Measurement of Fuel Use and Emissions of Over-Snow Vehicles at Yellowstone National Park

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1.0 INTRODUCTION

The National Park Services (NPS) is developing a supplemental winter use plan and environmental impact statement (SEIS) for Yellowstone National Park (YNP) in 2012 (NPS, 2012). The purpose of the SEIS is to establish a framework for managing the park to better service the public.Minimizing environmental impacts to resources including visibility and aquatic systemsare primary goals of the SEIS. The NPS allows over-snow vehicles (OSVs) which meet the Best Available Technology (BAT)standards (NPS, 2009; NPS, 2011) to visit YNP, with a limited number per day. In addition, the NPS requires data for emissions rates of nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC) from OSVs that are operated in YNP as input to modeling of the air quality impacts of various in-park usage scenarios.

OSVs are customized to operate on snow surfaces. There are two categories of OSVs of interest: (1) snow coaches; and (2) snowmobiles. Snow coaches are buses that can carry typically a dozen people or more. Snowmobile are analogous to motor cycles in that they operated by one driver who sits in the open, and the snowmobile might be able to carry one passenger. OSVs use treads rather than wheels for propulsion, and may use treads or skis for steering. Some snow coaches were designed and built as specialized OSVs, whereas others are highway vehicles to which treads have been added. Snowmobiles are designed and built as OSVs. Because there is no standard chassis dynamometer testing protocol for OSVs, emission rates for the types of OSVs that operated in YNP are quantified here based on in-use measurements using Portable Emissions Measurement Systems (PEMS).

In-use emission measurements of OSVs were made using a PEMS and remote sensing (Bishop *et al.*, 2006a; Bishop *et al.*, 2006b) during the 2004 to 2005 winter season. The emission rates of CO, NO_x, and HC from the tail-pipe of the OSVs were reported. Nine snow coaches were measured using PEMS during the tests in winter 2005. The mean emissions rates for tested snow coaches were 300, 10, and 24 grams per mile for CO, HC, and NO_x, respectively. A total of 965 measurements of snowmobiles were conducted using remote sensing. An additional 1,210 measurements of 2-stroke snowmobiles were previously measured using remote sensing (Bishop *et al.*, 1999). The mean CO and HC emissions rates from 4-stroke snowmobiles were 670 and 80 grams per gallon of fuel, respectively in 2005. These mean CO and HC emissions rates were found to be lower by 61 and 96 percent, respectively, compared to the mean emissions rates from 2-stroke snowmobiles measured in 1999.

During the 2005-2006 winter season, emissions measurements were made on an additional10 snow coaches and 2 snowmobiles using PEMS (Bishop *et al.*, 2009). The NO_x, CO, and HC emissions were found to be 54, 60, and 83 percent lower than from the previous tests in winter 2005, respectively. The average age of the measured OSVs were approximately 5 years newer than the OSVs tested in the previous winter season, and 9 out of 10 of the snow coaches included fuel injection. In contrast, only 4 out of 9 of the OSVs measured in the previous year were equipped with fuel injection. Emissions rates were found to decrease with decreasing vehicle age. Large variations of the emissions were found when comparing one set of five nearly identical OSVs (i.e. for the same make, engine and track). The five OSVs had similar power to weight ratio, same engine, same body style, same passenger loadings and same track systems, and were driven on the same route. Each vehicle was measured at a different time, and the condition of the snow on the road varied over time. Thus, it is possible that a significant factor leading to variability in results was variability in the condition of the snow cover on the road. OSV operators report, anecdotally, that changes in snow cover conditions affect fuel economy.

Only two snowmobiles were measured using PEMS over the same route as the snow coaches (Bishop *et al*., 2009). The reported fuel economy of the two snowmobiles was 25.1 and 28.3 miles per gallon. However, the basis of these fuel economy estimates is not very clear. As shown later in this report, the fuel economy of snowmobiles may be significantly lower than 25 miles per gallon, and is typically around 15 miles per gallon.

Here, measurements were made in March 2012 using PEMS on five snow coaches and three snowmobiles, to supplement the previous data. The vehicles measured in this work are of more recent model years than those measured in the two previous field studies or, in the case of one snow coach, have undergone a substantial rebuild. A few of these newer vehicles are equipped with advanced emissions controls to meet 2010 emissions standards that are far more stringent than the standards that applied to the earlier measured vehicles.

The objective of this work is to apply a methodology to measure the real-time emissions for selected OSVs in service at YNP under actual operating conditions. Emission rates of CO, NO_x, and HC and the fuel use rates for different OSVs in different operating modes were obtained. The emission rates are intended for use by the National Park Service as input to air quality modeling for various in-park usage scenarios. Another objective is to evaluate the uncertainty of the emissions measured by quantifying confidence intervals on the estimated emission rates.

2.0 METHODS

The technical approach for this work includes five major components: (1) study design; (2) instrumentation; (3) data collection; (4) data quality assurance; and (5) data analyses. The details of these five major components are described below.

2.1 Study Design

Measurements of the tailpipe emissions of CO_2, CO, HC, and NO were made for selected OSVs using PEMS. The study design includes specification of what vehicles are to be measured, who operates the vehicles, what fuels are used, the route selected, and the date and time of each measurement.

Five snow coaches and three snowmobiles were measured. These vehicles have a variety of chassis and track types. Table 1 lists the date and time of the measurements of each OSV. Table 2 summarizes the characteristics of each tested vehicle. Figures 1 through 8 are pictures of each tested vehicle. All of the tested vehicles were equipped with port fuel injection technology. Although the Bombardier chassis was manufactured in 1956, the engine was replaced recently with a 2002 Suburban engine. The snow coaches based on converted gasoline highway vehicles have catalytic converters for control of CO, HC, and NO_x. The late model diesel-engine snow coaches, which are also converted from highway vehicles, are equipped with selective catalytic reduction (SCR) and diesel particulate filters (DPF). There is not clear information on what emission controls, if any, are part of the engine or post combustion system of the snowmobiles. The snowmobile emissions are based on engine dynamometer certification tests to meet non road engine emission standards, and thus are different than the standards that apply to the snow coaches. Based on stickers in the engine compartments of the Arctic Cats, the HC emissions are reported to be certified at a level of 9 and 8 grams per kWh of engine shaft output for the TZ1 and T660, respectively. Likewise, the CO emissions are reported to be certified to a level of 99 and 105 grams per kWh, respectively. All of the OSVs were driven by professional snow vehicle drivers who normally operate these vehicles.

Table1. Sampling Date and Time for Each Snow coach and Snowmobile.

Snowcoach	**Sampling Date and Time**	**Snowmobile**	**Sampling Date and Time**
Bombardier	03/05/12 11:40-2:53	Arctic Cat TZ1	03/09/12 14:07-16:15
Chevy Express	03/07/12 15:10-17:27	Arctic Cat T660	03/10/12 12:38-14:45
Ford E350	03/08/12 10:50-12:37	Ski Doo	03/06/12 16:35-18:23
Ford F450	03/07/12 11:10-13:25		
Ford F550	03/08/12 14:45-17:57		

Table2. Summary of the Characteristics of the Tested Over-Snow Vehicles [a,b]

Type	Chassis Characteristics			Engine Characteristics			Track Type[c]	Emission Control[d]
	Year	**Make**	**Model and Nickname**	**Fuel**	**Number of Cylinders**	**Displacement (Liters)**		
Snow coach	1956	Bombardier	B12 “Kitty”	Gasoline	8	5.3	Two skis and two tracks	Not reported
Snow coach	2008	Chevy	Express Van	Gasoline	8	6.0	Mattrack	Catalytic Converter
Snow coach	2011	Ford	E-350 “SY3”	Gasoline	10	6.8	Mattrack	Catalytic Converter
Snow coach	2011	Ford	F-450 “Glaval”	Diesel	8	6.7	Mattrack	SCR DPF
Snow coach	2011	Ford	F-550 “SY8”	Diesel	8	6.7	GripTrac	SCR DPF
Snowmobile	2011	Arctic Cat	TZ1	Gasoline	2	1.06	Two skis and one track	Not reported
Snowmobile	2008	Arctic Cat	T660	Gasoline	2	0.66	Two skis and one track	Not reported
Snowmobile	2012	SkiDoo	Expedition 600Ace	Gasoline	2	0.6	Two skis and one track	Not reported

[a] All of the listed OSVs have 4-stroke engines

[b] Four snowcoaches (Chevy Express, Ford E350, Ford F450, and Ford F550) were modified from highway passenger vans to OSVs by replacing the wheels by tracks. The Bombardier was originally designed as snowcoach.

[c]Mattracks and GripTracks are commercial brands of snow treads that can be retrofitted to the axles of highway vehicles. For the retrofitted highway vehicles, there are four snow treads (one per wheel). Vehicles that are designed as OSVs, including theBombardier and the snowmobiles, have two skies in the front used for steering, and one or two treads in the back used for propulsion.

[d] SCR = Selective Catalytic Reduction; DPF = Diesel particulate Filter

Figure1.   1956 Bombardier Snow coach with Two Skis in Front and Two Tracks in Rear.

Figure2. 2008 Chevy Express Snow coach with Mattrack Tracks.

Figure3. 2011 Ford E350 Snow coach with Mattrack Tracks

Figure4. 2011 Ford F450 Glaval Snow coach with Mattrack Tracks,

Figure5. 2011 Ford F550 Snow coach with GripTrac Tracks.

Figure6. 2011 Arctic Cat TZ1 Snowmobile with Two Skis in Front and One Track in Rear. The PEMS analyzer was placed inside an insulated box on the back side, with power provided by a portable generator mounted just in front of the insulated box..

Figure7. 2008 Arctic Cat T660 Snowmobile with Two Skis in Front and One Track in Rear.

Figure8. 2012 SkiDoo Snowmobile with Two Skis in Front and One Track in Rear

The measurements were made following the same designed route for each OSV as shown in Figure 9. The route started from the West Gate of YNP, and followed the West Entrance Rd toward the east to Madison Junction. A right turn was made to follow state Highway 89 southbound to a designated turn around point, at which the OSVs made a U-turn and returned to the West Gate. The outbound trip differed slightly from the inbound trip because of a stop made at Madison Junction Lodge just before reaching Highway 89. A closer view of the turn off point is provided in Figure 10.The turn off added an extra approximately 0.2 miles to the outbound trip. The total distance for this round trip was approximately 32 miles. Typical time for OSV to travel on this route was approximately 2 hours. Figure 11 shows the elevation above sea level along the round trip. The elevations were measured by altimeter from the Garmin GPS unit during the Chevy Express measurement.

