Winter Motor-Vehicle EMISSIONS *in* Yellowstone National Park

Against a backdrop of lawsuits, a new study shows that reductions in snowmobile emissions highlight the need for the snowcoach fleet to modernize.

GARY A. BISHOP
DANIEL A. BURGARD
THOMAS R. DALTON
DONALD H. STEDMAN
UNIVERSITY OF DENVER
JOHN D. RAY
NATIONAL PARK SERVICE

Air-pollution emissions from off-road recreational vehicles have risen in national importance, even as emissions from these vehicles have declined (*1*). Yellowstone National Park in the U.S. has a long history of balancing tourist access and ecosystem protection and has become a battleground over snowmobile usage. Approximately 3 million people visit the park annually, but <5% of them visit during winter (*2*). Historically, winter motorized access has been allowed only over groomed roads by snowcoach or 2-stroke snowmobile. The snowcoach fleet includes a number of vintage Bombardiers (see photo on the next page) and an assortment of modern, wheeled vans, buses, and large sport utility vehicles that have been converted to over-snow use with various track and ski systems (*3*).

GARY BISHOP

Increased snowmobile visits in the mid-1990s led to a series of lawsuits against the National Park Service (NPS). In 1997, the Fund for Animals led a group that sued the park to impose a ban on all wintertime road grooming that would effectively eliminate all winter motorized access. NPS settled the suit in November 2000 via an environmental impact study decision that only allowed snowcoach use (*4*, *5*). Snowmobiling interests successfully counter-sued, winning a court-ordered supplemental environmental impact study (SEIS). The study recommended replacing the snowmobiling ban with daily entrance limits and guided tours, and it required the use of new-technology snowmobiles—essentially banning 2-stroke snowmobiles (*6*). Each side continued the fight, filing separate suits in different U.S. District Courts. The snowmobile ban was briefly reinstated by a Washington, D.C., judge in 2003, only to be overruled by a Wyoming judge (*7*, *8*). While additional studies are under way, NPS instituted a set of temporary wintertime rules, similar to those required under SEIS, to be enforced for 3 winters beginning with the 2004–2005 season (*9*).

Over the snow and through the woods. A vintage Bombardier snowcoach showing the heated exhaust probe inserted in the passenger-side exhaust pipe.

Consequently, what had been a fleet of unregulated 2-stroke snowmobiles and vintage snowcoaches has transitioned to guided groups of modern 4-stroke snowmobiles and a mix of older and newer snowcoaches. Winter on-road emissions and air quality have improved. In 1998–1999, ~87,000 entries emitted ~570 t of carbon monoxide (CO) and 670 t of hydrocarbons (HC), mostly from 2-stroke snowmobiles (*10*). With fewer entries in 2004–2005, ambient-air monitors at the park's west entrance and at the Old Faithful geyser site have recorded improvements in air quality that show that winter mean CO and particulate matter (PM) levels are now comparable to summer levels (*11*).

In-use emissions data from snowcoaches and snowmobiles are scarce. Researchers with the University of Denver measured 2-stroke snowmobile emissions at the west entrance gate in 1998–1999 (*10*, *12*). Several researchers have previously reported in-use and chassis dynamometer measurements from 2- and 4-stroke snowmobiles and a single snowcoach by using a simulated load (*13–17*). This current study, which was designed to compare in-use emissions from the new 4-stroke snowmobiles with previous data and to collect as much snowcoach emissions data as possible, illustrates the changes now occurring in the park (*18*).

Snowcoaches

During February 7–18, 2005, 9 Yellowstone snowcoaches (8 gasoline and 1 diesel) were each instrumented with a portable emissions monitoring system (PEMS) to collect emissions and engine data during their daily round-trip excursions into the park, to yield >34 h and 500 mi of valid data (see Supporting Information online; *19*). Data collected included CO, CO_2, HC (from gasoline-powered snowcoaches only, corrected for the known discrepancy between data from nondispersive IR spectrometers and flame ionization detectors), oxygen, nitric oxide (NO), PM (diesel-powered snowcoach only, light-scattering data), engine-intake mass airflow (reported directly by the engine computer or calculated from engine rpm, intake air temperature, and intake manifold pressure), longitude, and latitude (*20*).

