Snowmobile Contributions to Mobile Source Emissions in Yellowstone National Park

GARY A. BISHOP,*
JEROME A. MORRIS,† AND
DONALD H. STEDMAN
Department of Chemistry and Biochemistry, University of Denver, Denver, Colorado 80208

Increases in the number of winter visitors to Yellowstone National Park during the past decade have raised concerns over the environmental impacts of snowmobiling in the park. During the 1998−99 season, more than 62000 snowmobile and 1300 snow coach trips entered the park. Using the University of Denver's vehicle exhaust remote-sensing equipment, 1385 measurements of carbon monoxide (CO) and hydrocarbon (HC) emissions were collected from in-use snowmobiles at the west and south entrances to the park. Overall means of 392 ± 4 g CO and 237 ± 1 g HC were observed per kilogram of fuel consumed. In addition, using an ultraviolet monochromator, 460 measurements of toluene emissions were collected with a mean of 39 ± 1 g toluene/kg of fuel. Using these data, a mobile source emissions inventory based on fuel use for Yellowstone National Park shows that snowmobiles account for 27% of the annual emissions of carbon monoxide and 77% of annual emissions of hydrocarbons using an equivalent best estimate for the summer mobile source emissions. Use of oxygenated fuels in snowmobiles was found to reduce CO emissions by 13.2 ± 6.5% without an observed effect on HC emissions. Liquid-cooled sleds were found to have HC emissions 9.5 ± 2.2% higher than those from fan-cooled sleds because of the increased intake and exhaust port sizes required in the larger liquid-cooled engines, which increases blowby in the 2-stroke engines.

Introduction

Yellowstone National Park encompasses more than 2.2 million acres in the northwest corner of Wyoming and southern portions of Montana. The park is extremely popular, and had more than 4 million visitors in 1999. The park operates a summer session and a winter session: the winter session usually runs from mid-December to mid-March. During this period, access to the park is limited to foot travel (snowshoes/skis), snow coaches, and snowmobiles (sleds), with snowmobiles being the preferred choice. Snowmobile usage was first encouraged by the National Park Service during the early 1960s and has grown along with the popularity of Yellowstone. During the 1992−93 season more than 77000 snowmobile visits exceeded original growth projections made in 1990 for the year 2000 (*1*). The numbers have since declined into the low 60 thousands (*2*).

The snowmobiles used in Yellowstone are manufactured and marketed in the U.S. by Arctic Cat, Bombardier (Ski-Doo), Polaris, and Yamaha. They are powered with 2-stroke liquid- or fan-cooled engines ranging in size from a 340 cm^3 twin-cylinder engine to 1-L triple-cylinder engines. These engines provide high power outputs but large amounts of blowby (the exhaust port and intake port are open at the same time), which contributes to excess exhaust emissions and poor fuel economy (*3*). All current sleds utilize direct oil-injection systems and a transmission consisting of a centrifugal clutch (which is very switch like, as the engine is either loaded or unloaded) and a belt-driven track. The majority of sleds entering the park are rentals obtained in the neighboring towns, and the west entrance to the park located next to West Yellowstone, MT accounts for more than 70% of the snowmobile entries (*1*). The West Yellowstone rental fleet is a modern fleet, because all of the large rental operators replace their fleets on a yearly basis.

The lack of emission measurements on snowmobiles and absence of realistic comparisons with other mobile-source emissions has fostered a number of unlikely comparisons in an attempt to eliminate snowmobiles from the park (*1*). This is largely due to the fact that snowmobiles have not been regulated by the Environmental Protection Agency and robust in-use emissions research data are limited. As part of a settlement to a 1997 lawsuit, the National Park Service prepared an environmental impact statement detailing alternatives which attempt to address Yellowstone's winter visitation issues (*1*). The preferred alternative of this report would phase out the use of snowmobiles by visitors within Yellowstone National Park and require the use of snow coaches for wintertime access.

Using the University of Denver's nondispersive infrared remote sensor fuel efficiency automobile tests (FEAT), we first surveyed a large in-use fleet of snowmobiles at the park's west entrance in 1998 (*4*). There we found large emissions of carbon monoxide (CO) and hydrocarbons (HC) which were normally distributed; the CO distribution had a larger relative standard deviation than the HC emissions. We were able to expand our measurements during the 1999 winter season to evaluate emission benefits of oxygenated fuels use in snowmobiles and to compare for the first time the summer and winter visitor mobile source CO and HC emission inventories.

