emissions were 490, 74, and 4.9 grams/mile.

Table 14. Estimated off-cycle operation by route segment for non-idle operation.

Vehicle	Segment	Seconds Collected	Percent Off-Cycle Operation (%CO > 3)
NPS Van	In	6,077	0%
NPS Van	Out	9,568	0%
NPS Van	Total	15,645	0%
Xanterra 163	In	8,859	36.1%
Xanterra 163	Out	6,135	50.3%
Xanterra 163	Total	14,994	41.9%
Xanterra 164	In	8,488	20.6%
Xanterra 164	Out	5,326	50.2%
Xanterra 164	Total	13,814	32.0%
Xanterra 165	In	5,403	15.1%
Xanterra 165	Out	6,030	41.2%
Xanterra 165	Total	11,433	28.9%
Xanterra 166	In	0	
Xanterra 166	Out	6,545	44.1%
Xanterra 166	Total	6,545	44.1%
Xanterra 416	In	5,997	6.3%
Xanterra 416	Out	0	
Xanterra 416	Total	5,997	6.3%
Xanterra 419	In	821	0%
Xanterra 419	Out	0	
Xanterra 419	Total	821	0%
Alpen Guides	In	6,042	0.08%
Alpen Guides	Out	4,684	0.06%
Alpen Guides	Total	10,726	0.07%
Xanterra 709	In	2,835	98.1%
Xanterra 709	Out	0	
Xanterra 709	Total	2,835	98.1%

the morning drive to Old Faithful or Canyon is filled with many stops and starts connected by short cruise segments. This activity pattern is for sight seeing and stopping to watch the animals encountered. With the exception of Xanterra 709, all of the coaches tested have very low idle emissions (see Table 13). The afternoon drives are often filled with weary travelers that just want to get home. Consequently, there are long periods of high-speed cruise. Table 15 breaks out these differences, excluding all of the idle data, for four of the coaches where we have ample data from the inbound and outbound trips. The Alpen Guides coach trip was not truly a commercial trip due to a last minute passenger cancellation, but we even acted more like tourists in the morning. As evidenced by the differences in average speeds the outbound trips consequently have longer periods of high-speed operation increasing the amount off-cycle emissions (see Table 14).

Table 15. A Comparison of inbounds versus outbound emissions for four coaches.

Vehicle	Segment	Sampled		Mean GPS Speed	Gram/mile Emissions		
		Hours	Miles		CO	HC	NO_x
Xanterra 163	In	2.5	45.5	18.5	550	6.6	29
Xanterra 163	Out	1.7	38.1	22.4	650	6.3	22
Xanterra 164	In	2.4	43.6	18.5	350	4.8	26
Xanterra 164	Out	1.5	34.4	23.3	580	5.5	9.5
Xanterra 165	In	1.5	28.7	19.2	200	4.4	21
Xanterra 165	Out	1.7	40.9	24.4	380	5.3	12
Alpen Guides	In	1.7	29.9	17.8	5.6	1.2	1.3
Alpen Guides	Out	1.3	31	23.8	4.9	0.6	1.4

The differences in the amount of high speed driving is an important distinction because, as discussed above, the higher the power demand the more likely the vehicle will cross its load threshold and enter rich engine operation. This is in fact seen for the three Xanterra coaches where CO emissions are larger for the outbound trips. The Alpen Guides coach does not show this difference as it had ample power to stay out of the power enrichment region. Any of the coaches that experience rich engine operation due to higher loads on the inbound trip would be expected to have higher average emissions on the outbound trip.

Previously the only snowcoach emissions data was available from a V-10 powered Ford E350, 15 passenger van collected by Southwest Research Inc.[12] Under the maximum load conditions possible with their chassis dynamometer they reported 99, 1.6 and 1.8 g/mile emissions for CO, HC and NO_x representing a maximum off-cycle emissions level. The NO_x emissions are very low (even lower for the on-cycle measurements) when compared to the current data set and indicate that the dynamometer operating conditions are not as demanding as we observed in actual use. Our field experience would suggest that with a V-10 powered van the load point that separates lean (on-cycle) and rich (off-cycle) operation would be pushed higher than we observed for a similar sized van with a smaller engine (Xanterra coach 416 with cruise emissions of 94, 0.8 and 27 g/mile). Since the larger engine in the Ford should lead to less off-cycle excursions than Xanterra 416, we would expect lower CO and HC emissions and much higher NO_x emissions than observed on the dynamometer.

COMPARISON OF SNOW VEHICLE EMISSIONS

The data collected during this study allow one to estimate the emissions impacts from the various transportation options available in Yellowstone during the winter. Table 16 combines emission measurements, winter visitor statistics obtained from the National Park Service Public Use Statistics Office with fuel economy assumptions for the snowmobile fleets to calculate a gram/mile/person emissions estimate. The snowmobile CO and NO values are averages of the entrance and exit measurements and the snowmobile NO measurements have been converted to NO_2 emissions for a direct comparison. The snowcoach emissions are a time weighted average of all the data collected (see Table 11). To convert the snowmobile gram/gallon measurements to grams/mile estimates we have assumed a 2-stroke fuel economy of 13 miles per gallon and for 4-strokes 18 miles per gallon.[7, 24] Snowmobile entries for 1999 were 62,878 with 76,271 passengers for a 1.2 persons/snowmobile average. Snowmobile entries for 2005 were 18,364 with 24,049 passengers for a 1.3 persons/snowmobile average. Snowcoach entries for 2005 were 2,201 with 17,218 passengers for a 8.5 persons/coach average.

Mean snowmobile emissions/person have dropped 61% for CO and 96% for HC with the introduction of 4-stroke snowmobiles. Previous work has shown than 4-stroke snowmobiles emit considerably more NO than 2-strokes and therefore it is a safe assumption that 4-stroke snowmobiles have increased per person NO emissions.[11] Also, as the price of snowmobile rentals has increased there has been a slight increase in the number of riders doubling up. When comparing the measured mean snowmobile with the measured mean snowcoach emissions/person the snowmobiles are a little better for CO and a little worse for HC and NO_x. The comparison can swing from one extreme to the other by having a snowcoach fleet of all vintage (the highest gram/mile/person emissions) or all upgraded (the lowest gram/mile/person emissions) Bombardiers. The comparison will also be negatively impacted on the snowmobile side if Ski Doo riders were increased disproportionately.

The nine snowcoaches we measured should not be construed as adequately representing the average snowcoach fleet used in the park during the winter months. For example 1/9 or our measured fleet was a vintage Bombardier and 1/9 was a diesel. The number of vintage Bombardiers with uncontrolled carbureted engines still operating in the park means that the percentage of passengers being transported by them is much higher than the average weighting in Table 16. This will most likely result in a higher CO and HC and lower NO_x emissions per person than the snowcoach means in Table 16. However, these data allow the construction of a more representative 2005 fleet emissions average by distributing the measured emissions by technology class across the passenger fractions carried by each technology class.

Table 16. Estimated gram/mile/person emissions for Yellowstone winter transportation options.

Data	Mean grams/gal[a,b]			Mean g/mile (Estimated g/mile)[c]			Estimated g/mile/person[d]		
	CO	HC	NO_x	CO	HC	NO_x	CO	HC	NO_x
1999 Mean 2-stroke Snowmobile	1100	1400	NA	(85)	(110)	NA	71	92	NA
2005 Mean 4-stroke Ski Doo Fleet	1400	110	6.6	(78)	(6.1)	(0.4)	60	4.7	0.3
2005 Mean 4-stroke Snowmobiles	670	80	64	(37)	(4.4)	(3.6)	28	3.4	3.4
2005 Mean 4-stroke Arctic Cat Fleet	570	72	78	(32)	(4)	(4.3)	25	3.1	3.3
2005 Highest Emissions Snowcoach[e]	2200	180	27	630	50	7.7	74	5.9	0.9
2005 Mean Snowcoach	1000	37	71	300	10	24	35	1.2	2.8
2005 Lowest Emissions Snowcoach[f]	36	6.5	9.1	5.3	1	1.4	0.6	0.1	0.2

[a] grams/gallon calculations for the snowmobiles assume a fuel density of 726 g/l.
[b] Snowmobile NO emissions have been converted to NO_2.
[c] Snowmobile g/mile estimates use 13 mpg for 2-strokes and 18 mpg for 4-strokes.
[d] Data obtained from the National Park Service Public Use Statistics Office
[e] Xanterra coach 709, vintage Bombardier with carbureted engine.
[f] Alpen Guides Delacy, vintage Bombardier converted to a modern fuel injected engine with exhaust after treatment.