The snowcoaches can be divided into 3 engine/emissions-control groupings: a diesel-conversion van with a direct-injection, turbocharged engine and no after-treatment; post-1990 on-road vans converted for winter use and an upgraded Bombardier, all with modern, gasoline, closed-loop, computer-controlled, fuel-injected engines with 3-way catalytic converters; and a vintage Bombardier with a carbureted gasoline engine and no after-treatment. The reported emission results have a precision of ~±10% (*20*). Variations in individual vehicle emissions under diverse driving conditions and vehicle-to-vehicle differences are a much greater source of variance.

The diesel-conversion van (a 2000 Ford E350) provided the simplest snowcoach-emission picture. Low CO and HC emissions are typical for compression-ignition engines. Although we did not measure the HC emissions, it is expected that they mirror the measured low (<8 g/mi) CO emissions (*21*). For the very high engine loads required to plow through the snow, it is also not a surprise that the van's 49 g/mi NO_x emissions (NO measured, reported as mass of NO_2) are the highest for any of the vehicles. PM emissions were low at 120 mg/mi.

These vans operate under extreme snow and track loads. For example, all of the converted on-road vans are expected to achieve ~15 mpg for on-road fuel economy, but the same vehicles had a time-weighted measurement average for good snow conditions of 3.7 mpg. Diesel-powered coaches would usually be a natural choice for this type of high-load environment, but the low overnight temperatures necessitate the extra expense of garaging these vehicles or heating the engine block and fuel tank overnight.

With fewer entries in 2004–2005, ambient-air monitors at the park's west entrance and at the Old Faithful geyser site have recorded improvements in air quality.

A tightly specified dynamometer cycle was used to certify the post-1990 gasoline-powered vans for emissions limits of ≤5, ≤0.41, and ≤1.1 g/mi for CO, HC, and NO_x, respectively. The low-idle emissions measured (4–150 mg/s) suggest that most of these engines may still meet those original standards. However, the operating loads produced by the tracks and snow conditions ensure that these engines are rarely operated in an on-cycle situation.

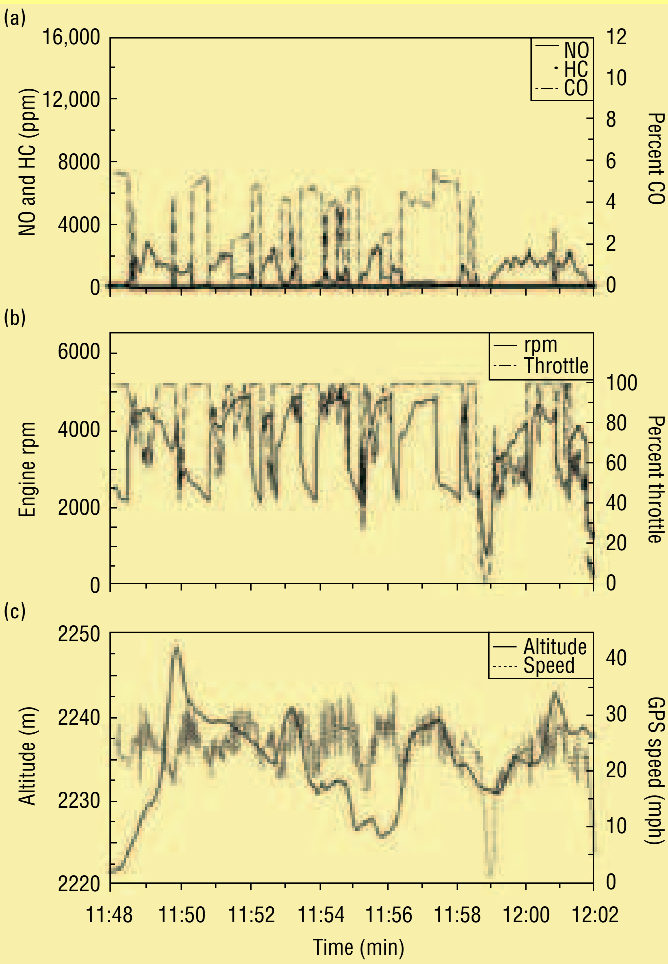
When conditions force a vehicle into an operating mode that is outside the federal-certification-test-cycle conditions, it is said to be in a "commanded-enrichment" or "off-cycle" mode. Many off-cycle excursions do not result in excessive emissions. However, rich engine operation in these vans only occurs during off-cycle driving. The observed emissions alternate between periods of low (on-cycle) and very high (off-cycle) driving for these snowcoaches. This accounts for the very high and widely varying over-snow emissions observed, with overall averages of 5–600, 1–34, and 1–26 g/mi for CO, HC, and NO_x, respectively (*18*).