Experimental Section

Two sites were used to collect in-use emissions data in Yellowstone National Park: (1) the express entrance lane from West Yellowstone, MT (west entrance, elev. 2020 m) and (2) the Snake River ranger station at the south entrance (elev. 2087 m) to the park from Flagg Ranch, WY (Figure 1). Most snowmobiles used in the park are rented, and data collected at both entrances are predominately from rental sleds. The west entrance site was the same location used to collect snowmobile emissions data previously reported (*4*). In addition, we collected repeat emission measurements before and after a fuel switch on our work sleds and on two identically prepared 1999 Ski-Doo Rotax 600 sleds (one using oxygenated fuel and its twin using non-oxygenated fuel).

These two entrances were chosen because of their similar physical characteristics (both have slopes less than 0.5%) and because they would maximize (west entrance) and minimize (south entrance) oxygenated-fuel usage. A survey of local rental operators in West Yellowstone showed that all of the large operators were using a 10% ethanol splash blended fuel in their rental fleets. Ethanol blends were not

* Corresponding author phone: (303) 871-2584; fax: (303) 871-2587; e-mail: gbishop@du.edu.
† Current address: Pharmacia Corporation, 1140-230-4, 7000 Portage Road, Kalamazoo, MI 49001-0199.

10.1021/es010513l CCC: $20.00

Published on Web 00/00/0000
PAGE EST: 7.5

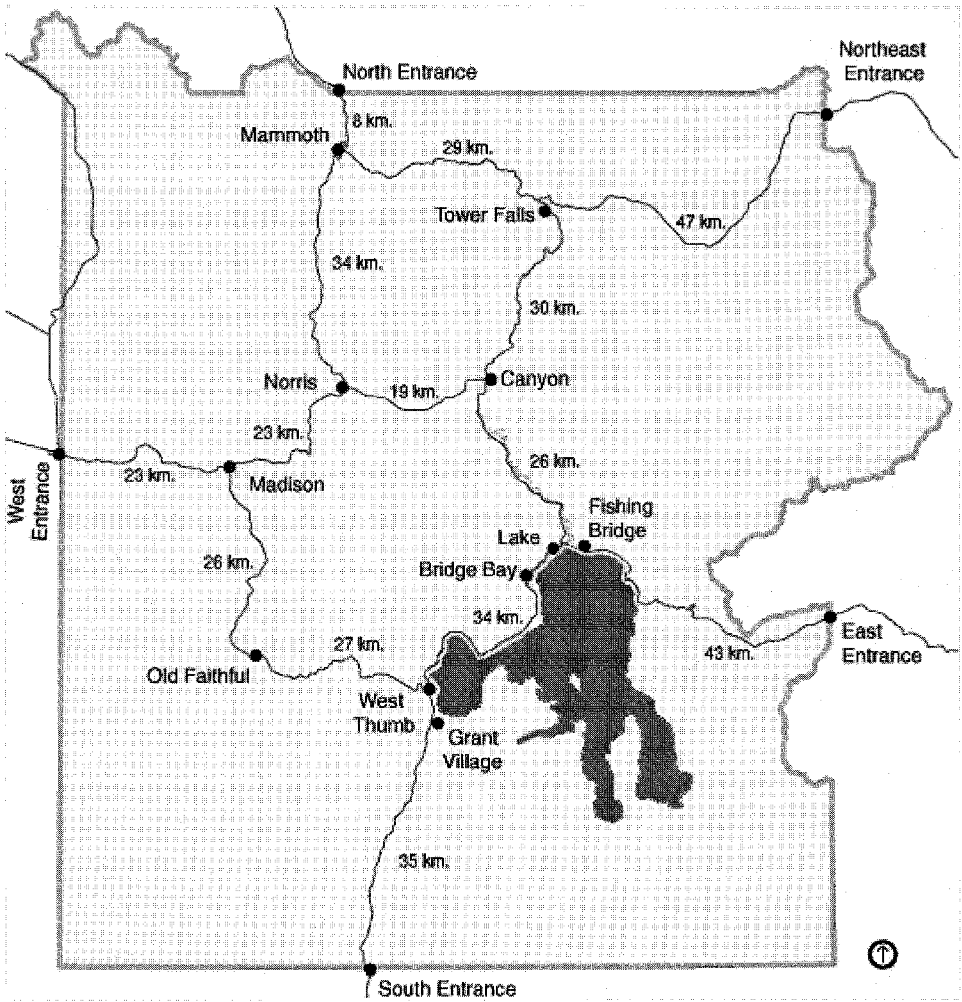

FIGURE 1. Map of Yellowstone National Park highlighting all of the entrances and the major roadways. During the winter season, only the road between the north entrance and the northeast entrance is plowed for wheeled traffic, and the road between Canyon and Tower Falls is closed to all traffic.