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APPENDIX A: FEAT Validity Criteria.

Not measured:

1) Beam block and unblock and then block again with less than 0.5 seconds clear to the rear. Often caused by elevated pickups and trailers causing a “restart” and renewed attempt to measure exhaust. The restart number appears in the database.
2) Vehicle which drives completely through during the 0.4 seconds “thinking” time (relatively rare).

Invalid:

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 in 8 cm path length. Often heavy-duty diesel trucks, bicycles.

2) Too much error on CO/CO_2 slope, equivalent to $\pm$20% for %CO. >1.0, 0.2%CO for %CO<1.0.

3) Reported %CO, <-1% or >21%. All gases invalid in these cases.

4) Too much error on HC/CO_2 slope, equivalent to $\pm$20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.

5) Reported HC <-1000ppm propane or >40,000ppm. HC “invalid”.

6) Too much error on NO/CO_2 slope, equivalent to $\pm$20% for NO>1500ppm, 300ppm for NO<1500ppm.

7) Reported NO<-700ppm or >7000ppm. NO “invalid”.

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the YPsled05.dbf database.

The YPsled05.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

Make	Manufacturer of the vehicle.
Year	Model year of the vehicle.
Stroke	Engine type.
Guide	"Y" indicates a snowmobile driven by the professional guide.
Snow_Coach	"Y" indicates an exhaust measurement from a snowcoach.
Location	"I" denotes entrance and "O" denotes exit.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_co	Carbon monoxide concentration, in percent.
Co_err	Standard error of the carbon monoxide measurement.
Percent_hc	Hydrocarbon concentration (propane equivalents), in percent.
Hc_err	Standard error of the hydrocarbon measurement.
Percent_no	Nitric oxide concentration, in percent.
No_err	Standard error of the nitric oxide measurement reported as NO.
Percent_co2	Carbon dioxide concentration, in percent.
Co2_err	Standard error of the carbon dioxide measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
Hc_flag	Indicates a valid hydrocarbon measurement by a "V", invalid by an "X".
No_flag	Indicates a valid nitric oxide measurement by a "V", invalid by an "X".
Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor; indicates the strength of the observed plume.
Speed_flag	Indicates a valid speed measurement by a "V", an invalid by an "X", and slow speed (excluded from the data analysis) by an "S".
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Ref_factor	Reference detector voltage.
CO2_factor	CO_2 detector voltage. Used along with "Ref_factor" to observe calibration shifts.

APPENDIX C: Montana System Specifications

Gas	Measurement Range	Accuracy	Repeatability	Noise (rms)	Resolution
HC n-Hexane	0 - 2000 ppm 2001 - 1500 ppm 15001 - 30000 ppm	±4 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±3 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	2 ppm abs. or 0.8% rel.	1 ppm
HC Propane	0 - 4000 ppm 4001 - 30000 ppm 30001 - 60000 ppm	±8 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±6 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	4 ppm abs. or 0.8% rel.	1 ppm
CO	0 - 10 % 10.01 - 15%	±0.02% abs. or ±3% rel. ±5% rel.	±0.02 abs. or ±2% rel. ±3% rel.	0.01% abs. or 0.8% rel.	0.001 vol. %
CO_2	0 - 16% 16.01 - 20%	±0.3% abs. or ±3% rel. ±5% rel.	±0.1% abs. or ±2% rel. ±3% rel.	0.1% abs. or 0.8% rel.	0.01 vol. %
NO_x	0 - 4000 ppm 4001 - 5000 ppm	±25 ppm abs. or ±4% rel. ±5% rel.	±20 ppm abs. or ±3% rel. ±4% rel.	10 ppm abs. or 1% rel.	1 ppm
O_2	0.00 - 25%	±0.1% abs. or ±3% rel.	±0.1% abs. or ±3% rel.	0.1% abs. or 1.5% rel.	0.01 vol. %

APPENDIX D: Explanation of the SC_YST05.dbf database.

The SC_YST05.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

Vehicle	Name of vehicle that includes the company and vehicle identifier.
Sheet_name	Companion excel spreadsheet name which contained the original records.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Time_sec	Time of measurement, in seconds.
Org_valid	Gram/sec validity flag reported at time of data collection (YES or NO).
Valid_g_s	Gram/sec validity flag used for calculations in the report after known leaks and instrument problems have been removed (YES or NO).
Bag_no	Virtual collection bag number for labeling data collection events.
Bg_dist_mi	OBD (if available) reported mileage accumulation for Bag_no.
Bg_time_s	Accumulated time in seconds for Bag_no.
Mph	OBD (if available) reported speed in miles per hour.
Accel	OBD (if available) reported acceleration in mph/sec.
Sensed_rpm	Sensor array (if used) measured engine rpm.
S_temp_c	Sensor array (if used) measured intake air temperature in centigrade.
S_map_kpa	Sensor array (if used) measured absolute intake manifold pressure in kilopascals.
Eng_rpm	OBD (if available) reported engine rpm.
Coolant_c	OBD (if available) reported coolant temperature in centrigrade.
Throttle	OBD (if available) reported percent throttle.
Map_kpa	OBD (if available) reported absolute intake manifold pressure in kilopascals.
Iat_c	OBD (if available) reported intake air temperature in centigrade.
Torque_lbf	OBD (if available) reported engine torque in foot-pounds.
Ntkair_g_s	Calculated grams per second of intake air.
Dryexh_g_s	Calculated grams per second of dry exhaust.
Totex_scfm	Calculated total exhaust flow in standard cubic feet per minute.
Fuel_g_s	Calculated fuel consumption in grams per second.
Fuel_mpg	OBD (if available) reported fuel economy in miles per gallon.

V_fuelmpg Validity flag for OBD reported Fuel_mpg (YES or NO).

Nox_ppm Mean NO emissions in parts per million.

HC_ppm Mean HC emissions in parts per million in propane units.

CO_p Mean percent CO emissions.

CO2_p Mean percent CO_2 emissions.

O2_p Mean percent O_2 emissions.

Pm_pfs PM Percent full scale of back scattered laser light.

Pm_mg_m3 Calculated PM in milligrams per cubic meter of exhaust if valid.

Nox_g_s Calculated NO_2 emissions in grams per second if valid.

Hc_g_s Calculated HC emissions in grams per second if valid.

Co_g_s Calculated CO emissions in grams per second if valid.

Co2_g_s Calculated CO_2 emissions in grams per second if valid.

Pm_mg_s Calculated PM emissions in milligrams per second if valid.

A_valid Validity flag for analyzer bench A (Yes or No). This flag is misreported in all of our data sets. It is always No even when the data is used in the composite average.

A_stats Decimal representation of a series of binary bench A status flags.

A_nox_ppm Bench A reported NO emissions in parts per million if valid.

A_hcppm Bench A reported HC emissions in parts per million if valid.

A_co_p Bench A reported percent CO emissions if valid.

A_co2_p Bench A reported percent CO_2 emissions if valid.

A_o2_p Bench A reported percent O_2 emissions if valid.

B_valid Validity flag for analyzer bench B (Yes or No). This flag is reported correctly in all of our data sets.

B_stats Decimal representation of a series of binary bench B status flags.

B_nox_ppm Bench B reported NO emissions in parts per million if valid.

B_hcppm Bench B reported HC emissions in parts per million if valid.

B_co_p Bench B reported percent CO emissions if valid.

B_co2_p Bench B reported percent CO_2 emissions if valid.

B_o2_p Bench B reported percent O_2 emissions if valid.

Gps_fix Status of GPS receiver fix (No fix or Fix OK).

Gps_sats If GPS receiver is lock in this reports the number of satellites used to calculate the receivers position.

Gps_time Time reported by the GPS receiver.

Gpsspd_mph Calculated vehicle speed in miles per hour using the second by second GPS position data if available.

Latitude GPS latitude reported in degrees and decimal minutes of the vehicle if fixed.

Lat_deg Latitude converted to decimal degrees.

Longitude GPS longitude reported in degrees and decimal minutes of the vehicle if fixed.

Long_deg Longitude converted to decimal degrees.

Alt_m GPS reported altitude in meters if fixed.

Gpsdist_m Calculated changed in distance in meters from the last valid GPS location.