Figure 1 shows this alternating behavior with data from a 2001 Chevrolet snowcoach (MT416, 5.7-L, fuel-injected V8 engine) as it approaches Old Faithful. The vehicle alternates between regions of "leaner" and "richer" operation because of a lack of power. The engine-rpm trace indicates periods of operation in second gear (higher rpm values) and third gear (lower rpm), and this is particularly noticeable during the first 10 min. Each time the transmission shifts into third gear, a large commanded-enrichment CO peak is observed (Figure 1a). The emissions trace indicates, by means of low CO and high NO concentrations, that when the transmission is in second gear the operation is lean, except for two obvious occasions. Just before 11:51 and at 11:57, commanded enrichment is apparent even when the vehicle is in second gear. This vehicle had overall average emissions toward the lower end of the observed range (CO, HC, and NO_x emissions of 84, 0.9, and 26 g/mi, respectively), an indication that most of its operating time is spent in the lean combustion region.

FIGURE 1

Second-by-second (a) emissions, (b) engine, and (c) vehicle data collected during a 14-min (5.6-mi) segment for snowcoach MT416 as it neared Old Faithful

For this segment, the average CO, HC, and NO_x emissions were 310, 1.2, and 28 g/mi, respectively.

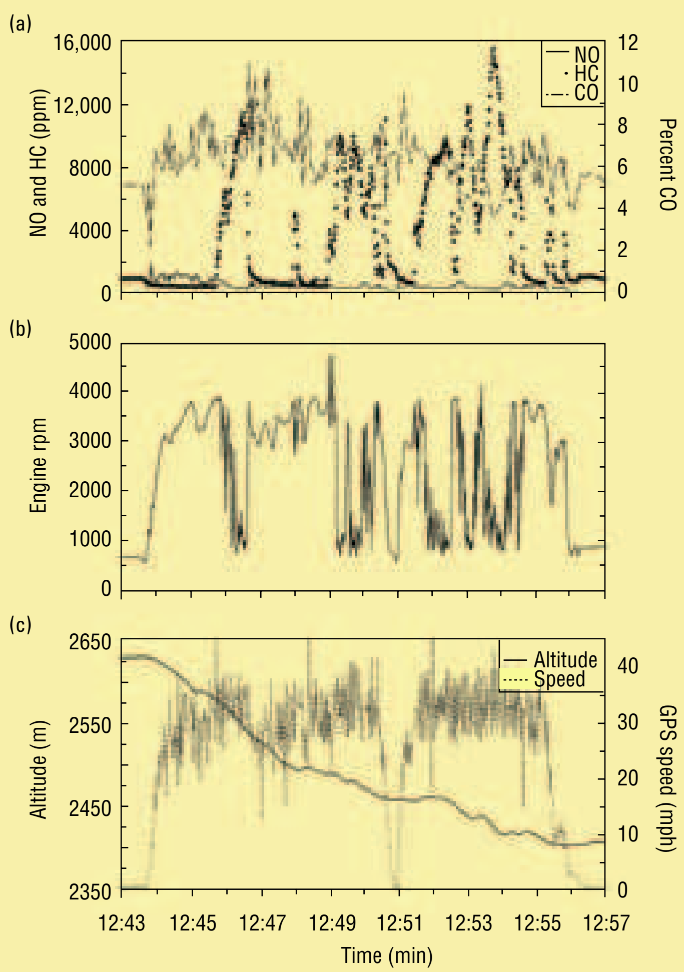


All of the snowcoaches tested in this group had an operational load point that, when exceeded, caused them to alternate between leaner and richer operation. Depending on the vehicle's power-to-weight ratio and the snow conditions, this load point can change from day to day. How the vehicles are driven also impacts the amount of time spent in rich operation. If we define off-cycle/commanded-enrichment operation as any time that the tailpipe CO level is >3%, then the time-weighted off-cycle operations for these gasoline snowcoaches averaged 20% for the inbound trips and 29% for the outbound. The outbound trips had longer periods of uninterrupted high-speed driving, and this increased emissions. Since the power-to-weight ratio of the vehicle is so important, one, perhaps unexpected, conclusion is that gasoline-powered vehicles that are to be converted in winter into snowcoaches need to be equipped with the largest engine available. For example, MT416's sister van MT419 is equipped with an 8-L engine, and the extra power enables it to easily maintain speed in third gear. This results in lower emissions and better fuel economy.