Figure9. Aerial View of the Emission Test Route in Yellowstone National Park

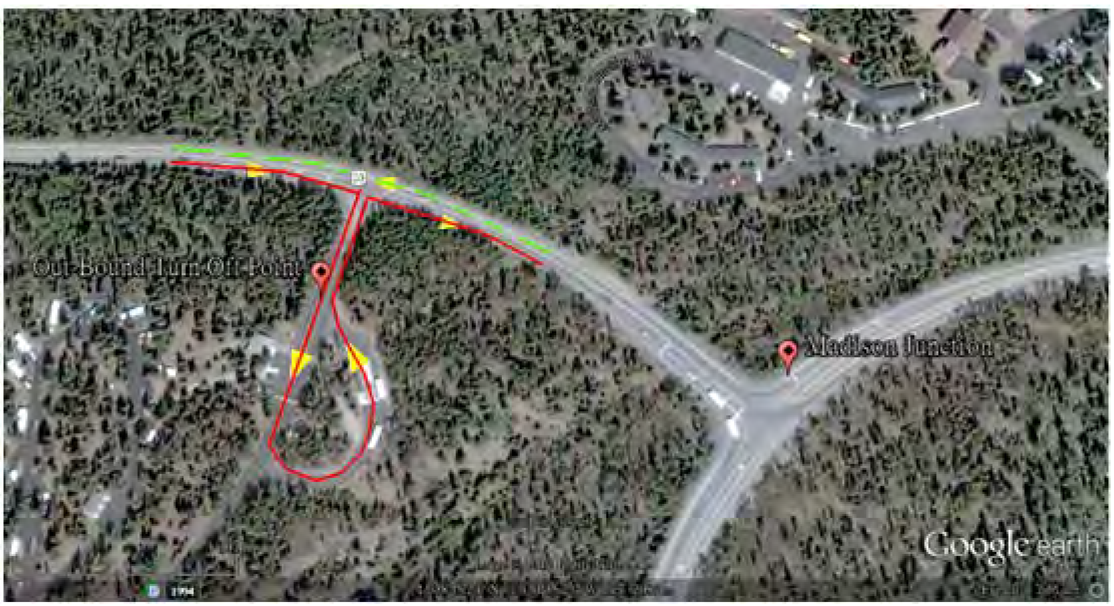

Figure10. Aerial View of the Out-Bound Trip Turn Off Point at Madison Junction Lodge. Red Solid Line Indicates Out-Bound Trip with the Turn Off Loop while Green Dashed Line Indicates In-Bound Trip.

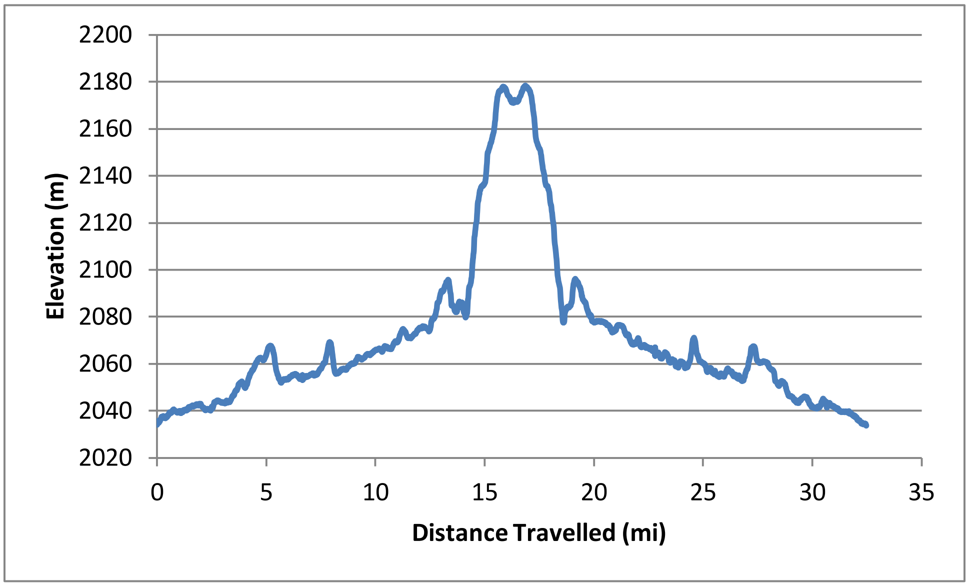

Figure11.   Elevation along the Round Trip of the Route.

2.2 Instrumentation

The instruments used to measure tailpipe emissions during operation of the OSVs included: (a) Portable Emissions Measurement System (PEMS); (b) engine sensor array; (c) On-Board Diagnostic (OBD) system data logger; (d) Global Positioning System (GPS) receiver with barometric altimeter.

The engine sensor array was used to measure engine data on the snowmobiles. The OBD data logger was used to record engine data from the snow coaches. All light duty highway vehicles sold in the U.S. for model year 1996 and newer are equipped with an OBD interface to the vehicle electronic control unit (ECU). The ECU records data from in-built sensors and estimates data from proprietary manufacturer look-up tables and engine maps that were calibrated based on extensive engine dynamometer testing. Thus, the ECU, via the OBD interface, is a useful source of information for data such as engine revolutions per minute (RPM) and other parameters that are useful for characterizing mass air flow and engine fuel consumption. Because the snow mobiles are not equipped with OBD, sensors were temporarily installed to measure key engine variables needed for estimating engine mass air flow.

In addition to describing each instrument, descriptions are given of the PEMS software and the calibration procedure.

2.2.1 Portable Emissions Measurement System

The OEM-2100AX Axion portable emissions measurement system (PEMS) from Clean Air Technologies International (CATI, Buffalo, NY) was used for all of the measurements (CATI, 2007; CATI, 2008). The Axion PEMS is based on MS Windows and LabVIEW.

The PEMS has two identical parallel operation 5-gas analyzers, a PM measurement system, an engine sensor array, a global position system (GPS), and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxide (NO), and oxygen (O_2) in the vehicle exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. PM is measured only for diesel vehicles. The detection methods for each sensor are described:

(1) HC, CO and CO_2 using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used.
(2) O_2 and NO measured using electrochemical sensors.
(3) PM is measured using light scattering, with measurement ranging from ambient levels to low double digits opacity.

All pollutants are measured continuously, on a second-by-second basis. Where analyzer modules require periodic zero and/or span calibration, two modules are used in parallel. Exhaust flow is calculated from engine operating data, known engine and fuel properties, and exhaust gas concentrations. The complete system comes in two weatherproof plastic cases, one of which contains the monitoring system itself, and the other of which contains sample inlet and exhaust lines, tie-down straps, AC adapter, power and data cables, various electronic engine sensor connectors, and other parts. The monitoring system weighs approximately 35 *lbs*.

The system consumes power at 6-8 Amps at 12 V DC. For all the snowcoaches, power for the PEMS was obtained from a deep cycle marine battery at 12V DC. The battery was placed in the cabin of each snowcoach near the PEMS main unit. For all of the snowmobiles, of the power for the PEMS was obtained from a portable Honda generator. The generator was placed adjacent to the sampling box on the back side of the snowmobile.

2.2.2 Sensor Array

Because the snowmobiles are not equipped with an OBD interface, a temporary mounted sensor array was used to obtain the engine operating data, including manifold absolute pressure (MAP), intake air temperature (IAT), and engine speed (RPM) in order to estimate air and fuel use. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1997). The components of the sensor array, including the MAP sensor, engine RPM sensor, and IAT sensor, are briefly described below.

Manifold Air Boost Pressure Sensor

To measure MAP, a pressure sensor is installed on a port on the engine. An existing bolt is removed and a barb fitting is screwed into the port. Plastic tubing is used to connect the MAP sensor to the barb fitting. Alternatively, the existing vehicle MAP sensor is removed, and a "T" fitting is used to allow both the vehicle MAP sensor and the sensor array MAP sensor to simultaneously measurement MAP. The MAP sensor is attached to a convenient location in the engine, away from a hot surface, using plastic ties. For example, Figure 12 depicts the location of an existing port on the intake air manifold of a snowmobile engine. The MAP sensor provides manifold absolute pressure data for the computer of the main unit through a cable that connects the sensor to the MAP port located at the back of the main unit.

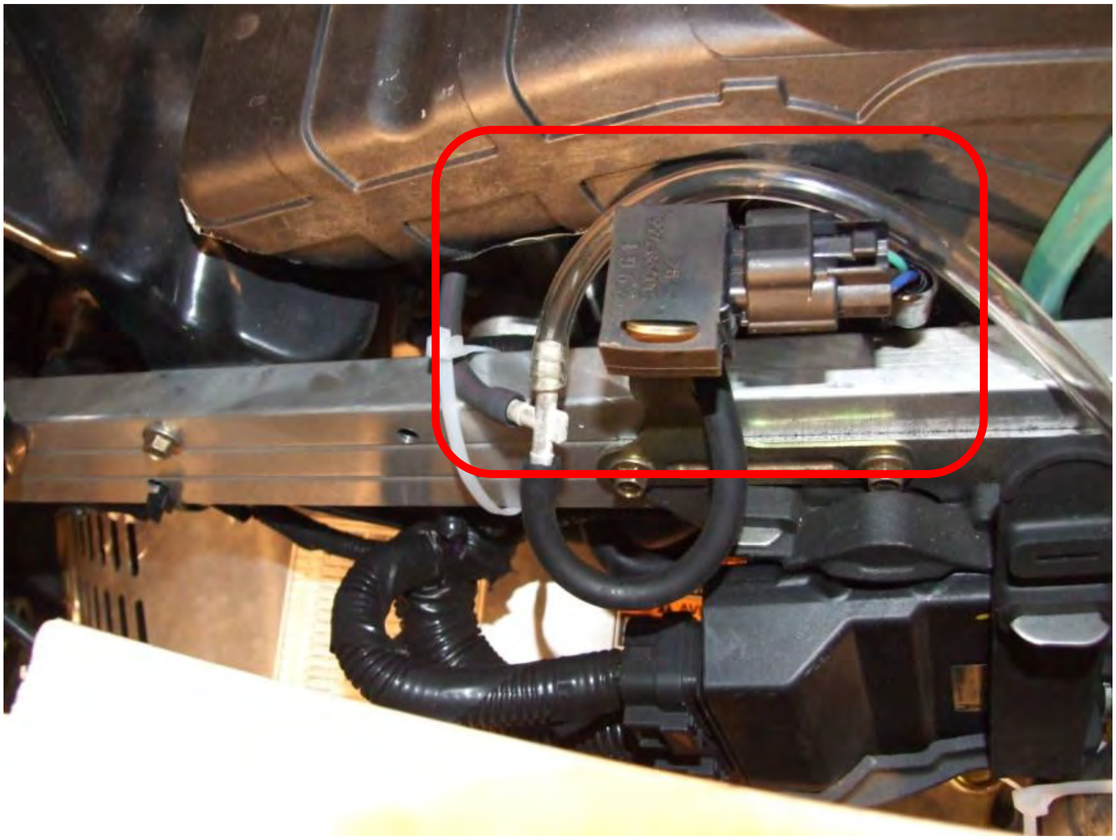

Figure12. Existing Port on Intake Air Manifold (in the red box) of a Snowmobile Engine

Engine Speed Sensor

The engine speed sensor is an optical sensor used in combination with reflective tape to measure the time interval of revolutions of a pulley that rotates at the same speed as the engine crankshaft. The engine speed sensor has a strong magnet to attach easily on metal materials. The reflective tape must be installed on a pulley that is connected to the crankshaft. The placement of the reflective tape and the optical sensor for a snowmobile engine is shown in Figure 13. Some of the key factors in placement of the sensor include: (1) avoid proximity to the engine cooling fan and other moving components; (2) place the sensor in a location where the magnet can securely affix the sensor to a surface; and (3) place the sensor so that its cable can reach the sensor array box, which is located in the driver cabin. The signal from the RPM sensor is transmitted by cable to a sensor array box, which in turn transmits the signal by a second cable to the main unit.