APPENDIX E: Summary of invalidated snowcoach data.

This appendix does not include every invalidated record but does try and describe the majority of the records that have been invalidated and the reasons for that classification. Note that many problems were intermittent in nature and may have caused problems with data collection over an extended period of time until resolved.

NPS Diesel (2/7/05) - 146 seconds of data invalidated.
16:28:03 - 16:28:58 - no exhaust.
17:18:57 - 17:20:26 - no exhaust.

NPS Diesel (2/8/05) - 3,501 seconds of data invalidated.
09:48:06 - 09:49:41 - no exhaust, purge line frozen.
10:40:22 - 10:40:38 - no exhaust.
13:57:00 - 14:03:44 - no exhaust, power problems.
14:07:25 - 14:58:47 - frozen inlet / melted sampling line.
15:08:42 - 15:18:09 - no exhaust.
16:07:25 - 16:07:47 - no exhaust.

Snowbuster 164 - 3,344 seconds of data invalidated.
07:12:56 - 07:25:57 - no exhaust.
07:45:49 - 07:45:48 - no exhaust.
08:16:03 - 08:16:14 - water in filter.
08:29:52 - 08:31:27 - no exhaust, negative CO_2.
08:52:11 - 08:53:10 - no exhaust, negative CO_2.
09:12:29 - 09:13:27 - no exhaust, negative CO_2.
09:26:42 - 09:27:04 - no exhaust, negative CO_2.
11:00:12 - 11:00:33 - no exhaust, negative CO_2.
11:45:41 - 11:47:48 - no exhaust, negative CO_2.
13:41:19 - 13:41:47 - no exhaust.
13:46:22 - 13:48:26 - no exhaust.
13:51:21 - 14:08:22 - no exhaust, flow restriction.
14:11:54 - 14:13:46 - no exhaust, flow restriction.
14:17:03 - 14:18:59 - no exhaust, flow restriction.
16:55:56 - 16:57:25 - no exhaust, frozen purge line.
17:30:13 - 17:44:06 - no exhaust, end of run.

Bombardier to Canyon - 3,354 seconds of data invalidated.
08:29:56 - 08:51:37 - no exhaust.
08:58:22 - 09:00:19 - no exhaust.
09:03:26 - 09:06:45 - flow restriction.
09:16:03 - 09:17:59 - flow restriction.
09:21:06 - 09:27:55 - flow restriction.
09:31:08 - 09:37:58 - flow restriction, no exhaust.
09:41:09 - 09:43:03 - frozen inlet, no exhaust.
09:46:08 - 09:54:34 - no exhaust.

09:56:09 - 09:59:02 - flow restriction.

Mat-trax 419 - 17,860 seconds of data invalidated. We know from the following days activities that this measurement run suffered terribly from a cracked inlet hose fitting. This allowed cold air to be sucked into the inlet hose creating ice that blocked the sampling hose. Most of the morning data was lost because the ice would reform as soon as it was cleared. All of the afternoon data has been invalidated because the instrument was unattended for the return trip and while data was collected, the inlet iced very soon after leaving Old Faithful restricting the inlet flow.
07:09:55 - 07:11:35 - no exhaust, startup.
07:41:19 - 07:44:56 - flow restriction.
07:46:00 - 07:58:04 - flow restriction, no exhaust.
08:44:38 - 09:06:52 - major intermittent problems with flow. Large positive and negative emission values.
09:13:47 - 09:15:39 - remove because the data is sandwiched between two sections with major flow problems.
09:23:49 - 09:25:40 - leak evident.
09:32:05 - 09:33:59 - flow restrictions with negative CO's.
09:38:54 - 09:40:49 - flow restriction.
09:48:56 - 09:50:47 - flow restriction.
09:55:55 - 09:57:46 - no exhaust.
10:05:57 - 10:07:48 - no exhaust.
10:15:58 - 10:17:50 - no exhaust.
10:23:04 - 10:25:03 - flow restriction.
10:39:30 - 10:40:51 - engine data invalid.
10:48:58 - 11:00:52 - engine data invalid.
11:09:02 - 11:10:52 - engine data invalid.
11:16:22 - 11:18:17 - engine data invalid.
11:24:07 - 11:26:02 - engine data invalid.
11:34:09 - 11:36:04 - engine data invalid.
11:41:23 - 11:53:16 - engine data invalid.
12:01:26 - 12:03:17 - engine data invalid.
13:42:01 - 17:27:42 - unattended afternoon run, flow restriction developed within 5 minutes of start of data collection.
20:01:01 - 20:01:52 - no exhaust.

Snowbuster 165 - 6,436 seconds of data invalidated.
07:23:12 - 07:23:57 - no exhaust.
07:26:03 - 07:27:04 - no exhaust.
07:31:53 - 07:58:15 - no exhaust, leaks, flow restrictions.
08:06:39 - 08:19:44 - no exhaust, major leak.
08:21:25 - 08:39:33 - no exhaust, major leak.
08:41:34 - 09:17:24 - no exhaust, major leak.

09:19:38 - 09:32:34 - no exhaust.
09:34:12 - 09:37:02 - no exhaust. Cracked fitting found and temporarily repaired with duct tape.
11:03:07 - 11:03:58 - no exhaust.
11:19:50 - 11:20:48 - no exhaust.
13:46:46 - 13:50:46 - no exhaust.
16:05:19 - 16:05:22 - flow restriction.

Snowbuster 166 - 1 second of data invalidated.
15:16:63 - negative CO_2 reading.

Mat-trax 416 - 194 seconds of data invalidated.
07:34:36 - 07:37:49 - no exhaust.

Snowbuster 163 - 509 seconds of data invalidated.
07:47:43 - 07:54:25 - no exhaust.
08:14:13 - 08:14:41 - no exhaust.
08:39:13 - 08:40:29 - no exhaust.

Alpen Guides Bombardier - 54 seconds of data invalidated.
09:23:44 - 09:24:16 - no exhaust.
12:33:49 - 12:34:09 - no exhaust.

APPENDIX F: Snowcoach travel maps with location of valid gram/second emissions.

Figure B2. NPS diesel Van trip on February 7, 2005. This was a roundtrip from the maintenance garage to the Mammoth Post Office.

Figure B1. NPS diesel Van trip on February 8, 2005. Roundtrip from the north entrance traveling clockwise around the lower loop.

Figure B3. Xanterra Van #163 trip on February 15, 2005. This was a roundtrip from the north entrance to Old Faithful.

Figure B3. Xanterra Van #164 trip on February 9, 2005. This was a roundtrip from the north entrance to Old Faithful.

Figure B5. Xanterra Van #165 trip on February 12, 2005. This was a roundtrip from the north entrance to Old Faithful.

Figure B6. Xanterra Van #166 trip on February 13, 2005. This was a one way trip from Old Faithful to the north entrance.

Figure B7. Xanterra Van #416 trip on February 14, 2005. This was a roundtrip from the north entrance to Old Faithful.

Figure B3. Xanterra Van #419 trip on February 11, 2005. This was a one way trip from the north entrance to Old Faithful.

Figure B9. Xanterra Bombardier #709 trip on February 10, 2005. This was a roundtrip from the north entrance to Canyon. This vehicle had two labeled periods where valid data was collected but the GPS was not reporting.

Figure B10. Alpen Guides Bombardier Delacy trip on February 18, 2005. This was a roundtrip from the west entrance to Old Faithful.