FIGURE 2

Second-by-second (a) emissions, (b) engine, and (c) vehicle data collected during a 14-min (5.7-mi) segment for snowcoach B709 in the Canyon area

Throttle position information was not available from this snowcoach. For this segment, the average CO, HC, and NO_x emissions were 490, 74, and 4.9 g/mi, respectively.



The last snowcoach group is represented by a vintage Bombardier (B709, 5.7-L, carbureted V8 engine) that had the highest CO and HC emissions of any of the coaches (CO, HC, and NO_x emissions were 630, 50, and 7.7 g/mi, respectively). Figure 2 shows data from this snowcoach as it traverses a downgrade in the Canyon area. The HC emissions are so high that rich-cylinder misfires—too much fuel, not enough air—inadvertently help to lower the CO emissions because fuel is not combusted during these events (Figure 2a). This engine is only low-emitting when turned off, and simply adding emissions after-treatment will do little to reduce emissions. One solution for these vintage coaches is to upgrade the power train with a modern fuel-injected engine. This was done for one of the snowcoaches (Delacy, 5.3-L, fuel-injected, V8 engine) in our group.

Snowmobiles

Concurrently with the snowcoach study, a remote emissions analyzer collected 965 tailpipe measurements (Table 1) from snowmobiles entering and leaving the park's west entrance. These data provide fuel-based mass emissions for CO, HC, and NO (*22*). The snowmobile rental fleet consists of modern, fuel-injected, 4-stroke touring sleds with no exhaust after-treatment.

Snowmobiles show large reductions in CO and HC emissions, which complement observations of reduced visible exhaust plumes, odor, and noise as well as improved fuel efficiency.

Three manufacturers, Arctic Cat, Polaris, and Bombardier (Ski-Doo), sell models that claim to meet NPS's best-available-technology (BAT) requirements (*23*). Snowmobile make, engine type, and model year were assigned from the video record. When compared with the 1999 data, they show large reductions in CO (>60%) and HC (>96%) emissions, which complement observations of reduced visible exhaust plumes, odor, and noise as well as improved fuel efficiency. The Arctic Cat and Polaris 4-stroke snowmobiles emitted roughly half as much CO and had lower HC emissions than the Ski-Doo snowmobiles (*18*). These measurements suggest that the Ski-Doo snowmobiles may not meet the NPS BAT requirements (*23*). No statistically significant differences in emissions were observed by model year. Snow, dust, and water vapor do not affect the validity of remote-sensing results. When excessive, snow and dust cause more invalid readings because of the scattering and absorption of the source light on the way to the detector.

TABLE 1

1999 and 2005 snowmobile emissions measurements and their standard errors of the mean

The grams-per-kilogram calculations assume a carbon mass fraction of 0.86 in the fuel. 1999 data are in the last column.

Type of engine	4-stroke		2-stroke		
Measurement	**Entrance (2005)**	**Exit (2005)**	**Entrance (2005)**	**Exit (2005)**	**Entrance (1999)**
Mean CO/CO_2	0.16 ± 0.01	0.19 ± 0.01	0.54 ± 0.07	0.78 ± 0.1	0.69 ± 0.01
Mean g-CO/kg	240 ± 6	240 ± 7	370 ± 35	550 ± 50	380 ± 4
Samples	589	362	14	9	1018
Mean HC/CO_2	0.006 ± 0.001	*a*	0.23 ± 0.02	0.16 ± 0.01	0.27 ± 0.01
Mean g-HC/kg	28 ± 2		480 ± 25	370 ± 13	480 ± 3
Samples	489		14	9	1018
Mean NO/CO_2	0.009 ± 0.001	0.017 ± 0.001	*b*	*b*	*c*
Mean g-NO/kg	15 ± 0.5	25 ± 1			
Samples	587	359			
Mean speed (mph)	9.6 ± 0.1	15.5 ± 0.2	8.8 ± 0.9	13.3 ± 2.1	*c*
Mean acceleration (mph/s)	0.4 ± 0.2	0.8 ± 0.2	0.2 ± 0.9	0.7 ± 2	
Samples	341	215	7	4	

[a] Exit HC measurements were unavailable for all the 4-stroke engines because of snow spray.
[b] The 2-stroke NO measurements were obscured by interferences from large emissions of unburned fuel.
[c] Speed and acceleration measurements were not collected in 1999.