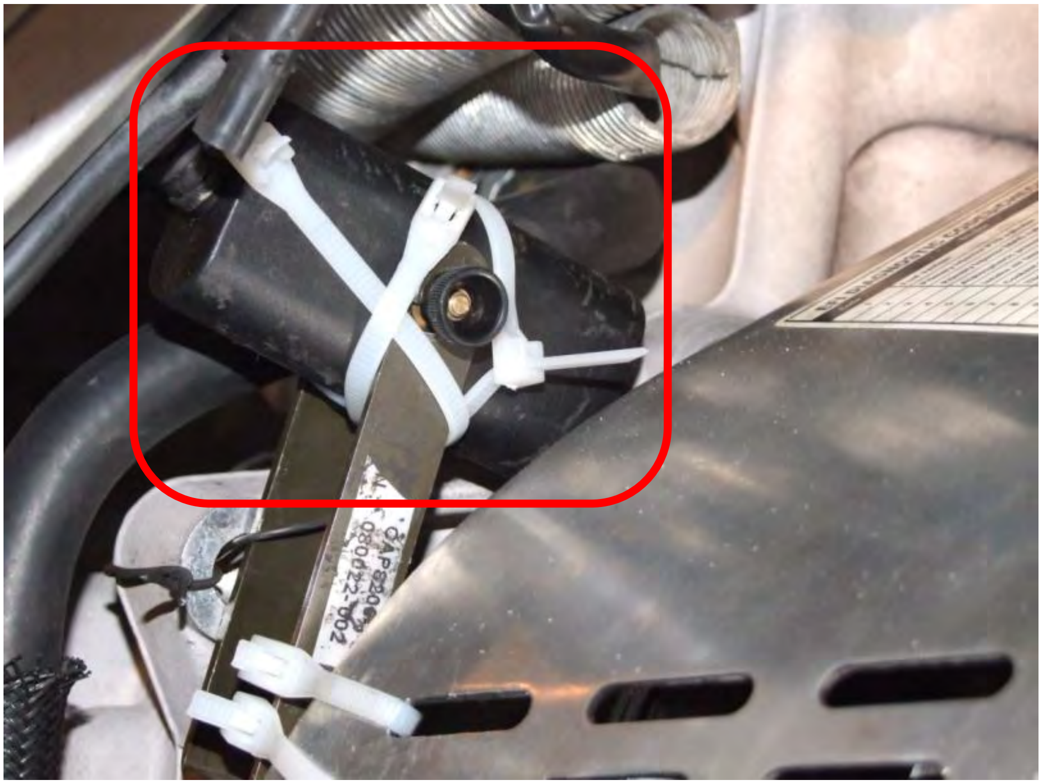

Figure13. Placement of Optical Engine RPM Sensor (in the red box) on a Snowmobile Engine

Intake Air Temperature Sensor

The engine intake air sensor is a thermocouple that is installed near the intake air flow path. Installation of the IAT sensor is somewhat easy compared to the engine speed and MAP sensors. Using duct tape or a plastic tie, the IAT sensor can be fixed near the engine cylinder head. This location is generally near the MAP sensor.

Sensor Array Box

The sensor array box provides signal conditioning and data acquisition for the intake air temperature and engine speed sensors. The temperature and speed signal data is collected by the sensor array box and converted from an analog signal to a digital RS-232 serial signal which is transmitted to the PEMS main unit. The sensor array box was placed in the cabin close to the PEMS main unit. The temperature and speed sensors which were in the engine compartment are connected to the sensor array box using appropriate cables.

2.2.3 On-Board Diagnostics

For the snow coaches, engine operating data were acquired via the OBD interface. The following parameters were measured from the OBD interface: intake manifold absolute pressure (MAP), engine speed (RPM), vehicle speed, intake air temperature (IAT), mass air flow rate (MAF), fuel to air commanded equivalence ratio (LAMBDA), ambient air temperature (AAT), and fuel flow rate (FFR). An OBDPro USB Scantool was used to connect between the OBD link and the data-acquiring laptop. The OBD data link is under the dashboard and is readily accessible. The OBD laptop was powered through the 12V DC vehicle electrical system, using the cigarette lighter outlet. The software used to record OBD data was ScanXL^{TM} Professional from Palmer Performance Engineering, Inc.

2.2.4 GPS Receivers

Three additional GPS units were used besides the one that is part of the PEMS. Three Garmin GPSMAP76CSx portable tracking units were installed on each OSV. These units provide position data accurate to within ±3m. They measure elevation using a barometric altimeter, which is more accurate than the uncorrected elevation measurement of the PEMS GPS receiver. The precision of the Garmin GPS measured elevation is ±1m.

2.2.5 Operating Software

The PEMS includes an in-built computer that is used to collect and synchronize data obtained from the engine scanner, gas analyzers, and GPS system. Data from all three of these sources are reported on a second-by-second basis. The computer is controlled either using a keyboard and mouse. Upon startup, the computer queries the user regarding information about the test vehicle, fuel used, test characteristics, weather conditions, and operating information. Most of this information is for identification purposes. However, the fuel type and composition, engine displacement, sample delivery delays, unit configuration, intake air sensor configuration, and volumetric efficiency are critical inputs that affect the accuracy of the reported emission rates. The details of the definition and significance of each of these are detailed in the Operation Manual of the instrument (CATI,2007; CATI, 2008).

The software provides a continuous display of data during normal operation, including gas analyzer data, engine scanner data, GPS data, and calculated quantities including the emission rate in units of mass per time. The following parameters are typically available on-screen on a second-by-second basis: engine rpm, MAP, pollutants concentrations, exhaust flow, fuel consumption, and mass flow rates of the measured pollutants. The on-board computer synchronizes the incoming emissions, engine, and GPS data.

2.2.7 Instrument Validation and Calibration

The PEMS gas analyzer utilizes a two-point calibration system that includes “span” calibration and “zero” calibration. The “span” calibration was performed for each OSV prior to the test on a daily basis. Additional “span” calibration was performed prior to the test when the fuel type of the tested OSV differed from the previous one. For example, if a diesel-engine OSV was about to test after a gasoline-engine OSV, a “span” calibration was done prior to the test of the diesel-engine OSV. The “zero” calibration was periodically performed during the test period.

Span calibration is performed using a BAR-97Low calibration gas mixture for diesel engine OSVs and a BAR-97High calibration gas mixture for gasoline engine OSVs. The BAR-97Low calibration gas contains 200 ppm propane (HC), 0.50% CO, 6.00% CO_2, 300 ppm NO, with the balance being N_2. The BAR-97High calibration gas contains 3200 ppm propane (HC), 8.00% CO, 12.0% CO_2, 3000 ppm NO, <30 ppm NO_2, with the balance being N_2.The calibration gas includes a mixture of known concentrations of CO_2, CO, NO, and hydrocarbons, with the balance being N_2. Span gas calibration was conducted at the start of both measurement phases. The gas analyzer NDIR subsystem used in the gas analyzers is very stable and tends not to drift significantly from their span calibrations.

During zeroing, ambient air is used as a reference to recalibrate the oxygen sensors to ambient concentration and the CO_2, CO, HC, and NO concentrations to baseline values to prevent instrument drift. Although zero-air stored in bottles or generated using an external zero-air generator can be used, it is believed that the ambient air pollutant levels are negligible compared to those found in undiluted exhaust; therefore, ambient air is viewed as sufficient for most conditions. For zero calibration purposes, it is assumed that ambient air contains 20.9 *vol*-% oxygen, and negligible NO, HC, or CO. CO_2 levels in ambient air are approximately 300-400 ppm, which are negligible compared to the typical levels of CO_2 in exhaust gases. Both benches zero every 15 minutes but never together thus providing uninterrupted data recording.

A study conducted by Battelle and prepared for the Environmental Technology Verification (ETV) program of the U.S. EPA compared the CATI PEMS to standard testing equipment using 40 CFR Part 86 reference methods (Myers *et al*., 2003). The tests were conducted on a sample of light duty highway vehicles on a chassis dynamometer and used FTP and US06 test cycles. Linear regression slopes for measurements from the PEMS and reference facility ranged from 0.97 to 1.03 for CO_2, 0.95 to 1.05 for CO, and 0.92 to 1.03 for NO_x, indicating that CO_2, CO, and NO_x measurements from the PEMS are accurate to within 10% of reference measurements. HC measurements are biased low by a factor of approximately two because the PEMS used NDIR and reference method used Flame Ionization Detection (FID) (Myers *et al*., 2003; Stephens and Cadle, 1991). PM measurements are analogous to opacity and used for relative comparisons. The accuracy of HC and CO measurements depends on the fuel used and on the emission levels (Vojtisek-Lom and Allsop, 2001).

2.3 Data Collection

Field data collection involved three major steps: (1) instrument installation; (2) data collection; and (3) Decommissioning. The key aspects of data collection for a vehicle are described below.

2.3.1 Instrument Installation

The instruments were installed to the OSV before a scheduled test. For snow coaches, this step involved installing the exhaust gas sampling lines, power cable, and OBD data link on the vehicle. Exhaust gas sampling lines have a probe that is inserted into the tailpipe. The probe is secured to the tailpipe using a hose clamp. The sampling line is secured to various points on the chassis of the vehicle. The sampling line is routed through the top window of the Bombardier or the passenger side window of the snow coach cab so that it can be connected to the PEMS main unit. Part of the sampling lines from the exhaust outside the cabin to the PEMS main unit inside the cabin was covered by insulated tubes. Two pumps were placed in the passenger's cabin to absorb warm air from inside the cabin to pass through the insulated tubes to keep the sampling lines warm. The PEMS main unit was placed on a passenger seat inside the snow coaches. A deep cycle marine battery was placed inside all the snow coach cabins to provide 12V DC power to the PEMS main unit. The battery was recharged prior to the tests to provide sufficient power. The OBD data-acquiring laptop used the cigarette lighter outlet from the snow coach for power. Three Garmin GPS units were turned on and placed in the cabin to receive positioning data.