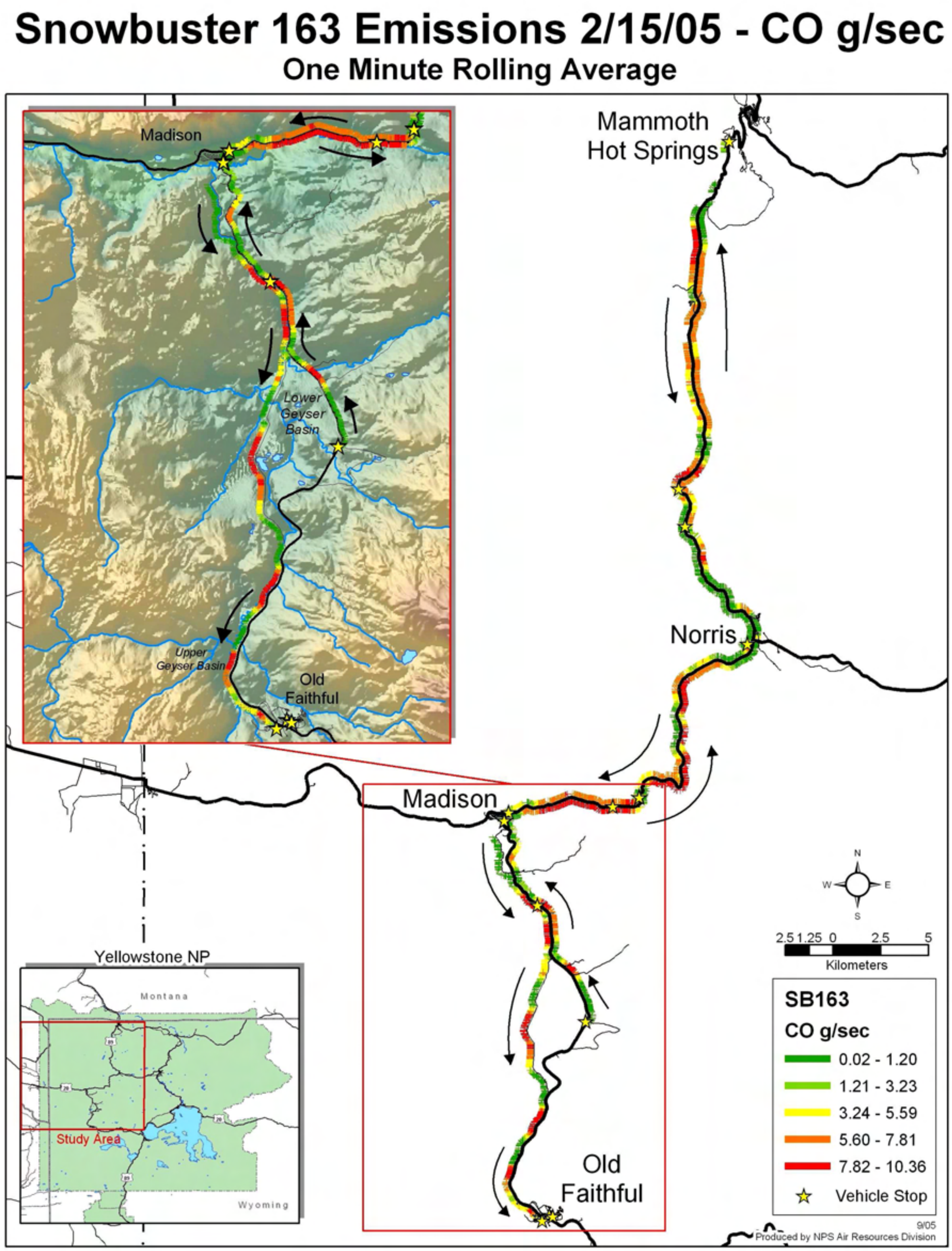

Figure B11. A more detailed graphing of Xanterra #163 CO emissions during its roundtrip excursion to Old Faithful on February 15, 2005.

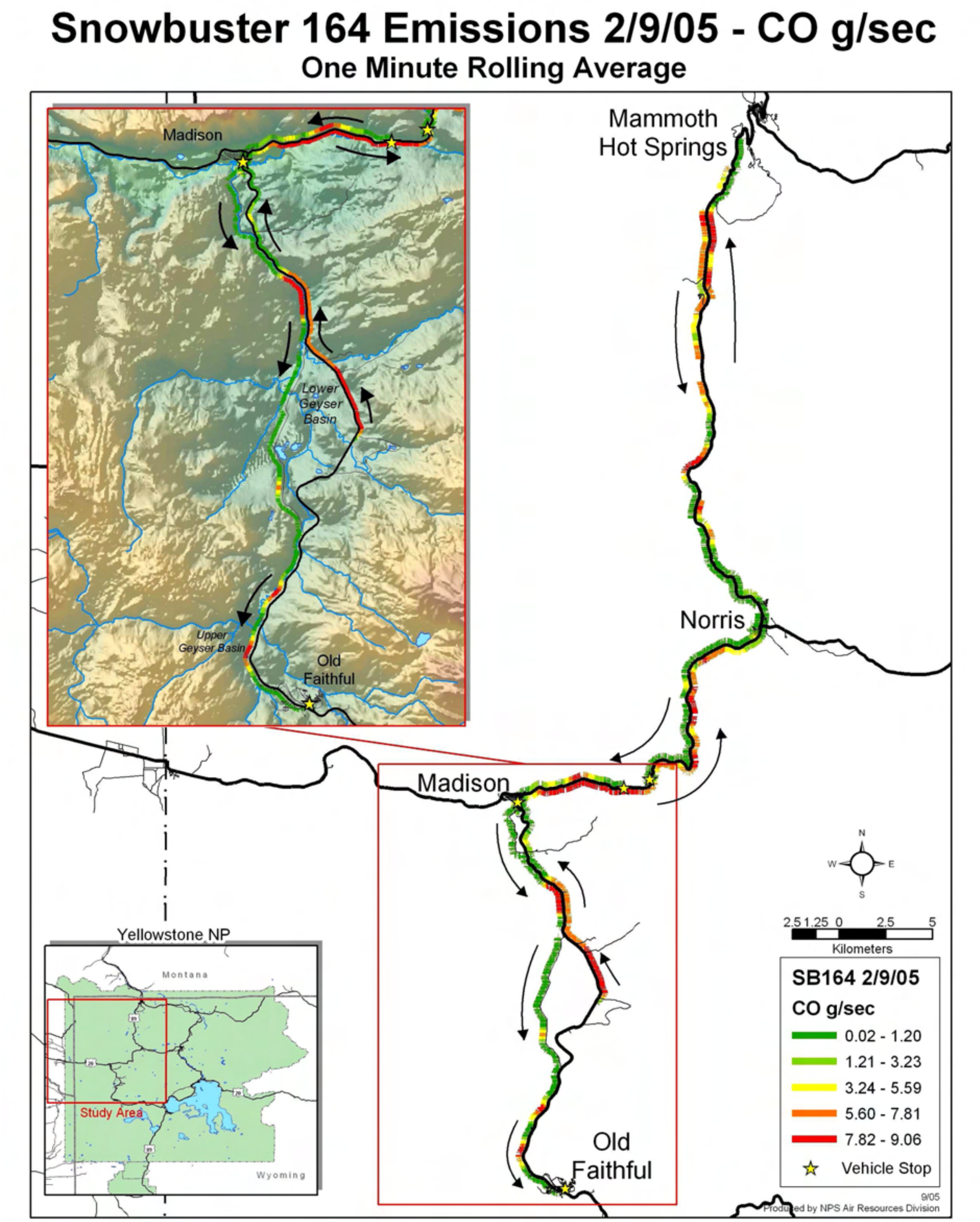

Figure B12. A more detailed graphing of Xanterra #164 CO emissions during its roundtrip excursion to Old Faithful on February 9, 2005.

APPENDIX G: Society of Automotive Engineers Publication 2001-01-3641.

2001-01-3641

Development Of Heavy-Duty Diesel Portable, On-Board Mass Exhaust Emissions Monitoring System With NO_x, CO_2 And Qualitative PM Capabilities

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ABSTRACT

To complement laboratory emissions tests and to obtain emissions data for events that are difficult to simulate, a portable, on-board mass exhaust emissions monitoring system has been developed. The system utilizes NDIR for CO and CO_2, an electrochemical cell for NO_x and laser light scattering detectors for PM real-time concentrations measurements. Exhaust flow is determined computationally from engine operating data using mass balance equations. The system is designed to easily and quickly install on a large variety of vehicles, including buses with passengers on board, and to produce a wealth of on-road data with minimal downtime and travel of the vehicle tested.

INTRODUCTION

Internal combustion engines are a substantial (and often leading) source of various air pollutants, primarily volatile organic compounds (VOC), carbon monoxide, nitrogen oxides, and respirable aerosols and carbonaceous particulate matter. As a response to stricter emissions standards, late-model engines tested new or early in their useful lives exhibit significantly lower emission levels than in the past. As this is accomplished primarily by sophisticated electronic engine controls and high-efficiency aftertreatment devices, it is possible - and in many cases documented - that a large portion of total emissions is attributable to (a) the small fraction of vehicles exhibiting high emission levels, (b) high-emissions episodes consisting of a small fraction of the total operating time, and in some cases, (c) high emissions produced under environmental and operating conditions different from those covered by standard laboratory engine or vehicle emissions tests (i.e, Wenzel and Ross, 1998; Kelly and Groblicki, 1993; St. Denis et al., 1994). Further, it has been documented that otherwise identical vehicles may have significantly different emissions characteristics (i.e., Deaton and Winebrake, 2000). In addition to emission characteristics inherent to the engine, emission levels also depend on the conditions under which the engine or vehicle is being operated.