If we assume a conservative fuel economy of 18 mpg for the 4-stroke snowmobiles, then our measured emission averages are ~37, 4.5, and 3.2 g/mi for CO, HC, and NO_x(measured as NO, reported as NO_2), respectively. These same snowmobile engines with complete, modern emission-control systems can be found in small cars that meet the U.S. EPA Tier 1 standards of 3.4, 0.41, and 0.4 g/mi, respectively. Therefore, snowmobile emissions could possibly be further reduced by a factor of ~5. Because of their significantly greater power-to-weight ratio than the snowcoaches, the 4-stroke snowmobiles are less likely to enter a commanded-enrichment regime.

To test the applicability of our low-speed entrance measurements to overall park operation, we instrumented a single 2002 Arctic Cat 4-stroke snowmobile with the same PEMS unit used for the snowcoaches and collected emissions data from a variable-speed 2.3-mi drive (average 28.2 mph, maximum 42.0 mph). CO and HC emissions were greatest during startup and idle, and CO emissions were not observed to increase with speed as previously reported (*14*). Overall CO, HC, and NO_x emissions during the drive were measured at 17, 1.9, and 9.7 g/mi, respectively, and the fuel economy was 21.9 mpg. Emissions ratios measured directly by the PEMS unit spanned those collected by remote sensing in the gate area.

Emissions comparison

By combining the emissions data with winter-visitor

TABLE 2

Comparison of snow-vehicle emissions

In 1999, 62,878 snowmobiles entered the park, with 76,271 passengers (1.2 passengers/snowmobile). In 2005, 18,364 snowmobiles entered with 24,049 passengers (1.3 passengers/snowmobile), and 2021 snowcoaches entered with 17,218 passengers (8.5 passengers/snowcoach) (*2*). We have assumed fuel economies of 13 mpg for 2-stroke and 18 mpg for 4-stroke snowmobiles (*4*). All data are from 2005, except mean 2-stroke snowmobile values. NO_x is measured as NO, reported as NO_2.

	Snowmobile emissions (g/mi/passenger)				Snowcoach emissions (g/mi/passenger)		
Pollutant	**Mean 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	4.1	0.4	2.8	0.2	0.9

statistics and fuel-economy estimates for the Yellowstone snowmobile fleet, we can estimate g/mi/passenger emissions (*2*). Table 2 shows that mean CO and HC emissions per passenger have dropped with the introduction of 4-stroke snowmobiles. Although NO emissions could not be measured from the 2-stroke snowmobiles, we can reasonably assume from other research that 4-stroke snowmobiles have increased per-passenger NO emissions (*14*). The comparison between snowmobile and snowcoach contributions shown in Table 2 could swing from one extreme to the other if the actual snowcoaches in the fleet were all vintage (B709) or upgraded (Delacy) Bombardiers or if use of Ski-Doo snowmobiles were to increase disproportionately without enforcement of the BAT emission rules.

With the assumption that each vehicle travels 104 mi/trip, the mean emissions given in Table 2 would have resulted in 130, 11, and 11 t of CO, HC, and NO_x being emitted last winter from the measured winter vehicles. However, the snowcoaches measured do not perfectly represent the average in-use fleet. A larger percentage of vintage Bombardiers still operate in the park than represented in the mean weighting in Table 2. This would result in higher CO and HC and lower NO emissions/passenger. The numerical results above are for the measured vehicles under the (generally good) conditions that we encountered. The professional snowcoach drivers indicated that, during very heavy snow conditions, power demand and fuel consumption both significantly increase. On the basis of the results of this study, these conditions could be expected to lead to as much as a further 5-fold increase in CO and HC emissions.

Remarkably, modern snowmobile HC emissions are down by a factor of >12/vehicle and CO emissions by a factor of >2. The measured snowcoaches emit significantly more per mile than the snowmobiles. Measured snowcoach emissions of CO, even when calculated per passenger mile, now exceed modern snowmobile emissions. If lower emissions are deemed necessary, both fleets' emissions could be further reduced by forcing snowcoach retirement or upgrades and by requiring snowmobiles to comply with current on-road vehicle-emissions standards.