For snowmobiles, the installation step involves installing the exhaust gas sampling lines, power cable, and engine sensor array on the vehicle. The exhaust gas sampling probe is inserted into the tailpipe and secured using a hose clamp. An insulated box was placed on the back side on the snowmobile. The PEMS main unit sits inside the insulated box, and the sampling lines are routed from the tailpipe to the PEMS main unit. The sampling lines from the exhaust to the PEMS main unit were covered by insulated tubes. The Garmin GPS units were placed inside the insulated box. A portable Honda generator was used to provide 12V DC power to the PEMS main unit. The generator was placed in front of the insulated box, sitting on the back side of the snowmobile. The sensor array was connected to the engine.

The instruments installation usually took 45-60 minutes. As part of final installation, the PEMS main unit was warmed up for about 45 minutes. The research assistant entered data into the PEMS regarding vehicle characteristics and fuel type.

Figures 14 to 16 illustrate several aspects of the installation of the PEMS, OBD, and GPS using the example of Ford E350. In Figure 14, the PEMS Main Unit is shown, including its placement inside the snow coaches and the connections for sampling lines, exhaust lines, and engine data. Figure 15 shows the sampling probes attached to tailpipe, and routing of zeroing line. Insulation placed around the sample lines is visible in the figure. Figure 16 shows the connection to the OBD port, and the Garmin GPS in the snow coaches. Figure 17 shows the placement of the insulated box and the portable generator on the snowmobile, for the Arctic Cat TZ1.

Figure14. Installation of the Portable Emissions Measurement System (PEMS) Main Unit in Ford E350. (*left) PEMS Main Unit on passenger seat (front-view);(right) PEMS Main Unit backside connections*

Figure15. Installation of Sampling Probes, and Zeroing Line in Ford E350 (shown in the red boxes).*(left) Sampling exhaust gases using a probe secured with a hose clamp, covered by insulated tubes; (right) Zeroing line*

Figure16. Installation of the On-Board Diagnostics and Garmin GPSs in Ford E350 (shown in the red boxes). *(left) Connection port of the OBD ;(right)Three Garmin GPS units*

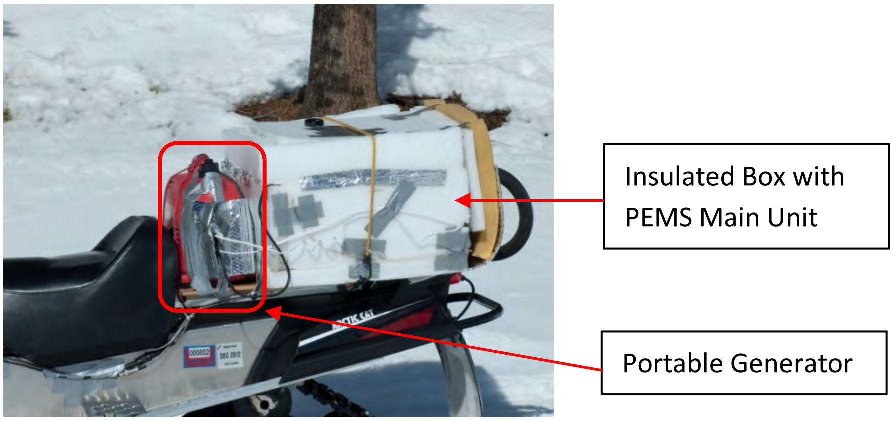

Figure17. Placement of the Insulated Box and the Portable Generator (shown in the red box) of Arctic Cat TZ1 Snowmobile. The PEMS Main Unit was Placed inside the Insulated Box.

2.3.2 Data collection

The data collection involved fueling, and continuously recording exhaust gas concentration, engine data, and GPS data on a second-by-second basis. Before and after the measurement, the tank of the tested OSV was fueled to the maximum in the same gas station. The actual fuel use was recorded. During testing, periodic checks of the system status were made. For example, the security of all connections with the vehicle was evaluated. This was done by determining whether instrument was securely connected to DC power, whether engine data was updated on the instrument display in an appropriate manner, whether the gas concentrations were reasonable, and whether GPS sensor had satellite connectivity. Other checks include checking if the sampling bowl had any excess condensate which may indicate poor drain pump operation and checking if the PEMS main unit was seated firmly. If any of the data relating to gas concentration and/or engine parameter were “frozen” (meaning that the recorded values do not change over time even though they should vary) or the values were unreasonable, then it was necessary to restart either one or both bench or reboot the PEMS main unit.

2.3.3 Decommissioning

After the end of the test period, decommissioning was performed. During decommissioning, the NCSU research assistant discontinued data collection, copied data that have been collected, powered down the PEMS, and removed the exhaust sample lines, power cable, data cable, and GPS receiver and cable.

2.4 Data Quality Assurance

For quality assurance purposes, the combined data set for a vehicle run was screened to check for errors or possible problems. If errors were identified, they were either corrected or the affected data were not used for data analysis. First, the types of errors typically encountered are described followed by a discussion of methods for making corrections.

2.4.1 Engine Data Errors

On occasion, communication between the vehicle's onboard computer and the engine scanner may be lost, leading to loss of data. Sometimes the loss of connection is because of a physical loss of electrical contact, while in other cases it appears to be a malfunction of the vehicle's on-board diagnostic system. This rarely happens. However, when it happens, this error can be solved easily by rebooting the system in the field. After rebooting, the computer begins logging a new data file automatically. Thus, when this is noticed in the field, this error can be addressed. Loss of engine data is also obvious from the data file, since the missing data are evident and any calculations of emission rates are clearly invalid. The following types of engine errors are included in the quality assurance procedure:

(1) Unusual Engine RPM

During the measurements, engine RPM was typically around 600 RPM during idling during snow coach operation. The upper bound of engine RPM during snow coach operation was approximately 4,800, 4,300, 4,100, 3,500, and 3,000 for Bombardier, Chevy Express, Ford E350, Ford F450, and Ford F550, respectively. For snowmobiles, the engine typically idled at around 1,400 RPM, and operated at about 6,500 RPM maximum. The valid RPM range checks used in QA were typically 500 to 6,000 RPM for the snow coaches and 0 to 8,000 RPM for the snowmobiles. There were no outliers for engine RPM for both snow coaches and snowmobiles to the ranges used in the QA step.

(2) Engine RPM Freezing

"Freezing" refers to situations in which a value that is expected to change dynamically on a second-by-second basis remains constant over an unacceptably or implausibly long period of time. Engine RPM tends to fluctuate on a second-by-second basis even if the engine is running at approximately constant RPM. Therefore, we performed a check to identify situations in which engine RPM remained constant for more than three seconds. This problem occurs only in situations where the engine scanner became physically disconnected from the data logging computer. This type of error is rare.

2.4.2 Gas Analyzer Errors

The Axion system has two gas analyzers, which are referred to as "benches." Most of the time, both benches are in use. Occasionally, one bench is taken off-line for "zeroing." Therefore, most of the time, the emissions measurements from each of the two benches can be compared to evaluate the consistency between the two. If both benches are producing consistent measurements, then the measurements from both are averaged to arrive at a single estimate on a second-by-second basis of the emissions of each pollutant.

When the relative error in the emissions measurement between both benches is within five percent, and if no other errors are detected, then an average value is calculated based upon both of the benches.

However, if the relative error exceeds five percent, then further assessment of data quality is indicated. Aninter-analyzer discrepancy (IAD) in measurements might be due to any of the following: (a) a leakage in the sample line leading to one bench; (b) overheating of one of the benches; or (c) problems with the sampling pump for one of the benches, leading to inadequate flow. If one of these problems is identified for one of the benches, then only data obtained from the other bench was used for emissions estimation. When problems are identified in the field, then attempts are made to resolve the problems in the field. For example, if a leak or overheating problem is detected during data collection, then the problem is fixed and testing resumes. Data recorded during the period when a leak or overheating event occurred are not included in any further analyses.

2.4.3 Zeroing Procedure

For data quality control and assurance purpose, each gas analyzer bench is zeroed alternatively every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. After zeroing is finished, a solenoid valve changes the intake from ambient air to the tailpipe. There is a period of transition when this occurs. In particular, the oxygen sensor needs several seconds to respond the switching of gases, since there is a large change in oxygen concentration when this switch occurs. To allow adequate time for a complete purging of the previous gas source from the system, a time delay of 10 seconds is assumed. Thus, for 10 seconds before zeroing begins, the time period of zeroing, and 10 seconds after zeroing ends, data for the bench involved in zeroing are excluded from calculations of emission rates, and the emission rates are estimated based only upon the other bench.

2.4.4 Negative Emissions Values

Because of random measurement errors, on occasion some of the measured concentrations will have negative values that are not statistically different from zero or a small positive value. Negative values of emissions estimates were assumed to be zero and were replaced with a numerical value of zero.

2.4.5 Air Leakage

The Air Leakage data quality procedure is used to eliminate data affected by excessive dilution, which affects the ability to precisely detect exhaust gas concentrations using the gas analyzers. Air leakage represents infiltration of air into the exhaust gas flow path between the engine exhaust and the gas analyzers. Air Leakage is inferred based on values of Air to Fuel Ratio (AFR) that exceed a threshold. Data associated with AFR greater than the threshold are not used in analysis of modal fuel use and emission rates.

2.4.6 Invalid Data

The software used internally by the PEMS reports some data quality problems. In some instances, the PEMS would not record valid data for gas concentrations and/or RPM. In such instances, the value for the parameter is recorded as zero, and a corresponding column for validity is marked as “NO”. These seconds of data are marked as “invalid” by the QA procedure. This error occurs infrequently, and such data are deleted and not use for development of modal fuel use and emission rates.

2.4.7 Loss of Power to Instrument

A loss of power to the instrument results in a complete loss of data collection during the time period when power was not available. However, the system saves data up to the point at which the power loss occurs. A typical cause of power loss for manual transmission vehicles is stalling of the engine due to a problem shifting. Such problems typically occur when going from idle into first gear, or for the lower gears. After a loss of power, the instrument needs to be rebooted, which takes approximately five to ten minutes. During the power loss and rebooting, no data can be collected.

NCSU has developed a PEMS quality assurance software in LabVIEW. Raw data from the PEMS is processed through this software to identify data quality problems. Where possible, such problems are corrected. If correction is not possible, then the errant data are omitted from the final database used for analysis.

2.5 Data Analysis

Results for the fuel use and emission rates of each vehicle for idle, low speed, and cruise in units of mass per time, mass per gallon, and mass per mass of fuel were analyzed. Mass per mile emission rates for route averages was also estimated. The quantification of mass per time and mass per distance emissions depend on being able to measure engine parameters of IAT, RPM, and MAP or on being able to log OBD data. The fuel tank of each tested vehicle was topped off before and after PEMS measurements in order to have an independent basis for quantifying fuel use rate.

2.5.1 Validation of Fuel Use

Fuel use is estimated based upon a calculation involving assumptions regarding engine volumetric efficiency, data reported by the electronic control unit or sensor array regarding intake air temperature, manifold air pressure, and engine RPM, and the exhaust gas concentrations from the PEMS. It is possible that there are uncertainties or errors in these data. Thus, there is a need to validate the fuel usage estimates from the Axion system by comparison to independent data.