Because of the number of factors involved, an accurate evaluation of life-cycle emissions, even of an "ideal fleet" (in which all engines and/or vehicles are identical, run on the same fuel, and are all used for the same purpose in a set geographical area), would require the emissions measurement to be done (a) on a relatively large number of vehicles, (b) at various points throughout their actual operating life, and (c) during typical, everyday operation of the vehicles.

To reduce motor vehicle emissions, new fuels, engine technologies, exhaust aftertreatment devices, driver improvement programs and other emissions reduction strategies are being introduced, often at a considerable expense. In order to choose those strategies offering maximum emissions reduction for a given cost, it is desirable to evaluate the actual emissions benefits of each strategy. This may be done by comparing the emissions produced by a fleet employing the new strategy with emissions produced by an otherwise comparable "conventional" fleet.

The traditional emissions testing approach is to take a vehicle out of service, transport it to an emissions testing laboratory, and to operate it on a chassis dynamometer using a simulated driving pattern (driving cycle). Often, heavy equipment cannot be tested on a chassis dynamometer, and the engine needs to be removed for testing on an engine dynamometer. Due to the considerable expense of this type of testing, only a small number of vehicles are tested, during a limited range of climatic and operating conditions.

As an alternative to the traditional method, various on-board emissions monitoring systems have been developed, ranging from instrumented vehicles to portable, on-board emissions monitoring systems that can be easily and quickly moved from vehicle to vehicle. Key parameters of such a system typically include its size, weight, power requirements, initial and operating costs, robustness, reliability, installation time, the extent of modifications to the tested vehicle, the level of real or perceived danger to the public, the variety of pollutants measured and accuracy. As the parameters often represent competing goals, various on-board system designs are optimized for different parameters, depending on the application of a particular system.

The goal of this study was to develop a portable, on-board system for monitoring mass emissions of NO_x, CO_2 and particulate matter (PM) on heavy-duty diesel vehicles. The goal was to produce a system that can be easily and quickly installed on a large variety of vehicles, requires no modification to the tested vehicle, and can be safely used on buses during regular operation, with passengers on board.

This paper presents the technical description of the system and a discussion of design choices made given the application constraints, and presents the results of preliminary validation testing of the system and the path for future development.

APPARATUS DESIGN

DESIGN PROCESS - If the primary goal in designing a portable, on-board system is to obtain in-use emissions data on a variety of vehicles, then such a system has to be transferrable from vehicle to vehicle, and has to have the capability of being used while driving on the road, in traffic.

The design of the system presented in this study follows the design of the monitoring system developed at the University of Pittsburgh (Vojtisek-Lom and Cobb, 1997) of CNG and gasoline light-duty vehicles. Based on the feedback from drivers, passengers and fleet managers, the following criteria were identified:

1. The system must be capable of being installed quickly and easily on a wide variety of vehicles
2. The system should be capable of being used during the regular everyday duty of the vehicle, and should not excessively interfere with the use of the vehicle
3. The system must not pose an excessive amount of real or perceived danger to the vehicle drivers, passengers, or the general public
4. The system should not require any modifications to the tested vehicle

Based on these criteria, choices were made about exhaust flow measurement, sample conditioning, source of power, and detection methods.

FLOW MEASUREMENT - In the traditional laboratory settings, the exhaust is diluted, and the combined flow of exhaust plus dilution air is held constant using a constant volume sampler (CVS). During modal (real-time) measurements, the instantaneous mass emissions rates in grams per second are determined by multiplying the appropriate concentration data by the CVS flow. Due to the size of the CVS, its use would be impractical on the road. Therefore, mass emissions need to be determined by multiplying the instantaneous concentrations by the instantaneous flow. As both tend to vary in real-time, extreme care must be taken to match the concentration data with the appropriate flow data.

While the exhaust flow can be determined directly using a mass exhaust flow meter (Breton, 1998; Gautam et al., 2001; Weaver, 2001) or other physical device (Czachura, 2001) placed in or at the end of the exhaust system, this typically requires a straight run of exhaust pipe approximately ten times its diameter. This can make the field installation of the monitoring system difficult (Vojtisek-Lom and Cobb, 1997). For this reason, the exhaust flow is measured indirectly, by calculating the intake air mass flow and using mass balance equations to obtain the exhaust flow. The intake air mass flow is obtained from the engine intake mass air flow sensor, or from engine design (engine displacement and compression ratio) and operating parameters (engine rpm, intake manifold pressure, intake air temperature) using a speed-density method. This process has been described in detail elsewhere (Vojtisek-Lom and Cobb, 1998). Two other designs also use intake air flow, either vehicle-reported (Butler et al., 1999) or measured by an independent flow meter (Ikonen, 2001).

On late-model vehicles, the engine operating data is obtained from the engine control unit on-board diagnostics (OBD) port, which is typically located under the dash, in the engine compartment, and on some newer buses in the electrical panel in the rear of the bus, accessible from the inside.

On older vehicles, the engine operating data is obtained through a set of temporarily mounted sensors. On spark ignited engines, the engine rpm are measured by an inductive pickup clamped around a spark plug wire. On diesel engines, the engine rpm are measured by a piezoelectric sensor clamped around a fuel line between the injection pump and injector. This sensor, commonly used in repair shops (Snap-On Tools), senses pressure pulses corresponding to individual injections. While this approach does not work on direct ignition spark engines and common rail injection diesels, the operating data on these engines is typically obtained from the OBD port. As an alternative, engine rpm can also be measured from the frequency of the voltage ripple in the vehicle electrical system (RPM 8000, #manufacturer#). The intake air pressure is obtained by adding a short length of tubing (2") with a pressure transducer inline with a manifold vacuum hose on throttled engines, and inline with a turbo boost pressure line on turbocharged engines. On naturally aspirated, non-throttled engines barometric pressure is substitued for the manifold pressure. The intake air temperature is measured by inserting a thermocouple into the intake air stream. On naturally aspirated engines, the intake air temperature can also be estimated based on measured atmospheric air and engine oil temperatures, with engine oil temperature being measured by a thermocouple probe inserted into the dipstick tube. On turbocharged engines, intake air temperature can also be calculated from barometric and turbo boost pressures and ambient air temperature assuming an adiabatic compression of the intake air. On turbocharged engines with an aftercooler, pressure and temperature of the intake air can be measured either before or after the aftercooler, with both measured on the same side.

SOURCE OF POWER - The power necessary to run the portable, on-board system can be obtained either from the vehicle electrical system, or from an independent source, typically a battery bank or an on-board generator. Both approaches have their advantages and disadvantages. Drawing power from the vehicle electrical system increases the load on the engine, possibly changing its emissions characteristics, and poses a practical limit on the amount of power available, typically 10 A at 12 V for light and 15-20 A at 12 V for heavy-duty vehicles. Using an independent source adds to the complexity of the system, and placing a running generator or a battery bank onto or inside a moving vehicle poses safety concerns. In this study, one of the design goals was to monitor emissions on buses during their regular service, with passengers on board. Primarily for this reason, the choice was made to design the system to run on 12 V DC, to limit the power consumption to 15 A, and to extract the power from the vehicle electrical system.

To facilitate cold start testing, the system has been equipped with a battery backup, which allows for the system to run on its own power for up to one minute. This allows the system to run from an independent source (lead-acid battery, another vehicle, or grid power) until the engine has started, and then to be plugged into the vehicle electrical system.

SAMPLE CONDITIONING - In traditional laboratory settings, diesel exhaust is heated, primarily to avoid the condensation of the water and heavier hydrocarbons and to prevent the particulate matter and some gases from being entrapped or dissolved in the condensate. Typically, the exhaust is also diluted. Heated sampling systems, heated instruments and exhaust dilution systems add to the complexity of an on-board system, and often necessitate relatively large amounts of electric power to operate. Even though well insulated heated sample lines and mini-diluters are being developed, the penalty associated with their use was deemed excessive for this application. The choice was made to sample raw, undiluted exhaust using an unheated 20-foot (6 m) long, ¼" (6 mm) diameter sample line. The line runs from the sample probe attached to the tailpipe using a hose clamp, and into the vehicle, typically through a partially open window. The sample line is placed in such a way that "low spots" where condensate could accumulate are avoided. The sample is routed into a condensate separation bowl, from the bottom of which the condensate is continuously drawn into a sample pump and exhausted from the system. The condensate-free sample is drawn from the top into gaseous and particulate matter analyzers. Both condensate and sample are then routed to the outside of the vehicle.