Acknowledgments

The authors gratefully acknowledge support from NPS as part of cooperative agreement H2350042097. We appreciate the assistance of Mary Hektner, Kevin Schneider, Bob Seibert, the Mammoth maintenance crew, and the west-entrance employees, all of NPS; Michal Vojtisek-Lom of Clean Air Technologies, Inc.; Todd Scott and Dejan Covac of Xanterra Parks and Resorts; and Scott Carsley and Don Perry of Alpen Guides.

Gary A. Bishop is a research engineer, Daniel A. Burgard and Thomas R. Dalton are research assistants, and Donald H. Stedman is a professor of chemistry at the University of Denver. John D. Ray is an atmospheric chemist with NPS. Address correspondence to Bishop at the Department of Chemistry and Biochemistry, University of Denver, Denver, CO 80208 (gbishop@du.edu).

References

(1) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. Emissions Reductions as a Result of Automobile Improvement. *Environ. Sci. Technol.* **2003**, *37*, 5097–5101.

(2) National Park Service Public Use Statistics Office, www2.nature.nps.gov/mpur/index.cfm.

(3) Bombardiers are named after Joseph-Armand Bombardier, who has the distinction of being the founding father of both the snowcoach and the snowmobile, http://en.wikipedia.org/wiki/Joseph-Armand_Bombardier.

(4) National Park Service. Winter Use Plans: Final Environmental Impact Statement, for the Yellowstone and Grand Teton National Parks and John D. Rockefeller, Jr., Memorial Parkway, Vol. 1, 2000; www.planning.nps.gov/document/yellwinterusevol1.pdf.

(5) National Park Service. Record of Decision: Winter Use Plans for the Yellowstone and Grand Teton National Parks and John D. Rockefeller, Jr., Memorial Parkway, 2000; www.planning.nps.gov/document/yellrodwinteruse.pdf.

(6) National Park Service. Winter Use Plans: Final Supplemental Environmental Impact Statement for the Yellowstone and Grand Teton National Parks and John D. Rockefeller, Jr., Memorial Parkway, 2003; www.nps.gov/grte/winteruse/fseis/intro.htm.

(7) U.S. District Court for the District of Columbia, Dec 16, 2003, ruling; www.nps.gov/yell/planvisit/winteruse/12_16opinion.pdf.

(8) U.S. District Court for Wyoming, Feb 10, 2004, ruling; www.nps.gov/yell/planvisit/todo/winter/brimmer_order.pdf.

(9) National Park Service. Temporary Winter Use Plans Environmental Assessment, 2004; www.nps.gov/yell/planvisit/winteruse/tempwinteruseea8-18.pdf.

(10) Bishop, G. A.; Morris, J. A.; Stedman, D. H. Snowmobile Contributions to Mobile Source Emissions in Yellowstone National Park. *Environ. Sci. Technol.* **2001**, *35*, 2874–2881.

(11) Ray, J. D.; Bishop, G. Poster Presentation at the Fall National Atmospheric Deposition Program Technical Meeting, 2005, Jackson, WY.

(12) Bishop, G. A.; et al. An In-Use Snowmobile Emission Survey in Yellowstone National Park. *Environ. Sci. Technol.* **1999**, *33*, 3924–3926.

(13) Snook-Fussell, L. M. Carbon Monoxide Exposure by Snowmobile Riders: Emissions Pose Potential Risk. *Park Sci.* **1997**, *17*, 7–10.

(14) White, J. J.; Carroll, J. N.; Haines, H. E. Emissions from Snowmobile Engines Using Bio-Based Fuels and Lubricants; Society of Automotive Engineers; *Soc. Automot. Eng.* **1998**, Paper No. 972108.

(15) Wright, C. W.; White, J. J. Development and Validation of a Snowmobile Engine Emission Test Procedure; Society of Automotive Engineers; *Soc. Automot. Eng.* **1998**, Paper No. 982017.

(16) Lela, C. C.; White, J. J. *Laboratory Testing of Snowmobile Emissions*; Southwest Research Institute Report to Yellowstone National Park and Howard Haines, SWRI No. 08.05486, 1998; http://deq.mt.gov/cleansnowmobile/publications/Reports/EmissionsfromSnowmobileEngines.pdf.