available for sale within the park or at Flagg Ranch. Measurements were carried out Feb. 9−10 and 17−18, 1999 at the west entrance and Feb. 12−15, 1999 at the south entrance. The south entrance measurements were chosen to coincide with President's Day weekend in hopes of increasing the number of measurements (this weekend usually has the largest number of visitors during the winter season) and to avoid the large influx of private sleds (less likely to be using oxygenated fuels) at the more popular west entrance. The measurements for the fuel switch sleds were made at the entrance locations, but the measurements on the two matched Ski-Doo sleds were made in a nearby parking lot.

The remote sensor used in this study is composed of a combination of nondispersive infrared optics and a dispersive ultraviolet (UV) monochromator and is capable of measuring ratios of CO, HC, and NO emissions to carbon dioxide (CO_2) in less than a second from passing vehicles independent of wind or turbulence (*5*). Double-blind studies sponsored by the California Air Resources Board and the General Motors Research Laboratories have shown that the sensor is capable of CO measurements which are correct to ±5% of the values reported by an onboard analyzer, and within ±15% for HC measurements (*6, 7*). For this study, spectral modifications were made to the monochromator to enable us to make a number of real-time snowmobile measurements of toluene emissions at the west entrance on February 17 and 18 (*8*).

For the measurements at the two entrance locations, the FEAT source and detector were placed on insulating pads on top of the snow approximately 6 m beyond the park service attendant booths, and the sled emissions were measured during mild acceleration or cruise mode (6000 to 7000 rpm, speeds less than 10 mph). Snowmobile exhaust exits from under the front cowling toward the ground, so the beam height was lowered to approximately 6 in. above the snow. A 1-s sample of exhaust was made after each sled by using the standard FEAT software used for automobiles. A video camera photographed the front cowling of each sled as the sample was measured and the pictures were saved on videotape. The support equipment was housed inside a heated attendant booth. Ambient temperatures were automatically recorded every 5 min during the study. (Davis Instruments, Hayward, CA). Weather conditions were good for all of the measurement periods; only occasional snow flurries were experienced during some of the testing.

The FEAT instrument was calibrated according to standard operating procedures using a certified cylinder containing 6% CO, 1% propane and 6% CO_2 (Scott Specialty Gases, Longmont, CO). Field calibrations of the monochromator for toluene were made using a sealed cell with a laboratory-determined, path-integrated concentration of 945 ± 45 ppm-m (*9*). The standard multistep measurement acceptance criteria were applied to each measurement requiring a minimum amount of plume to be present (at least five 10 ms averages >0.25% CO_2) and that the errors of the measured slopes be within predefined noise limits. These limits are equivalent to ±20% of the slope but are relaxed to a larger

TABLE 1. Summary of 1999 Yellowstone National Park Emission Measurements[a]

location/sled (measurement type)	fuel[b]	mean CO/CO_2, g CO/kg[c] (samples)	mean HC/CO_2, g HC/kg[c,d] (samples)	mean toluene/CO_2, g toluene/kg[c] (samples)	mean temperature, K
west entrance (in-use)	oxy	0.69 ± 0.01 381 ± 4 (1018)	0.27 ± 0.01 239 ± 1 (1018)	0.022 ± 0.001 41 ± 1 (371)	267.2
south entrance (in-use)	non-oxy	0.70 ± 0.02 424 ± 8 (367)	0.23 ± 0.01 230 ± 2 (367)		263.0
1999 Polaris Sport[e] (fuel switch)	oxy	0.70 ± 0.03 495 ± 12 (31)	0.17 ± 0.01 189 ± 3 (31)		266.0
1999 Polaris Sport[e] (fuel switch)	non-oxy	0.59 ± 0.03 482 ± 20 (30)	0.15 ± 0.01 184 ± 6 (30)	0.011 ± 0.001 31 ± 2 (30)	273.7
1996 Polaris Lite GT[e] (fuel switch)	oxy	0.67 ± 0.04 502 ± 11 (33)	0.15 ± 0.01 173 ± 4 (33)		268.1
1996 Polaris Lite GT[e] (fuel switch)	non-oxy	0.67 ± 0.04 494 ± 21 (30)	0.17 ± 0.01 197 ± 7 (30)	0.012 ± 0.001 29 ± 3 (28)	274.7
1984 Arctic Cat Panther[e] (fuel switch)	oxy	0.79 ± 0.02 560 ± 12 (44)	0.16 ± 0.01 172 ± 3 (44)		267.2
1984 Arctic Cat Panther[e] (fuel switch)	non-oxy	1.33 ± 0.04 650 ± 10 (31)	0.30 ± 0.02 224 ± 6 (31)	0.026 ± 0.002 40 ± 2 (31)	273.9
1999 Ski-Doo Rotax[f] 600 DPM (matched)	oxy	0.67 ± 0.02 452 ± 11 (31)	0.20 ± 0.01 211 ± 6 (31)		270.9
1999 Ski-Doo Rotax[f] 600 DPM (matched)	non-oxy	0.80 ± 0.03 507 ± 15 (33)	0.23 ± 0.01 226 ± 6 (33)		270.9