The vehicle fuel tank was full prior to data collection, and then was refilled at the end of data collection for each tested OSV so that the total actual gallons of fuel consumed during the test can be estimated. The actual number of gallons of fuel can be compared to the total number of gallons of fuel estimated based upon summing second-by-second estimates of the OBD data. Although this was the goal, actual fuel consumption data were not available for some of the snowmobiles. In cases for which actual fuel consumption for the test run was not obtainable, comparisons were made between the fuel economy estimated from the in-use measurements versus that reported by other sources, such as maintenance records of the vehicle owner.

The benefit of such a comparison is that it can provide confidence that the flow rates estimated by the Axion system are reasonable. Furthermore, since CO_2 emissions are highly correlated with fuel flow, validation of fuel flow also provides credibility regarding the CO_2 emission values. Some of the limitations of this comparison might include the following: (a) the vehicle's fuel tank might not be "topped off" at exactly the same level from one filling to the next; (b) some vehicle idling occurs while the Axion system is warming up; and (c) some vehicle operation may occur at times when the Axion system is recovering from a power loss or other data collection outage.

2.5.2 Emission Rate Estimation

The emission rates were estimated for three different categories of driving modes: (1) idle mode; (2) low speed mode; and (3) cruise mode. The idle mode was defined as vehicle speed less than 0.5 m/s. Vehicle speed was typically estimated based on GPS data, because the OBD reported speed may be incorrect. For example, four of the snow coaches are converted highway vehicles to which treads have been retrofitted. The road speed from operation of the treads is different than that for operation of tires, but the ECU was not recalibrated as part of the retrofit. Therefore, the OBD speed is not accurate. GPS estimates of position are subject to some random errors than can lead to apparent speeds of typically less than 0.5 m/s even if the vehicle is not moving. Therefore, the criterion for idle was based on a GPS estimated speed of 0.5 m/s or less. The low speed mode was defined as vehicle speed was greater than 0.5 meters per second and less than 6.7 m/s (15 mph). The cruise mode was defined as vehicle speed greater than 6.7 m/s (15 mph).

For the measured emission data that successfully passed the QA steps, the second-by-second emission rates of CO, NO_x, and HC and fuel use rates, and the total time and distance travelled, were estimated. For idle mode, the mean emission rates were estimated in units of grams per second (g/s), initially. The mean emission rates in units of grams per gallon of fuel (g/gal) and grams per kilogram of fuel (g/kg) were estimated based on the total fuel used and fuel properties of density and weight percent carbon. For low speed mode and cruise mode, the mean emission rates were estimated in units of grams per mile (g/mi), initially, based on g/sec emission rates and the vehicle speed in miles per second. Emission rates in the unit of grams per gallon of fuel (g/gal) and grams per kilogram of fuel (g/kg) were estimated according to the total fuel used and the fuel property. A 95% confidence interval of the mean for the emission rates was calculated for each scenario.

3.0 RESULTS

Measurements on five snow coaches and three snowmobiles were conducted in this work. The results are shown and discussed below.

3.1 Snow coaches

The in-use emissions of five snow coaches were measured during operation on a designated route. A total of 10.24 hours of valid data were collected on a second by second basis among the five coaches. The collected data sets typically included time, concentrations of each pollutant (CO_2, CO, HC, and NO), engine speed, vehicle speed, fuel flow rate (FFR) and GPS position. The collected data sets also included intake air temperature (IAT) and manifold absolute pressure (MAP) for the gasoline fueled snow coaches. The OBD reported fuel flow rate was used to quantify second-by-second fuel use. The sum of the second-by-second OBD fuel flow rate was used to quantify cumulative fuel consumption.

Table 3 lists the summary of hours sampled and miles traveled for each snow coach in each defined driving mode. The mean speed for low speed mode and cruise mode are also listed. The sampling hours were longer for the Bombardier and the Ford F550 snow coach. The Ford F550 spent a significant longer time idling compared to other snow coaches because one of the tracks failed along the test route and had to be replaced in the field. The distances travelled for each snow coach ranged from 31.9 miles to 35.6 miles. The variation in distance was primarily because of differenced in where the turnaround occurred after the outbound trip and before the return inbound trip.

Table3. Valid Data Distributed for Three GPS Defined Driving Modes for Snowcoaches

Vehicle Measured	Hours Sampled (Miles Traveled)			Mean Low Speed 0 < GPS Speed < 15 mph	Mean Cruise Speed GPS Speed > 15 mph
	Idle	**Low Speed**	**Cruise**		
Bombardier	0.49 (0)	0.75 (6.6)	1.08 (27.2)	8.8	25.2
ChevyExpress	0.17 (0)	0.10 (0.8)	1.38 (31.6)	8.7	22.9
FordE350	0.29 (0)	0.17 (1.4)	1.35 (31.1)	8.4	23.1
FordF450	0.31 (0)	0.13 (1.0)	1.45 (34.6)	7.8	23.8
FordF550	0.86 (0)	0.36 (2.1)	1.36 (29.8)	5.8	21.9
Totals and Weighted Means	2.12 (0)	1.50 (12.0)	6.62 (154.1)	8.0	23.3

Fuel consumption was compared based on estimates from the measurement data versus the amount of fuel needed to top off the fuel tank after data collection. The actual fuel use should be theoretically greater than the estimated fuel use, because the estimated fuel use did not count the fuel use from the gas station to the test location, during which OBD data were not recorded. As shown in Table 4, except for the Bombardier, the fuel use estimated from OBD data and the fuel required to top off the tank from the fuel pump agreed to within 10% or less. The OBD fuel use estimate was less than the refueling amount for three of the vehicles, which is expected. The estimated fuel use was more than the actual fuel use for the Ford F450 snow coach, but there was less than 3% of difference between these values.

The refueling of the Bombardier fuel tank could not be done in a repeatable manner for the before and after cases. The Bombardier fuel tank is long and flat, and thus even a small difference in the depth of liquid in the tank could be associated with a large difference in the total volume of fuel contained. An attempt was made to top off the fuel level before and after the data collection, and to verify that the fuel level was the same using a dipstick. However, any differences in the slope of the surface that the vehicle was on, coupled with inaccuracies in exactly measuring the fuel level, can lead to large relative errors in the estimate. Given these factors, the 22 percent difference between the amount of fuel added to the tank versus the OBD estimate is within the range of expected error.

Table4. Fuel Use Comparison for Each Snow coach

Vehicle Measured	$Fuel_{pump}$ (gal)	$Fuel_{OBD}$[a] (gal)	Diff.[b] (%)	Distance[c] (miles)	MPG_{pump}[d]	MPG_{OBD}[e]
Bombardier[f]	6.1	7.4	21.7	35.5	5.8	4.8
ChevyExpress	16.2	15.0	-7.0	34.4	2.1	2.3
FordE350[g]	16.2	14.7	-9.2	43.7	2.7	3.0
FordF450	21.1	21.7	2.7	38.9	1.8	1.8
FordF550	17.6	16.8	-4.7	34.9	2.0	2.1

[a]Fuel use estimated from On Board Diagnostic(OBD) second-by-second gal/hour data
[b]Difference = $(Fuel_{OBD} – Fuel_{pump})/Fuel_{pump}$
[c]Distance estimated from Garmin GPS second-by-second data. Distance includesdriving from pre-test installation point up to post-test fuel top off at gas pump. Distance does not include the driving from pre-test fuel top off at gas pump to the pre-test installation point, which is typically less than 2 mile.
[d]MPG_{pump} = Distance/$Fuel_{pump}$
[e]MPG_{OBD}=Distance/$Fuel_{OBD}$
[f]Fuel top off before and after the test was not to the same level
[g]This vehicle was used for sound level measurements and did multiple passes for a section of the route; hence the larger distance in miles

Table 5 summarizes data quality assurance results. The data quality assurance procedure addresses 9 typical types of errors related to the engine, gas analyzer, and data, including invalid data (INV), unusual engine speed (RPM), unusual intake air temperature (IAT), missing manifold absolute pressure (MAP), both benches zeroing (ZERO), analyzer freeze (FRE), negative emission value (NEG), inter-analyzer discrepancy (IAD), and unusual air to fuel ratio (AFR). There were no occurrences of the error categories of INV, RPM, MPA, NEG, or IAD. There were very few instances of error category FRE. Thus, only IAT, ZERO, and AFR categories had any effect on the data. The total percentages are not the sum of percentages of individual error types since two or more types of error could occur in the same second and jointly affect data quality. Over 96% of the raw data were valid, and for two of the coaches 99.9% or more of the data were valid. The frequency of errors here is comparable to or lower than that in previous measurements of other types of vehicles.

Table5. Percentages of Different Errors after Quality Assurance for Each Snow coach (%)

Snow coach	**Percentage of Raw Data Affected by Indicated Error Type[a]**									
	INV	**RPM**	**IAT**	**MAP**	**ZERO**	**FRE**	**NEG**	**IAD**	**AFR**	**Total**
Bombardier	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Chevy Express	0.0	0.0	0.3	0.0	2.5	0.1	0.0	0.0	2.6	2.9
Ford E350	0.0	0.0	1.5	0.0	2.3	0.0	0.0	0.0	2.3	3.9
Ford F450	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	2.4	2.0
Ford F550	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0

[a] INV = Invalid Data; RPM = Unusual Engine Speed; IAT = Unusual Intake Air Temperature; MAP = Mission Manifold Absolute Pressure; ZERO = Both Benches Zeroing; FRE = Analyzer Freezing; NEG = Negative Emission Value; IAD = Inter-Analyzer Discrepancy; AFR = Unusual Air to Fuel Ratio.

Table 6 summarizes the measured emission rates for CO, HC, and NO_x for each snow coach for the three driving modes. Time-weighted means for each pollutant in each driving mode are also listed. The 95% confidence intervals for each pollutant for each snow coach in different units for idle mode, low speed mode, and cruise mode are provided in Tables7, Table 8, and Table 9, respectively.