(17) Lela, C. C.; White, J. J.; Carroll, J. N. *Determination of Snowcoach Emission Factors*; Southwest Research Institute Report to the Wyoming Department of State Parks & Cultural Resources, SWRI No. 08.05053, 2001.

(18) Fuel Efficiency Test Data, www.feat.biochem.du.edu.

(19) Vojtisek-Lom, M.; Allsop, J. E. Development of Heavy Duty Diesel Portable, On-board Mass Exhaust System with NO_x, CO_2, and Qualitative PM Capabilities; Society of Automotive Engineers; *Soc. Automot. Eng.* Paper No. 2001-01-3641, 2001.

(20) Vojtisek-Lom, M.; Cobb, J. T., Jr. On-Road Light-Duty Vehicle Emission Measurements Using a Novel Inexpensive On-Board Portable System. In *Proceedings of the 8th CRC On-Road Vehicle Emissions Workshop*; San Diego, 1998; www.crcao.org.

(21) Heywood, J. B. *Internal Combustion Engine Fundamentals*; McGraw-Hill: New York, 1988.

(22) Bishop, G. A.; Stedman, D. H. Measuring the Emissions of Passing Cars. *Acc. Chem. Res.* **1996**, *29*, 489–495.

(23) Yellowstone National Park. Snowmobiles Meeting Yellowstone and Grand Teton National Parks' BAT Requirements; www.nps.gov/yell/planvisit/todo/winter/batlist_current.htm.

File: 041506EST_SI

Supporting Information for Bishop, G. A., et al. Winter Motor-Vehicle Emissions in Yellowstone National Park *Environ. Sci. Technol.* **2006**, *40*, 2505–2510.

Second-by-second emissions data were collected from nine in-use snowcoaches (Table S1) with a commercially-available Clean Air Technologies International, Inc. Universal Montana portable on-board emissions monitoring system (PEMS) (*1*). Gram/sec emissions were calculated from the combination of emission concentrations and exhaust flow derived from the intake mass airflow (*2*). The PEMS was installed inside each coach and the sample lines; power and GPS receiver lines were routed via windows near the analyzer and tailpipe. Power was taken either from the 12V cigarette lighter outlet, or from a power cable run from the battery in the engine compartment. The tailpipe probe and sample line were wrapped in oversized foam pipe insulation and warmed with a battery powered fan that continuously passed warm cabin air down the inside of the pipe insulation. The data were stored to a compact flash-memory card and 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). Second-by-second data were screened to remove measurements adversely affected by inlet and outlet flow problems.

Only two of the nine coaches were garaged overnight—the NPS diesel van and the upgraded Bombardier (Delacy). The remaining coaches were all parked in a wooded area at the end of the plowed road. We generally spent 2–3 h with each coach the night before its use to install and calibrate the analyzer. Then we removed the analyzer and the sampling lines to store them at room temperature overnight. We arrived early the next morning to reinstall and allow the analyzer to warm-up along with the coach. The coach's schedule each day was warm-up from 7 – 8 a.m., depart the park entrance around 8:30 a.m., and arrive at destination for lunch around noon. After an hour and a half break, the return trip commenced at 1:30 p.m. and arrived back at the entrance between 5–6 p.m. An operator accompanied the analyzer during each trip.

The remote sensor used in this study has been fully described elsewhere and is composed of a combination of nondispersive IR optics and a dispersive UV monochromator capable of measuring ratios of CO, HC, and NO emissions to CO_2 in <1 sec from passing vehicles (*3*). Measurements were collected at the entrance to the park from West Yellowstone, MT (elev. 2020 m) on the mornings of Thursday, Feb. 10, through Tuesday, Feb. 15, and the morning of Thursday, Feb. 17, between 7:00 a.m. –12:00 p.m. Afternoon measurements were collected at the entrance between 1:30–5:00 p.m on Thursday, Feb. 10, through Wednesday. Feb. 16. The source, detector, and monochromator were placed on insulating pads on top of the snow ~6 m beyond the park service attendant booths. Emission ratios along with speed and acceleration were measured for each snowmobile as it entered or left the park. The sampling beam was angled ~30° to the path of travel to help ensure complete beam blockage. A 1-sec sample of exhaust was monitored at the rear of each sled using the same standard software as automobiles. A video camera photographed the front cowling of each tested sled, which were then read for snowmobile engine type (4-

or 2-stroke), make, and model year. The support equipment was housed inside an unused, heated attendant booth. The 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).