GASEOUS POLLUTANTS - On-road measurements require a small gas analyzer, capable of maintaining a reasonably high accuracy under varying conditions (temperature, humidity, supply voltage, movements, vibrations). Given the time and resource constraints, the choice was made to adopt a gas analyzer subsystem typically found in repair-grade five-gas analyzers commonly used for emissions inspection and maintenance programs, and to make minor modifications to obtain better stability, detection limit and response time.

The sample is drawn through two wire-mesh filters and one coalescing filter to remove most of the condensate, which is drawn from the bottom of the filter housing through a sampling pump and out of the system. The filtered sample is then re-heated using waste heat from electrical components and passed through a sample cell of a NDIR (non-dispersive infra-red) analyzer, which simultaneously measures the concentrations of hydrocarbons (measured and reported as hexane), CO and CO_2. The sample is then routed to two electrochemical cells, one measuring nitric oxide (NO) and the other O_2. As in most cases over 95% of NO_x is emitted in the form of NO, NO_x concentrations are then estimated from those of NO. The hydrocarbon reading is not considered accurate on diesel engines because only a fraction of diesel exhaust hydrocarbons is believed to reach the sample cell in gaseous form.

PARTICULATE MATTER - Condensed water is separated from the sample using a water separation bowl. The sample is then heated to prevent further condensation, and split into two parallel streams, with one stream being drawn at a large angle from the main stream of sample flow. Each parallel stream is then passed through two laser beams. A layer of filtered air is formed around the sample to protect the optics from being coated by oily particles. A photo detector mounted away from the path of laser beam detects the intensity of the light scattered by the particles. The sample is then filtered and exhausted by an internal sample pump.

The instrument has six orders of magnitude range, with exhaust from new generation “smokeless” diesels typically near the lower end, and concentrated cigar smoke being approximately one magnitude below the upper end.

The correlation of the response with particle mass, total surface area or count has not been well established at is point, and is dependent on the particle size distribution and the size of elemental and organic fractions. Preliminary comparison tests show relatively good correlation of the response with total particle mass (gravimetric method, diluted sample collected on filters, per 40 CFR 86, and real-time measurements using a TEOM-1105 diesel particulate monitor) for a particular engine, under a wide range of operating conditions.

VALIDATION DATA

To validate the readings produced by the portable, on-board monitoring system, the system has been installed on three full-size diesel pickup trucks, which have been tested in the New York State Dept. of Environmental Conservation Automotive Emissions Laboratory in Albany, NY. A 1999 and a 1998 Dodge Ram 2500 with 5.9-liter Cummins turbo diesel engine and a 1997 Ford F-350 with 7.3-liter Powerstroke turbo diesel engine were used. The vehicles were tested on I/M 240, LA-505, FET (Federal highway fuel efficiency test), New York City (NYCC) and Federal test protocol Bag 2 (FTP-2) driving cycles. Data was simultaneously collected by both the laboratory and the portable system. As the sole purpose of the tests was to establish a correlation between the two sets of results, and a range of emission levels was desirable, guidelines for vehicle preconditioning and engine starting (prior to vs. at the beginning of the cycle) were intentionally not followed. Two series of tests were performed in May and July 2000.

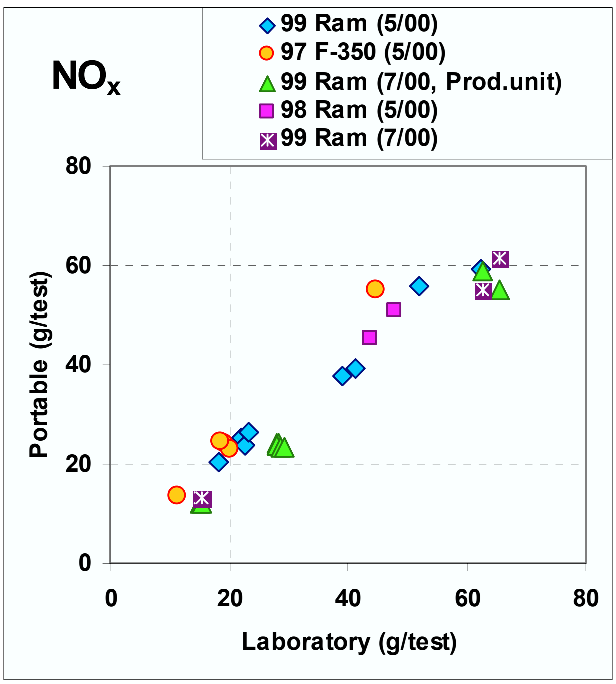

Figure 1: Comparison of grams per test NO_x data

The exhaust was collected by 4" silicon rubber and corrugated steel lines into an unheated dilution tunnel, in which a constant flow was maintained by a positive displacement blower. Real-time concentrations of HC, CO, NO_x, CO_2 and PM were measured by a heated FIR (flame ionization detector), NDIR (non-dispersive infra-red), chemilumiscence, NDIR and TEOM-1105 (Transient element oscillating microbalance, Rupprecht & Patashnick Co.), respectively. Total PM emissions were also measured by a gravimetric system.

The portable system (described earlier in this paper) was placed in various locations (bed of the truck, test cell, a corridor paralleling the test cell) and consisted of two separate units: an OEM-2100$_{TM}$ light-duty gasoline vehicle emissions monitoring system manufactured by Clean Air Technologies was used to determine exhaust flow and gaseous pollutant emissions, and a separate PM prototype unit was used to measure PM concentrations. On all three vehicles, engine operating data was obtained through the OBD-II interface.

In May 2000, all three vehicles were tested, as follows:

1. 1999 Dodge Ram 2500 - 4 x LA-505, 2 x FET, 1 x NYCC, 1 x steady state @ 60 mph
2. 1998 Dodge Ram 2500 - 1 x LA-505, 1x FET, 1 x NYCC; and
3. 1997 Ford F-350 - 2 x LA-505, 1 x FTP-2, 1 x FET, 1 x NYCC.

In July 2000, the 1999 Dodge Ram 2500 was tested, using the following cycles: 6 x LA-505, 2 x FET, 2 x I/M 240.

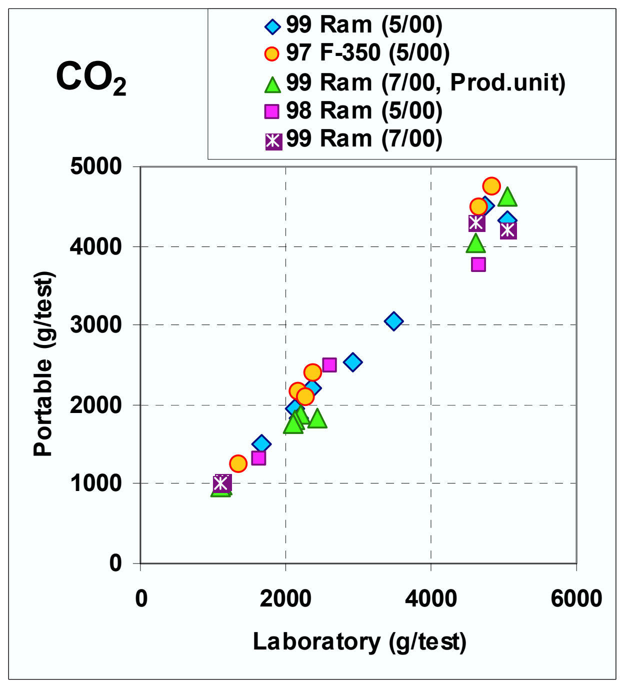

Figure 2: Comparison of grams per test CO2 data

During all May and a portion of July tests (FET and NYCC), a developmental OEM-2100 unit was used. During all July tests, a production OEM-2100 unit (serial no. 129) owned by the DEC laboratory was used.