Table6. Mass Emission Rates for the Three Driving Modes for Each Snowcoach[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
Bombardier	CO	3.64	29.9	10.7	9.5	45.9	16.4	7.1	35.5	12.7
	HC	0.10	0.8	0.3	0.1	0.7	0.2	0.1	0.5	0.2
	NO_x	0.24	1.9	0.7	3.1	14.9	5.3	4.9	24.5	8.8
Chevy Express	CO	6.40	45.9	16.4	38.7	94.5	33.8	454	1010	362
	HC	0.04	0.3	0.1	0.2	0.5	0.2	0.5	1.2	0.4
	NO_x	0.04	0.3	0.1	1.0	2.5	0.9	4.7	10.5	3.8
Ford E350	CO	0.62	3.6	1.3	5.4	16.1	5.8	13.4	39.8	14.3
	HC	0.10	0.6	0.2	0.1	0.4	0.2	0.2	0.5	0.2
	NO_x	0.01	0.1	0.0	0.1	0.2	0.1	0.3	0.8	0.3
Ford F450	CO	0.001	0.004	0.001	0.7	1.4	0.4	1.4	2.8	0.9
	HC	0.16	1.2	0.4	0.3	0.6	0.2	0.1	0.1	0.04
	NO_x	5.60	41.1	12.9	23.3	43.6	13.6	13.3	26.0	8.1
	PM	0.01	0.04	0.01	0.02	0.03	0.01	0.01	0.02	0.01
Ford F550	CO	3.71	45.3	14.2	1.3	2.7	0.9	0.01	0.01	0.004
	HC	0.07	0.9	0.3	0.1	0.3	0.1	0.1	0.3	0.1
	NO_x	1.76	21.4	6.7	5.8	12.4	3.9	6.9	16.3	5.1
	PM	0.01	0.08	0.02	0.02	0.04	0.01	0.01	0.03	0.01
Time-Weighted Means	CO	3	25	9	9	29	10	97	248	83
	HC	0.1	0.8	0.3	0.2	0.5	0.2	0.2	0.5	0.2
	NO_x	1.6	13.8	4.6	4.8	15.5	5.2	6.2	15.8	5.3
	PM	0.01	0.06	0.02	0.02	0.04	0.01	0.01	0.03	0.01

[a] g/mi, g/gal and g/kg results are calculated from the reported miles traveled, g/sec emissions, and g/sec fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon and for diesel 3,200 g/gallon.

Table7. Mass Emissions Rates with 95% Confidence Intervals for the Idle Driving Mode[a]

Vehicle Measured	Species	Idle					
		mg/sec		g/gal		g/kg	
		mean	CI[b]	mean	CI	mean	CI
Bombardier	CO	3.64	0.57	29.9	4.66	10.7	1.67
	HC	0.10	0.01	0.8	0.04	0.3	0.01
	NO_x	0.24	0.01	1.9	0.05	0.7	0.02
Chevy Express	CO	6.40	2.4	45.9	17.5	16.4	6.3
	HC	0.04	0.004	0.3	0.03	0.1	0.01
	NO_x	0.04	0.01	0.3	0.08	0.1	0.03
Ford E350	CO	0.62	0.1	3.6	0.4	1.3	0.1
	HC	0.10	0.01	0.6	0.03	0.2	0.01
	NO_x	0.01	0.001	0.1	0.004	0.0	0.002
Ford F450	CO	0.001	0.001	0.004	0.01	0.001	0.002
	HC	0.16	0.01	1.2	0.06	0.4	0.02
	NO_x	5.60	0.68	41.1	4.97	12.9	1.55
	PM	0.01	0.0004	0.04	0.003	0.01	0.001
Ford F550	CO	3.71	0.20	45.3	2.40	14.2	0.75
	HC	0.07	0.01	0.9	0.12	0.3	0.04
	NO_x	1.76	0.08	21.4	0.92	6.7	0.29
	PM	0.01	0.0001	0.08	0.001	0.02	0.0004
Time-Weighted Means	CO	3		25		9	
	HC	0.1		0.8		0.3	
	NO_x	1.6		13.8		4.6	
	PM	0.01		0.06		0.02	

[a] g/mi, g/gal and g/kg results are calculated from the reported miles traveled, g/sec emissions, and g/sec fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon and for diesel 3,200 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

Table8. Mass Emissions Rates with 95% Confidence Intervals for the Low Speed Driving Mode [a]

Vehicle Measured	Species	Low Speed					
		g/mile		g/gal		g/kg	
		mean	CI[b]	mean	CI	mean	CI
Bombardier	CO	9.5	0.72	45.9	3.44	16.4	1.23
	HC	0.1	0.005	0.7	0.02	0.2	0.01
	NO_x	3.1	0.16	14.9	0.77	5.3	0.28
Chevy Express	CO	38.7	4.4	94.5	10.9	33.8	3.9
	HC	0.2	0.02	0.5	0.04	0.2	0.02
	NO_x	1.0	0.4	2.5	1.0	0.9	0.3
Ford E350	CO	5.4	0.7	16.1	2.1	5.8	0.8
	HC	0.1	0.01	0.4	0.03	0.2	0.01
	NO_x	0.1	0.02	0.2	0.06	0.1	0.02
Ford F450	CO	0.7	0.40	1.4	0.75	0.4	0.23
	HC	0.3	0.04	0.6	0.07	0.2	0.02
	NO_x	23.3	1.85	43.6	3.46	13.6	1.08
	PM	0.02	0.002	0.03	0.004	0.01	0.001
Ford F550	CO	1.3	0.63	2.7	1.35	0.9	0.42
	HC	0.1	0.01	0.3	0.02	0.1	0.01
	NO_x	5.8	0.42	12.4	0.91	3.9	0.29
	PM	0.02	0.001	0.04	0.001	0.01	0.0005
Time-Weighted Means	CO	9		29		10	
	HC	0.2		0.5		0.2	
	NO_x	4.8		15.5		5.2	
	PM	0.02		0.04		0.01	

[a] g/mi, g/gal and g/kg results are calculated from the reported miles traveled, g/sec emissions, and g/sec fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon and for diesel 3,200 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

Table9. Mass Emissions Rates with 95% Confidence Intervals for the Cruise Driving Mode[a]

Vehicle Measured	Species	Cruise					
		g/mile		g/gal		g/kg	
		Mean	CI[b]	Mean	CI	mean	CI
Bombardier	CO	7.1	0.20	35.5	0.98	12.7	0.35
	HC	0.1	0.001	0.5	0.01	0.2	0.002
	NO_x	4.9	0.10	24.5	0.47	8.8	0.17
Chevy Express	CO	454	6.4	1010	14.3	362	5.1
	HC	0.5	0.01	1.2	0.01	0.4	0.005
	NO_x	4.7	0.1	10.5	0.3	3.8	0.1
Ford E350	CO	13.4	0.2	39.8	0.5	14.3	0.2
	HC	0.2	0.003	0.5	0.01	0.2	0.003
	NO_x	0.3	0.004	0.8	0.01	0.3	0.005
Ford F450	CO	1.4	0.10	2.8	0.19	0.9	0.06
	HC	0.1	0.003	0.1	0.01	0.04	0.002
	NO_x	13.3	0.09	26.0	0.18	8.1	0.06
	PM	0.01	0.0002	0.02	0.0003	0.01	0.0001
Ford F550	CO	0.01	0.002	0.01	0.01	0.004	0.002
	HC	0.1	0.02	0.3	0.04	0.1	0.01
	NO_x	6.9	0.26	16.3	0.61	5.1	0.19
	PM	0.01	0.0002	0.03	0.0004	0.01	0.0001
Time-Weighted Means	CO	97		248		83	
	HC	0.2		0.5		0.2	
	NO_x	6.2		15.8		5.3	
	PM	0.01		0.03		0.01	

[a] g/mi, g/gal and g/kg results are calculated from the reported miles traveled, g/sec emissions, and g/sec fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon and for diesel 3,200 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

For the gasoline-fueled Bombardier, the average CO emission rates on a gram per gallon basis were comparable among idle, low speed, and cruise modes at approximately 30 to 46 g/gallon. The HC emission rates averaged between 0.5 and 0.8 g/gallon among the three modes. The average NO_x emission rates varied between 1.9 and 24.5 g/gallon. Thus, the NO_x emission rates had the most relative variability among the modes, with the cruise mode emission rate being more than ten times greater than that at idle.

The gasoline-fueled Chevrolet Express had HC and NO_x emission rates that were typically lower than or comparable to those of the Bombardier. However, the CO emission rates were higher, ranging from 46 g/gallon at idle to over 1,000 g/gallon during cruise. The very high rate during cruise was double checked, and found to be a valid result based on the measured data. The Chevrolet appeared to be underpowered for this type of service, and the engine was often operated at or close to full throttle. Under conditions of high power demand, gasoline engines can be periodically commanded by the ECU to operate in a fuel rich mode, which can lead to high emissions of CO. Another possibility is that the engine combustion was itself inefficient, which would also account for the relatively low NO_x emissions. NO_x emissions tend to be higher during complete combustion that leads to higher flame temperature.

The gasoline-fueled Ford E350 had relatively low emissions for CO, HC, and NO_x compared to the other two gasoline-fueled snow coaches. Most remarkable is the very low NO_x emission rate. In contrast to the Express, the E350 appears to have adequate power for its needs.

The two diesel snow coaches also had relatively low emission rates. Diesel engines typically have lower emissions for CO and HC than gasoline engines because they operate with a much higher air/fuel ratio. The excess air promotes more complete oxidation of the fuel, thereby lower emissions of products of incomplete combustion. However, uncontrolled diesel engines tend to have much higher NO_x emissions than gasoline engines because the higher pressure ratio of the engine coupled with the larger proportion of oxygen entering the engine is conducive to more NO_x formation. In 2010, a new Federal vehicle emission standard went into effect that requires substantial reduction in uncontrolled NO_x emissions from diesel engines. The two tested diesel vehicles each use selective catalytic reduction (SCR) for NO_x control. The NO_x emission rates for the Ford F450 averaged between 26 and 44 g/gallon among the three operating modes. The Ford F550 averaged between 12 and 21 g/gallon. These rates are comparable to those of some of the gasoline vehicles, depending on the operating mode. These rates would have been much higher without SCR. The Particulate Matter emission rates per gallon of fuel consumed for the diesel vehicles tends to be higher at idle than when the engine is under load. The PM emission rates for the two diesel are low because they are both equipped with diesel particulate filters (DPFs).

The confidence intervals on the mean emission rates that are given in Tables 8, 9, and 10 were estimated based on statistical analysis of the second-by-second data. As an example, the idle

CO emission rate for the Bombardier of 29.9 g CO/gallon has a 95% confidence interval of ±4.7 g CO/gallon, or plus or minus 16 percent of the mean value. For the Chevrolet Express, the 95% confidence interval on the mean cruise CO emission rate is from 996 to 1024 g CO/gallon, which is an uncertainty range of less than plus or minus 2 percent. The confidence intervals on the mean emission rates are sufficiently narrow in most cases that the mean values are significantly different from zero and mean rates for the same vehicle for different modes are significantly different from each other. For example, for the Bombardier, the NOx emission rates have confidence intervals of 1.85 to 1.95 g/gallon at idle, 14.1 to 15.7 g/gallon at low speed, and 24.0 to 25.0 g/gallon at cruise. These intervals do not overlap and thus are significantly different from each other. The exception to these findings are that the CO emission rates of the diesel-fueled Ford F450 and F550 are not significantly different from zero for several of the operating modes, and thus are not significantly different from each other.

With the exception of CO emissions rates for the Chevrolet Express, the emission rates among the five snow coaches were either comparable or relatively low.