Table S1. Snow coach sampling dates, vehicle information and route summary.

Vehicle Date sampled	Year Make Type	VIN[a] Engine Fuel Type	Track type Entrance	Hours (Miles Sampled)	Destination Distance (miles)
NPS 2/7–2/8/05	2000 Ford E350 Van	1FBSS31F3YHB26376 DI 7.3-L V-8 Turbo Diesel	Mat-Trax North	6.3 (107)	Loop of park 145
SB163 2/15/05	1992 Chevrolet Van	2GAGG39K0N4165176 TBI 5.7-L V-8 Gasoline	Snowbuster North	6.0 (83.6)	Round trip to Old Faithful 103
SB164 2/9/05	1992 Chevrolet Van	2GAGG39K1N4142358 TBI 5.7-L V-8 Gasoline	Snowbuster North	5.9 (78.0)	Round trip to Old Faithful 103
SB165 2/12/05	1991 Chevrolet Van	2GJGG39K3M4515530 TBI 5.7-L V-8 Gasoline	Snowbuster North	4.0 (69.6)	Round trip to Old Faithful 103
SB166 2/13/05	1991 Chevrolet Van	2GJGG39K8M4513787 TBI 5.7-L V-8 Gasoline	Snowbuster North	3.6 (42.8)	One way to Old Faithful 52
MT416 2/14/05	2001 Chevrolet Van	1GAHG39R111132819 CPI 5.7-L V-8 Gasoline	Mat-Trax North	2.9 (32.9)	One way to Old Faithful 52
MT419 2/11/05	2001 Chevrolet Van	1GAHG39G811211760 MFI 8.1-L V-8 Gasoline	Mat-Trax North	0.6 (6.0)	One way to Old Faithful 52
DeLacy 2/18/05	2002 Engine Bombardier	ZGCEC19T021214428 MFI 5.3-L V-8 Gasoline	Twin Tracks West	3.5 (60.9)	Round trip to Old Faithful 63
B709 2/10/05	2001 Engine Bombardier	Carbureted 5.7-L V-8 Gasoline	Twin Tracks North	1.8 (22.7)	Round trip to Canyon 70

[a]Vehicle identification number

Table S2. Summary of all the valid second-by-second data collected for each coach.

HC data were only collected for the gasoline vehicles and the PM data only from the diesel coach. NA = not available.

Vehicle	Sampled		Mean speed (mph)	Fuel use (mpg)	Emissions (g/mi)			
	Hours	Miles			CO	HC	NO_x	PM
NPS Van	6.3	107.0	17.0	3.0	7.2	NA	49	0.12
SB163	6.0	83.6	14.1	2.9	600	7.2	26	NA
SB164	5.9	78.0	13.2	3.1	460	5.8	19	NA
SB165	4.0	69.6	17.5	5.0	310	5.5	16	NA
SB166	3.6	42.8	11.9	2.9	600	34	25	NA
MT416	2.9	32.9	11.4	2.5	84	0.93	26	NA
MT419	0.6	6.0	10.5	3.5	9.3	1.4	16	NA
Delacy	3.5	60.9	17.5	6.8	5.3	0.97	1.4	NA
B709	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

Table S3. Summary of measurements by make for only 4-stroke powered snowmobiles and standard errors of the mean.

The exit HC measurements were unavailable because of excessive noise caused by snow spray. The calculation of grams per kilogram assumes a carbon mass fraction of 0.86 in the fuel.

Measurement	Entrance			Exit		
	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 gCO/kg	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	NA	NA	NA
Mean gHC/kg	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 gNO/kg	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

References

(1) Vojtisek-Lom, M.; Allsop, J. E. *Soc. Auto. Eng.* 2001-01-3641, 2001.
(2) Vojtisek-Lom, M.; Cobb Jr., J. T. *On-road light-duty vehicle emission measurements using a novel inexpensive on-board portable system*, in the Proceedings of the eighth CRC on-road vehicle emissions workshop, CRC: San Diego, 1998.
(3) Bishop, A.; Stedman, D. H. *Acc. Chem. Res.* **1996**, *29*, 489.