During the testing, various problems were experienced with both portable and laboratory systems. During the sixteen tests in May, portions of OBD data (engine operating data) was missing on two tests, turbocharged boost data was biased on three tests, and NO_x data was lost on one test. On the laboratory end, TEOM data was lost on two tests and gravimetric PM data on one test, and a single gravimetric PM measurement was given for one pair of consecutive tests.

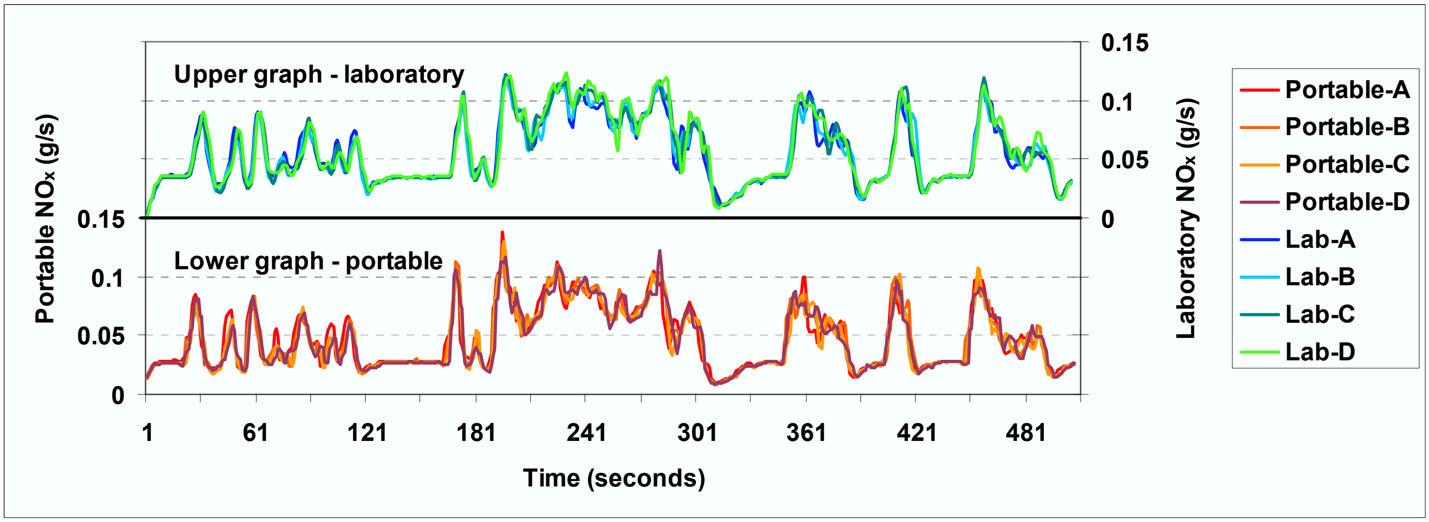

Figure 3: Comparison of transient response of laboratory (top) and portable (bottom) system, and the test-to-test repeatability for both systems, for NO_x on four LA-505 cycles driven with 1999 Dodge Ram 2500 with 5.9-liter Cummins turbo diesel

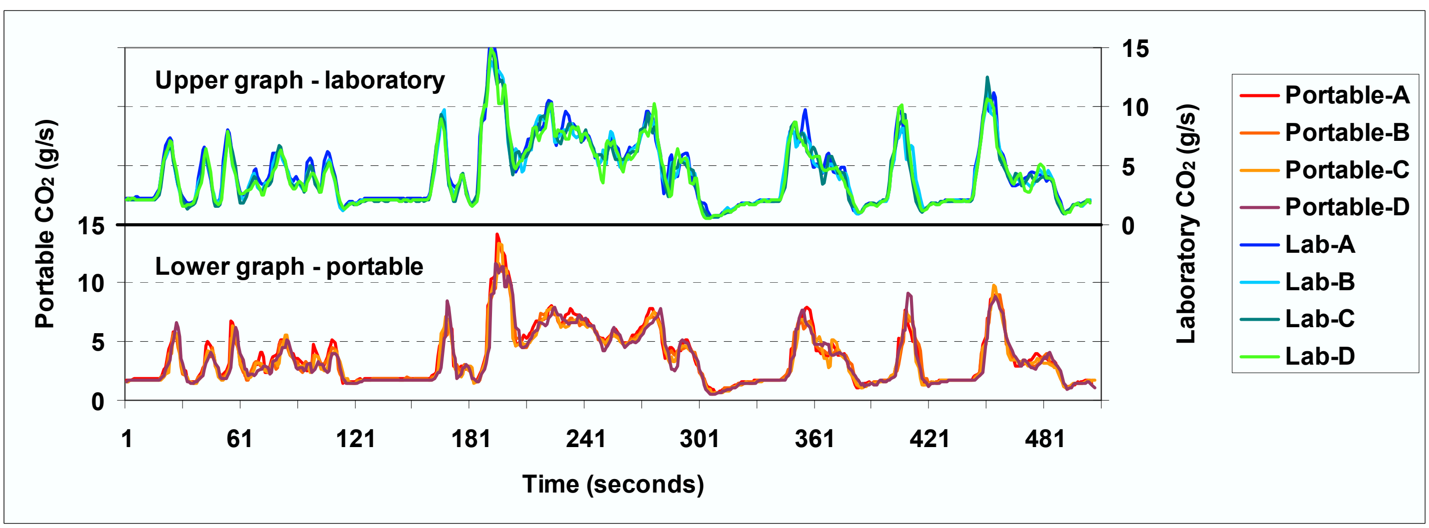

Figure 4: Comparison of transient response of laboratory (top) and portable (bottom) system, and the test-to-test repeatability for both systems, for NO_x on four LA-505 cycles driven with 1999 Dodge Ram 2500 with 5.9-liter Cummins turbo diesel

To qualitatively compare the real-time response characteristics, especially the variance between the two methods, and the repeatability and consistency of each method, second-by-second data for the last four of the six July LA-505 tests is shown in Figures 3 (NO_x) and 4 (CO_2). The second-by-second laboratory data for all four tests is plotted on the top portion of the graph; the portable, on-board system data for all four tests is plotted on the bottom.

The PM data for all May 2000 tests is plotted in Figures 5 (portable PM vs. real-time PM data collected by TEOM-1105) and 6 (portable PM vs. gravimetric), except when the data from that instrument was unavailable. During the July 2000 tests, the portable PM unit data was excessively noisy, and a source of noise was found within the data acquisition system at a later time; none of the July PM data is therefore included.

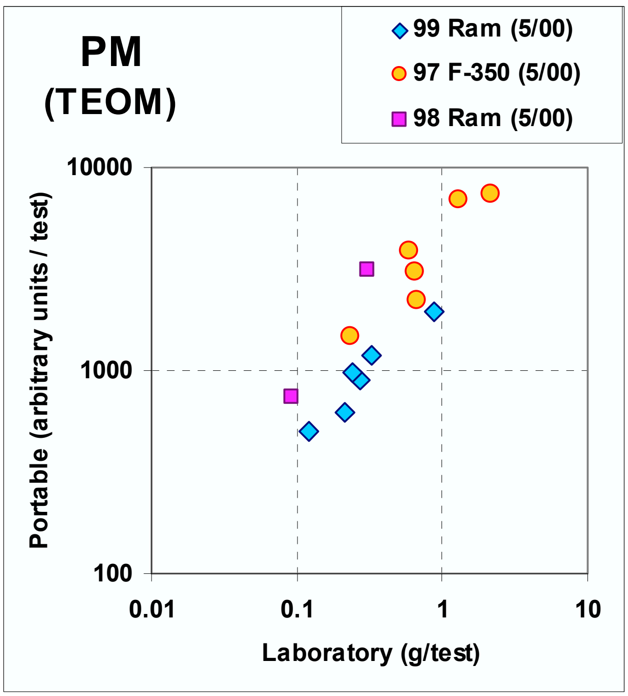

Figure 5: Comparison of prototype portable, on-board light-scattering PM monitor with TEOM-1105 measurements

DISCUSSION

Under ideal conditions, both exhaust flow and concentrations would be measured using compact, in-situ sensors similar to today's exhaust gas oxygen sensors. Unfortunately, the technology development has not progressed to that point. Design of practical portable, on-board emissions monitoring systems therefore involves a number of competing goals - namely size, portability, versatility, accuracy and cost - among which compromises need to be made after careful consideration of the intended application of the particular system.