[a] All errors are reported as the standard error of the mean. [b] Fuel designation for the entrances are assumed to indicate the predominant fuel. [c] Assumes a carbon fraction of 0.83 for oxy-fuel and 0.86 for non-oxy fuel. [d] All hydrocarbon values are reported in units of propane. [e] Fan-cooled engine. [f] Liquid-cooled engine.

fixed percentage as the ratios approach zero (*10*). The majority of invalid readings (>60%) were due to the instrument not "seeing" a sufficient amount of the exhaust plume, and the remainder were rejected by the signal-to-noise criteria. Snow spray was the largest single source of noise encountered during the measurements.

FEATs nondispersive hydrocarbon detection system does not have the same sensitivity to all hydrocarbon species and, as such, its response factors may be different for different fuel compositions (*11*). Samples of oxygenated fuel and non-oxygenated fuel in ratio to CO_2 were prepared in Tedlar bags by mixing 0.3 mL of fuel and 1 L of CO_2, and diluting with 5 L of nitrogen. The bags were allowed to equilibrate overnight, and then the HC/CO_2 ratios for each fuel type were measured using FEAT. No differences in the response factors were observed for the two fuels. In addition, the toluene/CO_2 ratio measured by FEAT for these samples was successfully compared with that measured by a GC/FID system to verify the concentration of the sealed calibration cell.

Results

Eight days of sampling in Yellowstone National Park resulted in 1648 valid measurements of CO and HC emissions out of 2115 attempts. Because of the high level of HC emissions from snowmobiles, the conversion to grams of pollutant per kilogram of fuel requires valid CO and HC measurements to complete the mass balance, so only sleds with successful measurements on both species are included in the database. Table 1 summarizes the measured CO/CO_2, HC/CO_2, and toluene/CO_2 ratios, along with grams of pollutant per kilogram of fuel consumed, derived through the combustion equation (*5*). All of the nonspeciated hydrocarbon emissions are reported in units of propane, and the g/kg values are reported using a carbon fraction of 0.83 for oxygenated fuels and using 0.86 for non-oxygenated fuels. All errors are reported as the standard error of the mean (SEM). Mean temperatures reported are the mean of the 5-min averages collected during each measurement period.

Videotapes of the measured sleds were transcribed where possible for make (Arctic Cat, Polaris, Ski-Doo, and Yamaha) and engine-cooling type (fan- or liquid-cooled). In total, 1330 sleds were identified by make and 1302 were identified for engine-cooling type out of the 1385 sleds measured at the two entrances. Individual sleds were not identified, and the database is known to contain some repeat measurements of the same sled. This does not in any way lesson its statistical validity as representing either the fleet of vehicles in the park or the measured fleet at either entrance. This information along with the valid emissions measurement information, measurement location, temperature, date, and time were assembled into a Foxpro database which is available from our web site at www.feat.biochem.du.edu.

Table 2 shows the mean fuel-specific emissions by make derived from the measured ratios from both entrances. Mean fuel-specific emissions as a function of engine cooling for each entrance are also shown along with the totals. All errors are reported as SEM.