The emission rates for CO, HC, NO_x, and PM were measured by 2006 (Bishop *et al*, 2009). The time-weighted mean emission rates of CO for all tested snow coaches in this study were 95%, 82%, and 19% lower for idle mode, low speed mode, and cruise mode, respectively. If the Chevy Express, which had very high CO emission rates, is excluded from the comparison, the observed CO emission rates were 96%, 92%, and 95% lower. Compared to the previous study, the time-weighted means of the emission rates of snow coaches were around 90% lower for HC, 0, 60%, and 44% lower for NO_x, and around 95% lower for PM, for idle mode, low speed mode, and cruise mode. Four out of five snow coaches measured here were made in 2008 or later, and the 1956 Bombardier has had a recent engine replacement. In contrast, the previous study included snow coaches of earlier model years from 1994 through 2006. The emission control technologies differ by model year.

3.2 Snowmobiles

Three snowmobiles were measured for which 4.0 hours of valid second by second data were obtained. The collected data sets included time, concentrations of each pollutant, engine speed, MAP, IAT, and vehicle position information.

For each snowmobile, Table 10 summarizes the hours sampled, the miles travelled in each defined driving mode, and the mean speeds for low speed mode and cruise mode. These vehicles operated at average speeds of 7 mph for the low speed mode and 29 mph for the cruise mode. The amount of data for the Arctic Cat T660 is less than that for the other two snowmobiles because there was a buildup of moisture in the gas analyzer sample line. High moisture interferes with the NDIR sensor used to measure tailpipe gas concentrations of CO_2, CO, and HC. However, there were 0.16 hours of idle, 0.13 hours of low speed, and 0.69 hours of cruise data that were not affected by high moisture levels in the sensors.

Fuel economy was assessed for each snowmobile based on available data. For the Arctic Cat T660, it was not possible to compare fuel economy estimated from the PEMS to the actual amount of fuel required to top off the fuel tank because the PEMS had to be disconnected during the scheduled roundtrip as a result of high moisture levels reaching the sensors. However, based on similar snowmobiles, the expected fuel economy is approximately 15 miles per gallon. For the Arctic Cat TZ1, fuel logs for a snowmobile of the same make and model operated in Yellowstone on similar routes indicate an average fuel economy of 14.4 mph. For the Ski Doo 600ACE snowmobile, the amount of fuel required to top off the tank was measured and found to be 3.8 gallons.

Estimates of second by second fuel use for the snowmobiles were not available from OBD because these vehicles do not have OBD. Therefore, the sensor array was used to measured MAP, RPM, and IAT. The mass flow through the engine is estimated using these dynamic data and static data for the engine, including engine displacement and number of strokes. Another parameter used in the calculation is the engine volumetric efficiency, which quantifies the relationship between the actual amount of air that enters the engine versus that calculated based only on displacement, revolutions per minute, and air intake pressure and temperature. Volumetric efficiency can be greater than one depending on where the pressure and temperature are measured. The engine volumetric efficiency of Arctic Cat T660 snowmobile was adjusted to 1.28 so the fuel economy was approximately equal to 15.0 mpg. The engine volumetric efficiency of Arctic Cat TZ1 was adjusted to 0.76 so the fuel economy was equal to the average snowmobile fuel economy of 65 fuel logs of the same model snowmobile as the one tested, which was 14.4 mpg. The engine volumetric efficiency of Ski Doo snowmobile was adjusted to 1.42 so that fuel use of the tested snowmobile was equal to the amount of actual fuel use (3.8 gallons).

Table10. Summary of Valid Data Distribution 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**		
Arctic Cat T660	0.16 (0)	0.13 (0.9)	0.69 (19.0)	7.2	27.4
Arctic Cat TZ1	0.32 (0)	0.24 (1.8)	1.11 (31.2)	7.4	28.0
Ski Doo	0.31 (0)	0.10 (0.6)	0.91 (28.6)	5.8	31.3
Totals and Weighted Means	0.79 (0)	0.47 (3.3)	2.71 (78.8)	7.0	29.0

Table 11 summarizes the mean emission rates for CO, HC, and NO_x for each snowmobile in each driving mode. Time-weighted means for each pollutant in each driving mode are also listed. The 95% confidence intervals for each pollutant for each snowcoach in different units for idle mode, low speed mode, and cruise mode are provided in Table 12, Table 13, and Table 14, respectively.

For the Ski Doo, the first attempt at data collection produced valid PEMS and engine sensor array data; however, the GPS data were not valid. Therefore, a second run was made, during which valid engine sensor array and GPS data were obtained, but the PEMS gas analyzer data were not valid. Therefore, there was not a simultaneous set of data from all three instruments. The GPS data are essential to estimating the speed of the vehicle. The PEMS and engine sensor array data are essential to estimating the mass per time emission rates from the tailpipe. Without GPS data, the speed of the snowmobile is not otherwise directly measured or observed. However, for the run in which there was simultaneous engine sensor array data, including engine RPM, and valid GPS data, a scatterplot was constructed of GPS-based speed versus engine RPM, as shown in Figure 16. The relationship between the two has a linear slope of 0.9999 and a coefficient of determination of 0.9855. Ideally, the slope would be identically equal to one and the coefficient of determination would be unity. However, despite some scatter in the data, the regression analysis indicates that engine RPM is a very good predictor of the GPS speed of the snowmobile. Therefore, data from the run with valid PEMS and engine sensor array data were used to estimate emission rates, and RPM was used to predict speed using the regression equation of Figure 18.

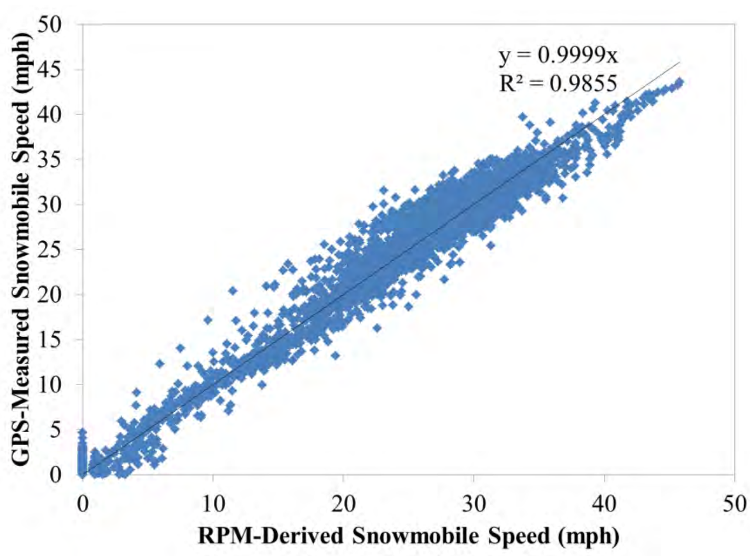

Figure18. Regression of the GPS-Measured Speed and the RPM-Derived Speed for the Ski Doo Snowmobile from the Run with Valid Engine RPM and Valid GPS Data

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Table11. Mass Emission Rates for the Three Driving Modes for Each Snowmobiles[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
Arctic Cat T660	CO	111	1869	584	34	392	123	17	336	105
	HC	4.0	67	21	4.3	50	15	2.1	42	13
	NO_x	0.35	5.9	1.8	15	169	53	18	359	112
Arctic Cat TZ1	CO	145	2017	630	240	2202	688	27	493	154
	HC	4.8	67	21	9.6	88	28	1.6	28	8.8
	NO_x	0.52	7.2	2.3	1.4	13	3.9	8.8	160	50
Ski Doo	CO	60	698	250	25	233	83	4.0	68	24
	HC	3.7	43	15	1.3	12	4.4	0.1	2.3	0.8
	NO_x	0.17	2.0	0.7	5.2	49	18	11	191	69
Time-Weighted Means	CO	105	1464	470	137	1276	401	17	310	98
	HC	4.2	57	19	6.4	61	19	1.2	19	7.2
	NO_x	0.35	4.9	1.6	5.5	58	19	12	221	72

[a] g/gal and g/kg results are calculated from the reported g/sec emissions, and fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon.

Table12. Mass Emissions Rates with 95% Confidence Intervals for the Idle Driving Mode [a]

Vehicle Measured	Species	Idle					
		mg/s		g/gal		g/kg	
		Mean	CI[b]	Mean	CI	Mean	CI
Arctic Cat T660	CO	111	19	1869	285	584	102
	HC	4.0	0.7	67	10	21	4
	NO_x	0.35	0.06	5.9	0.9	1.8	0.3
Arctic Cat TZ1	CO	145	8	2017	102	630	36
	HC	4.8	0.3	67	3	21	1
	NO_x	0.52	0.03	7.2	0.4	2.3	0.1
Ski Doo	CO	60	4	698	41	250	15
	HC	3.7	0.2	43	3	15	1
	NO_x	0.17	0.01	2.0	0.1	0.7	0.1
Time-Weighted Means	CO	105		1464		470	
	HC	4.2		57		19	
	NO_x	0.35		4.9		1.6	

[a] g/gal and g/kg results are calculated from the reported g/sec emissions, and fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

Table 13. Mass Emissions Rates with 95% Confidence Intervals for the low Speed Driving Mode [a]

Vehicle Measured	Species	Idle					
		mg/s		g/gal		g/kg	
		Mean	CI[b]	Mean	CI	Mean	CI
Arctic Cat T660	CO	34	5	392	50	123	18
	HC	4.3	0.6	50	6	15	2
	NO_x	15	2	169	21	53	8
Arctic Cat TZ1	CO	240	16	2202	128	688	46
	HC	9.6	0.6	88	5	28	2
	NO_x	1.4	0.1	13	1	3.9	0.3
Ski Doo	CO	25	3	233	24	83	9
	HC	1.3	0.1	12	1	4.4	0.4
	NO_x	5.2	0.5	49	5	18	2
Time-Weighted Means	CO	137		1276		401	
	HC	6.4		61		19	
	NO_x	5.5		58		19	

[a] g/gal and g/kg results are calculated from the reported g/sec emissions, and fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

Table14. Mass Emissions Rates with 95% Confidence Intervals for the Cruise Driving Mode [a]

Vehicle Measured	Species	Idle					
		mg/s		g/gal		g/kg	
		Mean	CI[b]	Mean	CI	Mean	CI
Arctic Cat T660	CO	17	1	336	15	105	6
	HC	2.1	0.1	42	2	13	1
	NO_x	18	1	359	16	112	6
Arctic Cat TZ1	CO	27	1	493	13	154	5
	HC	1.6	0.1	28	1	8.8	0.3
	NO_x	8.8	0.3	160	4	50	2
Ski Doo	CO	4.0	0.1	68	2	24	1
	HC	0.1	0.0	2.3	0.1	0.8	0.0
	NO_x	11	0	191	7	69	2
Time-Weighted Means	CO	17		310		98	
	HC	1.2		19		7.2	
	NO_x	12		221		72	

[a] g/gal and g/kg results are calculated from the reported g/sec emissions, and fuel consumption. The density of gasoline is assumed to be 2,791 g/gallon.

[b] CI = Confidence Interval. The number shown in this table is one half of the 95% confidence interval. The complete interval is mean±CI.