In this case, the intended application - to monitor emissions on various in-use fleets - called for a system which does not require any modifications to the tested vehicle and is safe to use on vehicles carrying passengers. This effectively excluded the use of a battery bank, a heated sampling and analytical system, a flame ionization detector, or any particulate monitoring technology requiring high vacuum to operate. As a result, the measurement of compounds which are soluble in water (NO_2, formaldehyde), compounds which condense at ambient temperatures (heavy hydrocarbons), and the measurement of nanoparticles is nearly impossible using this approach, with measured values being qualitative at best.

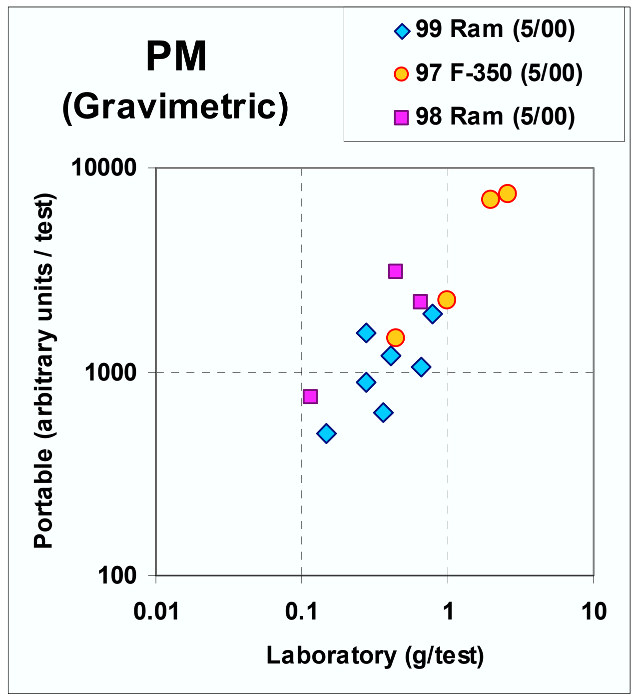

Figure 6: Comparison of prototype portable, on-board light-scattering PM monitor with gravimetric PM measurements

These requirements also effectively excluded the use of an exhaust mass flow meter. The advantage of measuring the flow near the exhaust sampling point is the ability to accurately match the flow and concentrations data. The downside of mass flow meters is that they require a laminar (turbulence-free) flow, and must be installed in a straight run of exhaust pipe with the length of or above ten times its diameter. Typically, the diameter is equal to or greater than the exhaust stack diameter. In heavy-duty vehicle applications, the use of exhaust flow meter therefore typically necessitates extending the stack by 40" or more, or replacing a section of the stack with the flow measurement system. While this approach does not pose large difficulties on some vehicles such as Class 8 over the road trucks, it can be installed only with great difficulties on other vehicles such as box trucks or buses. On these vehicles, there is not a readily accessible straight section of the exhaust, and the tailpipe is pointed to the ground, to the side, or upward. In many cases, a vehicle with the tailpipe extended could not be driven in traffic.

The benefits of this approach need to be considered in light of other sources of errors associated with emissions monitoring, notably vehicle-to-vehicle differences, and the emissions variability within the vehicle itself. In other words, one needs to consider the total of (1) the difference between what is measured and what is actually emitted during a test; (2) the difference between what is emitted during the test and what the vehicle emits during its everyday duties; and (3) the difference between the emissions characteristics of the tested vehicle and the overall emissions levels of the entire fleet. For example, when evaluating a benefit of cleaner fuels on a fleet of city buses, one needs to compare taking a bus out of service, installing a laboratory-grade monitoring system, loading it with sandbags and driving it on a simulated route (an approach described by Ikonen, 2001) against testing several buses on their regular routes, with passengers on board, using a simpler (and possibly less accurate) monitoring system.

The question of how accurate a monitoring system needs to be therefore cannot be objectively answered, neither can a monitoring system be easily designed, without first considering the intended application of the system and the errors associated with different approaches.

Within this context, the validation data will now be discussed. The NO_x and CO_2 data is presented as measured, and included several runs with data missing from a short portions of the test, several runs with an error up to 25% in real-time exhaust flow calculations due to error in reading the turbo boost pressure, and an unknown number of tests with misaligned flow and concentration data. Post-processing of the comparison data suggests that with careful preparations and quality control, a better correlation between laboratory and portable system results can be achieved.

The slope of the linear regression line on the scatter graphs showing the laboratory to portable system comparison for NO_x and CO_2 (Figures 1 and 2, respectively) is different from unity (1.0). This is due to both known and unknown factors. For example, it was discovered that the portable systems were calibrated using calibration gases designed for inspection and maintenance programs with observed differences between actual and advertised concentrations of up to 5%. But as long as the slope of the regression line is constant for different vehicles and also among the physical monitoring systems, this difference can corrected.

The qualitative evaluation of the real-time response characteristics shown in Figures 3 and 4 for NO_x and CO_2, respectively, do not reveal any apparent difference between the response time and the repeatability of the portable system and the laboratory. While the concerns about using an electrochemical cell for NO measurement due to its inferior response time and poor reliability cannot be disregarded, the data seems to support the validity of the use of electrochemical cells.

The particulate matter concentrations measured by the portable system are in arbitrary units, as they represent the intensity of the light scattered by the particles. The response of a light scattering detector is strongly dependent on particle size distribution, which is not well known. It can be speculated that most particles larger than one micron are excluded by sampling at 90-degree angle from the flow, that most aerosol particles "drop out" or condense onto larger particles, and that some particles are lost within the sampling system. This was the first comparison test of any kind for this device in a diesel exhaust monitoring application, therefore no factor correlating the response to the particulate mass has been established.

The comparison plots on Figures 5 and 6 show that there is a positive correlation between the portable system measurements and the laboratory measurements. According to Moosmüller et al. (2000), light scattering detector readings tend to correlate well with PM mass, although with a different slope (ratio between the reading and the PM mass) for each individual vehicle. The data on Figure 5 show a good correlation between light-scattering and the TEOM for the 1999 Dodge Ram, but not when comparing the light scattering results with the gravimetric measurements shown on Figure 6. The slope of the linear regression appears to be different for each vehicle - notably judging from the TEOM data - although the vehicle-to-vehicle differences could also be attributed to random variances. Also, a significant amount of noise was recently found in the data acquisition system and reduced by shielding and grounding all cables, by increasing the sampling rate, and by averaging the readings over a period of time before reporting a value.

The qualitative comparison of second-by-second data reveals that the light-scattering detector has a much faster response time than TEOM, and that the side-by-side comparison of the data requires using a 12-second rolling average for the portable system. The extent to which the 12-second rolling average of the portable system data follows the TEOM readings varies with each test. The signal noise within the portable system and the drift within the TEOM due to the accumulation and de-accumulation of water on the filter during the test were identified as two sources of discrepancies between the readings.

The selection of the vehicles for the comparison test also needs to be discussed. While full-size pickup trucks can be tested on a light-duty chassis dynamometer, nearly identical engines are used in school buses and smaller straight trucks, and the largest diesels used on the road are only two to three times the size and power of the engines tested here. Therefore, it is likely that the test results will have a similar validity for vehicles ranging from compact pickups to Class 8 trucks.

The type of engine needs to be also considered when validating any PM instruments, as there is a significant difference in PM composition between older, mechanically controlled and late-model, electronically controlled engines. All engines used in this test were of the latter type; therefore, additional tests would need to be performed on mechanically controlled engines to provide a better understanding of the characteristics of the portable system PM readings. The engine type is not believed to have a major impact on the NO_x and CO_2 measurements.

It follows that another, perhaps more extensive, set of comparison tests needs to be run, with close attention to the quality control (i.e., eliminating excessive signal noise and operator error and using a high-quality calibration gas), in order to determine the accuracy of the PM measurements, and the feasibility of this method in future systems.

CONCLUSION

A portable, on-board mass exhaust emissions monitoring system has been developed to measure NO_x, CO_2 and PM emissions on diesel vehicles. This system easily installs on a large variety of vehicles and allows for testing to be done during regular vehicle duties. The system does not require any modifications to the tested vehicle and can be safely used on buses with passengers on board. This is done at some sacrifice to the accuracy and to the variety of pollutants that can be measured. Comparison of the portable system and traditional laboratory results for three full-size diesel pickups shows a strong correlation between both real-time and total NO_x and CO_2 emissions. Additional validation data will need to be collected in order to characterize the PM measurements.

ACKNOWLEDGMENTS

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