Discussion

A second year of sampling has resulted in a data set which has magnitudes and characteristics similar to those in the data collected at the park in 1998. The previous findings of normally distributed CO and HC emissions along with HC emissions distributions exhibiting smaller relative standard deviations were borne out again in the 1999 data. As in 1998,

TABLE 2. Yellowstone National Park 1999 Snowmobile Emissions by Make and Engine-Cooling Type[a]

make/location	g CO/kg[b,c] liquid-/fan-cooled (samples)	g HC/kg[c,d] liquid-/fan-cooled (samples)	g toluene/kg[c] liquid-/fan-cooled (samples)
Arctic Cat	333 ± 14/303 ± 15 (94)/(81)	249 ± 3/211 ± 3 (94)/(81)	40 ± 2/41 ± 3 (27)/(19)
Polaris	353 ± 10/433 ± 5 (184)/(673)	248 ± 3/228 ± 1 (184)/(673)	43 ± 2/37 ± 1 (69)/(130)
Ski-Doo	403 ± 15/270± 13 (52)/(46)	234 ± 6/206 ± 6 (52)/(46)	45 ± 3/37 ± 2 (18)/(25)
Yamaha	359 ± 10/434 ± 21 (113)/(42)	269 ± 4/270 ± 7 (113)/(42)	46 ± 2/47 ± 3 (47)/(18)
south entrance	388 ± 23/437 ± 8 (60)/(290)	241 ± 5/227 ± 2 (60)/(290)	
west entrance	351 ± 6/398 ± 6 (383)/(552)	253 ± 2/228 ± 2 (383)/(552)	44 ± 1/38 ± 1 (161)/(192)
totals	356 ± 6/411 ± 5 (443)/(842)	252 ± 2/228 ± 1 (443)/(842)	44 ± 1/38 ± 1 (161)/(192)

[a] All errors are reported as the standard error of the mean. [b] CO data are not temperature-corrected. [c] Assumes a carbon fraction of 0.83 for oxy-fuel and 0.86 for non-oxy fuel. [d] All hydrocarbon values are reported in units of propane.

the liquid-cooled sleds were found to have HC emissions approximately 10% higher than those of the fan-cooled sleds (Table 2) (*4*).

Previously, we were concerned that this difference might be caused by an HC measurement interference produced by steam streaming off of the liquid-cooled sled's running boards (*5*). The ability to successfully measure toluene emissions using dispersive spectroscopy, which has no such interference, has now enabled us to rule out that possibility and confirmed that the observed HC increases are real. Toluene differences between fan- and liquid-cooled sleds exactly mirror the measured HC emissions (Table 1). The increased emissions are caused by the fact that most liquid-cooled sleds have larger engine displacements than the fan cooled sleds. Typically, fan-cooled sleds have 550 cm^3 or smaller engines whereas the liquid-cooled engines start at 500 cm^3 and increase to 1 L. As engine cylinder volumes increase, the intake and exhaust port areas must increase proportionately. This squeezes the distance between the two and increases the time during which the two are open simultaneously. The use of exhaust valves in the larger engines helps to compensate for some of the increased port size and improves scavenging efficiencies, by keeping the tailpipe emissions from simply scaling with the engine size (*12*).

A second research question remaining from the first year's measurements concerned the large differences in CO emissions, which we observed from the in-use sleds measured at normal snowmobiling temperatures (243 to 278 K) compared with dynamometer measurements made at laboratory temperatures (298 K) (*4, 13*). Figure 2 shows CO and HC data collected at the west and south entrances binned according to the temperatures under which the data were collected (unequal bin sizes are used to add an additional data bin at the west entrance for data which are beyond the temperature range observed at the south entrance). Data from both entrances show a small positive correlation (significant at the 95% confidence limit for the t and F statistics) between increasing temperature and increasing CO emissions (a weighted linear regression of the south entrance data resulted in a slope of 3.4 ± 0.4 g/kg/deg and for the west entrance data the slope is 4.1 ± 0.2 g/kg/deg), but the HC data fail to show any significant change with temperature. The temperature dependence is similar to data reported by Southwest Research (*14*) for a single sled at higher temperatures. This observation is attributable to air density changes with temperature which are made noticeable because air is the limiting reagent in combustion in these engines. This temperature effect cannot explain all of the previously