The CO emission rates on a gram per gallon basis for the three snowmobiles were typically highest at idle and lowest for the cruise mode. For example, at idle, the CO emission rates ranged from 700 to 2,020 g/gallon, with an average of 1,460 g/gallon. At cruise, the CO emission rates ranged from 68 to 490 g/gallon, with an average of 310 g/gallon.

The Arctic Cat TZ1 was found to have especially high CO emission rates compared to the other two snowmobiles. For example, at low speed, the TZ1 had an average CO emission rate of 2,200 g/gallon, which is nearly ten times greater than the rate for the Ski Doo and about four times higher than the rate for the T660. All of the results presented here are based on quality assured data, with any invalid data removed prior to the final analysis. The raw second by second data were inspected to determine whether there were any anomalies in the measurement that might account for the very high reported CO emission rate. For a well-functioning gasoline vehicle that operates near a stoichiometric air/fuel ratio, the typical exhaust composition includes approximately 14 vol-% CO_2, and typically less than 0.01 vol-% CO. However, during idle or low engine loads, there were data for which the exhaust CO_2 concentration was approximately 8 vol-% and the exhaust CO concentration was approximately 6 vol-%. Such data indicate that the engine may have been operating with insufficient air for complete combustion, also known as fuel-rich operation. It is possible that there was a malfunctioning in the system that governs the ratio of fuel and air for this particular vehicle. However, there is no evidence of a malfunction of the PEMS that would affect data quality for this set of measurements.

On a mass per fuel consumed (g/gallon) basis, the average CO emission rates for idle, low speed, and cruise were higher than the averages for the snow coaches. For example, the low speed average rate of 1,280 g/gallon for the snowmobiles is over 40 times greater than the average of 29 g/gallon for the snow coaches. However, because the snowmobiles consume about two thirds less fuel than a snow coach, the average low speed CO emission rate on a mass per distance (g/mile) basis for the snowmobiles is only about 15 times higher than for the snow coaches. If one considers that a snow coach can carry more people than a snowmobile, the emissions per passenger mile for the snow coach are likely to be substantially lower than for snowmobiles by an even larger ratio.

The HC emission rates for the snowmobiles were also substantially higher than those of the snow coaches. The average fuel-based HC emission rates range from 19 to 61 g/gallon among the operating modes, which is almost two orders-of-magnitude higher than the 0.5 to 0.8 g/gallon averages for the snow coaches. The snowmobile low speed and cruise average HC emissions rates of 1.2 to 6.4 grams per mile are substantially greater than the averages of about 0.2 g/mile for the snow coaches. The snowmobiles have much smaller and higher revving engines than the snow coaches, and thus it is not surprising that the CO and HC emissions rates would be higher.

The snowmobile NO_x emissions vary and are of approximately the same magnitude as the snow coach emissions when expressed on a mass per time or mass per distance basis. For example, the snowmobile average idle emission rate of 0.4 mg/s is only a factor of 4 lower than that for the snow coaches, whereas the average low speed and cruise emission rates of 5.5 g/mi and 12 g/mi, respectively, are higher than those of the snow coaches by approximately 15 percent to a factor of two. Thus, as an approximation, the NO_x emission rates are similar even though the snowmobiles have much smaller engines and carry fewer passengers.

The confidence intervals on the mean emission rates are narrow enough such that comparisons between different operating modes or between vehicles that differ by more than 10 to 40 percent are robust to uncertainty in the mean emission rates. For example, the idle emission rates for the Arctic Cat T660 are precise to within 20 percent, whereas the idle emission rates for the other two snowmobiles are precise to within 5 or 6 percent.

Bishop *et al*. (2006a), reported snowmobile fuel economy of 27 mpg, which is high compared to the observed fuel consumption for the Ski Doo and the maintenance log data for the TZ1. The snowmobile idle, low speed, and cruise emission rates reported by Bishop *et al*. (2006a) averaged 54 mg/s, 45 g/mi, and 14 g/mi for CO, 2.1 mg/s, 1.4 g/mi, and 0.94 g/mi for HC, and

0.30 mg/s, 2.2 g/mi, and 4.4 g/mi for NO_x, respectively. The average CO emission rate from the current study is approximately twice as high for idle, three times as high for low speed, and approximately the same for cruise. The cruise HC emission rate and the idle NO_x emission rate are approximately the same. However, the HC emission rates for idle and low speed, and the NO_x emission rates for low speed and cruise, are higher in the current study.

One of the challenges in making comparisons is that the vehicle sample size is very small. There can be substantial inter-vehicle variability even for the same year, make, and model of vehicle depending on factors such as accumulate engine hours or mileage, maintenance history, and whether there is a malfunction that can affect emissions. For example, the result here that the one 2011 Arctic Cat TZ1 that was measured has very high CO emissions does not necessarily imply that all 2011 Arctic Cat TZ1's have high CO emissions. On the other hand, the results as reported here have been checked for numerous data quality issues and are valid.

For some of the snowmobiles, the emission rate associated with the engine dynamometer certification test that demonstrated compliance with the applicable nonroad emission standard was reported in units of grams per kWh. The kWh refers to engine shaft output, which cannot be directly measured during in-use measurements of the entire vehicle chassis. The gram per gallon emission rates are based on the mass of pollutant emitted per volume of fuel consumed. For large engines operating at high load, the brake-specific fuel consumption (BSFC) is one gallon of fuel per 15.5 kWh. This value may be applicable to the larger diesel engines of the F450 and F550, but may not be applicable to the small gasoline engines of the snowmobiles. However, the actual BSFC for these latter engines may differ, and probably be higher, by 10, 20, or 50 percent. Thus, it is difficult to compare the PEMS measured emission rates for the vehicle chassis in real-world operation to the engine dynamometer emission rate. As an approximation, the fuel-based emission rate could be multiplied by gallon/(15.5 kWh) to arrive at an approximate estimate. Thus, for example, the average CO emission rate for cruise mode of 310 g/gallon would be equivalent to 20 g/kWh. However, if the small engine of the snowmobiles is less efficient, then the actual emission rate in g/kWh would be higher.

4.0 CONCLUSION

Eight over snow vehicles (OSVs) were measured during one week of data collection at Yellowstone National Park (YNP). These included five snow coaches and three snowmobiles. The measurements were conducted using a Portable Emissions Measurement System (PEMS) to measure tailpipe pollutant concentrations, either an engine sensor array or on-board diagnostic (OBD) data logger to record key engine parameter data, and a Global Positioning System (GPS) receiver to estimate vehicle speed. Measurements were completed successfully on all eight vehicles. Typically over 96 percent of the raw data passed nine quality assurance checks. The final quality assured data set included approximately 2 hours of data for each vehicle, based on a 32 mile round trip on a snow covered route. From these data, modal average emission rates were estimated for idle, low speed, and cruise.

The recent model year snow coaches were found to have relative low emission rates for CO, HC, and NO_x with the exception of a Chevrolet Express. The latter had very high CO emission rates during cruise, indicating that the engine may be struggling to provide enough power for sustained operation on snow. The two diesel snow coaches had low emission rates for NO_x and PM consistent with effective operation of the Selective Catalytic Reduction (SCR) NO_x control and Diesel Particulate Filter PM control systems.

The three snowmobiles were found, on average, to have much higher fuel-based CO emission rates than the snow coaches. The mass per distance CO emissions rates were also higher. On a per passenger basis, the comparison would likely be even more favorable for the snow coaches. To provide some perspective on this comparison, the converted snow coaches that are based on highway vehicles are certified to very stringent emission standards based on specific driving cycles. Other than the Express, which appeared to be operating well beyond the typical power range of the certification cycles, the other three converted vehicles appeared to be operating within engine loads not far beyond those of the certification tests. Thus, it is not surprising that the snow coach emission rates would be relatively low.

The smaller, higher revving engines of the snowmobiles appear to produce much higher CO and HC emissions per gallon of fuel consumed than the larger lower revving engines of the snow coaches. Higher revolutions per minute leads to less residence time in the combustion chamber during the power and exhaust strokes. During combustion, fuel is typically first partially oxidized to CO and then continues to oxidize to CO_2. However, if the residence time is too short, then there is not enough time for all of the CO to oxidize, leading to high uncontrolled 'engine-out' emissions of CO. If there are no downstream CO controls, such as an oxidation or three-way catalyst, then the uncontrolled CO emissions are emitted to the atmosphere. The HC emissions of the snowmobiles are also found to be substantially higher than those of the snow coaches. High uncontrolled engine-out HC emission rates are associated with incomplete combustion, but can be more sensitive to wall and crevice effects. These latter may be more pronounced for smaller cylinders. The NOx emission rates from the snowmobile were approximately of the same magnitude as those of the snow coaches.

Confidence intervals were estimated for each emission factor for each vehicle and operating mode. With the exception of some of the CO and HC emission rates of the diesel snow coaches, the emission rates are significantly greater than zero, and typically significantly differ from each other when comparing modes of operation for a given pollutant and vehicle. In cases where there were questions that an emission rate appeared to be very high, such as for CO emission rates for the Express or the snowmobiles, the data were rechecked. In addition to passing nine quality assurance checks, there was no evidence of measurement errors such as invalid sensor operation. Concurrent trends in exhaust gas concentrations between CO_2 and CO were consistent. For example, if the CO concentration went up, the CO_2 concentration went down, which is expected. Thus, the results reported here are deemed to be valid.

The snow coach fuel consumption estimates from OBD data agreed well with the amount of fuel required to top off the fuel tank. The snowmobile fuel economy was approximately 15 miles per gallon based on direct measurement for one snowmobile and detailed maintenance records for another. The PEMS-based fuel estimates for the snowmobiles are consistent with these data.

In comparison to previous measurements studies of snow coaches at YNP, the newer model year coaches and the rebuilt Bombardier were found to have lower average emission rates, as expected. However, the snowmobile CO emission rates in this study were higher than those of previous measurements. The HC and NO_x emission rates are approximately similar to those of previous measurements for some modes, but higher for others. The very high CO emission rates for one snowmobile in particular suggest that there could have been a malfunction that affected control of the air/fuel ratio for that vehicle, which could cause very high CO emissions. However, there was no specific evidence of a malfunction. Other factors that might account for high observe emission rates for a vehicle measured on a given day is that there can be inter-vehicle variability in emissions as a result of accumulated usage and maintenance practices, and differences in snow conditions could lead to different engine load. For example, the engine power needed to propel a vehicle through heavy wet snow may be different than that for well packed dry snow.

Overall, the results here based on field measurements are considered to be valid and to reflect the actual emissions of the measured vehicles as they occurred on the day of the measurements. This study was focused on providing emission factors to serve a near-term air quality analysis need. The variability in results among different vehicles in this study suggests that it is desirable to have a larger sample of vehicles from which to obtain a more robust average rate. Furthermore, because snow vehicle fuel economy is likely to be sensitive to the conditions of the snow cover on the selected route, it would be useful to conduct further research to quantify how much the modal average emission rates vary under a variety of road surface conditions.

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