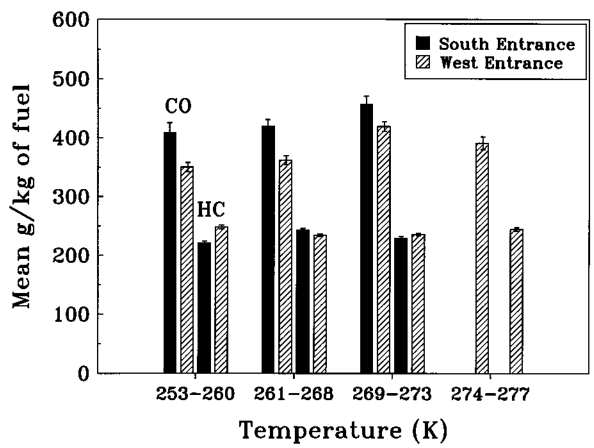

FIGURE 2. CO and HC snowmobile emissions data measured at the south (solid bars, 367 total with 103, 158, 106, and 0 readings distributed from left to right) and west (hatched bars, 1018 total with 226, 335, 315, and 142 readings distributed from left to right) entrances binned as a function of ambient temperature. All error bars are plotted as standard errors of the mean. All HC values have been reported in units of propane.

observed intercomparison differences. The remaining differences most likely are due to sampling bias caused by the small number of sleds (two) tested on the dynamometer.

A temperature correction averaged from the two entrance data regressions was used to compare the emissions distributions collected at the west and south entrances. The 4.2 degrees difference in data collection temperatures resulted in an adjustment of 15.8g CO/kg to the south entrance data. Figure 3 shows these two normally distributed data sets for CO. The observed differences between the two CO distributions are statistically significant (at the 95% confidence limit using a t test), and the CO emissions from the sleds at the west entrance are 13.2 ± 6.5% lower than those from the sleds measured at the south entrance. The HC emission difference of 4 ± 0.1% is also statistically significant, but as previously discussed is not fuel related. Table 2 shows that the percentage of liquid-cooled sleds is 17% at the south entrance and 41% at the west entrance. The 4% observed HC difference is the result of a larger fraction of liquid-cooled sleds operating at the west entrance.

The paired testing of sleds (data in Table 1) resulted in temperature-corrected CO emission changes of +8.7 ± 2.3% (Polaris Sport), +6.5 ± 1.8% (Polaris Lite GT), −10.0 ± 1.6% (Arctic Cat) and −10.8 ± 2.4% (Ski-Doo Rotax 600 DPM). The

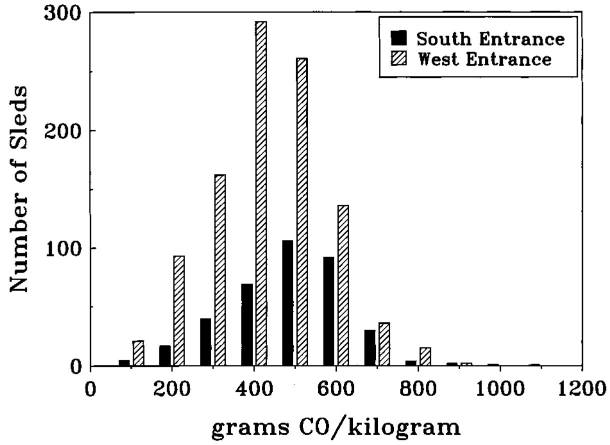

FIGURE 3. Temperature-corrected snowmobile CO emissions collected at the south (solid bars, 367 readings with a mean of 439 ± 8 g/kg) and west (hatched bars, 1018 readings with a mean of 381 ± 4 g/kg) park entrance stations in February 1999. Each bin on the *x*-axis is labeled with its upper terminus.

variability shown by this testing highlights that not all of the sleds experience an emissions benefit.

To successfully ascribe the lower CO emissions solely to the use of ethanol fuels is contingent upon our ability to have successfully separated the fuel usage and eliminated other possible contributing factors. Our attempt to separate the two fuels in part revolves around fleet separation, fuel use motivations, and access to the fuel. The two entrances are separated by an over-the-snow distance within the park of 111 km and by more than 300 km by plowed road outside of the park (Figure 1). Therefore, the individual snowmobile fleets are sufficiently isolated from each other for purposes of this study. The sleds using the south entrance to the park have few if any incentives to use, and no known access to, oxygenated fuels (West Yellowstone's rental fleets' use of ethanol fuels is generally motivated by environmental concern and the resulting positive publicity). We therefore fully expect to find that most sleds at the west entrance are using ethanol fuels and that most sleds at the south entrance are not.

The fraction of sleds using ethanol at the west entrance is controlled by the fraction of rental sleds which make up the database because privately owned sleds are less likely to be using ethanol fuels, and the anticipated dilution which will normally occur. By measuring only those sleds in the express lane (pre-purchased park passes which are standard with all rentals) during weekdays at the west entrance we will have measured very few, if any, privately owned sleds.

It is possible to travel between the west entrance and Old Faithful (by far the most popular destination in the park), a round trip of 98 km (see Figure 1), without buying fuel. The fear of being stranded in the cold leads most renters to purchase fuel in the park, and because there are no oxygenated fuels available in the park, many sleds will return with something less than 100% oxygenated fuel. In addition, snowmobile rentals are different from the more familiar automobile rentals in that renters are expected to return the sleds with empty fuel tanks because the fuel charge is included in the initial rental. Anecdotal information gathered by the National Park Service suggests that most sleds are returned with 1−2 gal of fuel remaining in an 11−13-gal tank (*2*). This will result in measuring emissions from many rental sleds which have a fuel mixture below the stock 10% ethanol blend.

Other factors we have tried to account for are altitude, temperature, operating conditions, and fleet differences. The altitudes were nearly identical at the two locations, and compensation for the temperature differences has already

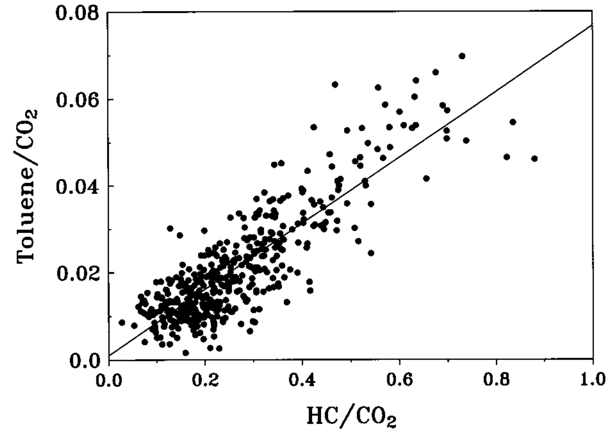

FIGURE 4. 460 snowmobile toluene/CO_2 emissions collected at the west entrance plotted as a function of their HC/CO_2 emissions. The regression line has a slope of 0.08 ± 0.002 with an intercept of 0.001 ± 0.007 and an R^2 of 0.73.

been discussed. Comparing the HC emissions between the two locations is one method we can use to evaluate similarities of the operating conditions. HC emissions are more sensitive to engine load in 2-strokes than CO emissions, and are well-correlated with load (higher loads have higher HC emissions). Table 2 shows that fan- and liquid-cooled sleds had similar HC emissions at the two entrances which indicates similar engine loading.

Measurements at both entrances were made up of predominately rental sleds as the extra influx of private sleds at the south entrance over President's day weekend did not materialize. At the south entrance, rental sleds arrive in large guided groups, which helps to distinguish them from the private sleds. The respective ages and maintenance levels of the fleets are not known; however, there are few, if any, combustion-related changes which have occurred to 2-stroke engines recently. There do appear to be some differences between makes for CO emissions. Table 2 shows a small difference in CO emissions between the air-cooled Polaris and Yamaha sleds, and the Arctic Cat and Ski-Doo sleds.

Trying to account for any differences make may have played in the evaluation, we compared the CO emissions of Polaris manufactured sleds (the largest make at both entrances: 42 liquid-cooled and 284 fan-cooled at the south entrance and 142 liquid-cooled and 389 fan-cooled at the west entrance). A temperature-adjusted comparison between the Polaris sleds at the two entrances results in a CO reduction at the west entrance of 5.9 ± 2.6% for the fan-cooled sleds and a 19.8 ± 10.8% reduction for the liquid-cooled sleds.

All of these comparisons suggest a statistically significant fleet reduction for CO emissions from using the ethanol fuels. The paired testing also showed that every sled will not experience the benefit. Our observed reductions are similar to those measured in dynamometer work from two engines showing a 4 to 9% CO benefit (*13*). The important bottom line is that using oxygenated fuels in 2-stroke engines does not magically transform them into modern low-emitting power plants, and one would expect that more substantial emissions reductions could be achieved with better engine designs (i.e., 4-stroke engines) and fuel management technologies which are readily available today.

Toluene measurements of a mobile emission source using a remote sensor have been previously reported only for thirteen automobiles (*15*). Figure 4 is a plot of the toluene/CO_2 versus the HC/CO_2 ratio for 460 measurements (note that 88 of these were repeat measurements made on the three sleds listed in Table 1 that were used as part of the fuel switch comparison). The mean toluene-to-hydrocarbon ratio of 0.08 from our measurements is consistent with reported

TABLE 3. 1999 Yellowstone National Park Visitor Mobile-Source Emission Inventory Data

data description	light-duty cars[a]	light-duty trucks[a]	RVs[b]	buses[c]	liquid-cooled sleds[d]	fan-cooled sleds[d]	snow coaches[e]	total vehicles, emissions and fuel consumed summer/*winter* (tonne[f])
summer vehicles	603801	494019	64345	6455				1168620
winter vehicles	*20835*	*17047*			*21674*	*41204*	*1396*	*102156*
fuel economy km/L[g]	12.01	8.74	3	2	4.4	5.5	3	
				High Estimate				
CO g/kg	65.9	53.9	81.5	38	361	408	202	2199/*723*
HC[h] g/kg	7.45	6.69	8.78	5	500	456	25	256/*851*
summer fuel (tonne[f])	13448	15074	5732	862				35116
winter fuel (tonne[f])	*94*	*105*			*710*	*1080*	*67*	*2056*
mean model year	1992.6	1993.4	1993.2					
				Best Estimate				
CO g/kg	52.5	48.5	81.5	38	361	408	202	1494/*570*
HC[h] g/kg	7.39	6.53	8.78	5	500	456	25	195/*674*
fuel (tonne[f]) summer	10369	11622	4420	665				27076
fuel (tonne[f]) *winter*	*67*	*75*			*563*	*856*	*53*	*1614*
mean model year	1993.7	1994.2	1993.2					
				Low Estimate				
CO g/kg	44.2	41.8	81.5	38	361	408	202	935/*419*
HC[h] g/kg	7.35	6.29	8.78	5	500	456	25	135/*497*
summer fuel (tonne[f])	7290	8171	3107	623				19191
winter fuel (tonne[f])	*40*	*45*			*415*	*632*	*39*	*1171*
mean model year	1994.4	1995.1	1993.2					

[a] Car and truck distinction based on U.S. emissions certification standards derived from vin information. [b] RVs assumed to be gasoline powered with gross vehicle weight greater than 4536 kg. Emission factors are from data collected in Denver, Phoenix, Chicago, and Riverside in 1999.[c] Buses are assumed to be diesel-powered. [d] Composite snowmobile emission factors are weighted based on entrance statistics (73.5% west entrance, 26.5% other). [e] Snow coach fleet assumed to be composed of 60% pre-emissions control Bombardier coaches and 40% modern conversions. [f] Metric tons. [g] Fuel economy estimates derived from remote-sensing vehicle activity statistics and model-year fuel economies for cars and trucks (*18*). [h] All HC values are reported in units of propane and have been scaled up by a factor of 2 to account for NDIR/FID differences (*11*).

toluene content of typical non-oxygenated gasoline (all of the oxygenated fuel used at the west entrance was splash-blended with fuel that was not specially refined for the addition of ethanol) and with laboratory mixtures we prepared (*9, 16*). The best fit line through the data in Figure 4 has an R^2 of 0.73 and is undoubtedly helped by the fact that the exhaust absorption properties are dominated by unburned fuel.

Singer and Harley have pioneered a fuel-based approach for generating mobile-source emission inventories which we will use to construct Yellowstone National Park's 1999 winter and summer visitor emission estimates (*17, 18*). With this estimate we will not attempt to include emissions from National Park Service vehicles. The relevant required components of Singer and Harley's technique are the number and types of vehicles visiting the park, emission factors for each type of vehicle, and the amount of fuel consumed during the visit. HC emission factors have been adjusted upward by a factor of 2 to normalize the remote-sensing nondispersive infrared absorption measurements with comparable flame ionization measurements (*11*).

A major strength of using remote-sensing data to construct a fuel-based inventory is the ability to collect emissions data during driving modes that account for the majority of the fuel consumption. For example, engine starts and deceleration events are not emphasized as they are with the travel-based methods because little fuel is consumed during these activities (*19, 20*). In addition, g/kg emission factors are less speed- and load-dependent than g/mile emission factors (*21*). For this inventory, we will use vehicle entrance counts compiled by the National Park Service, remote-sensing emissions databases for on-road and over-snow fleets, and fuel sales data supplied by the Yellowstone Park Service Stations. Table 3 details high, best, and low emissions estimates for the park winter and summer visitor fleets. For the over-the-snow fleet, only the amount of fuel consumed changes between each extreme, and for the on-road vehicles both the emission estimates and fuel consumed are variables.

According to Nuti, lower loads and higher rpm's, typical of cruise conditions, do display smaller relative HC emissions (*3*). However, typical park snowmobile driving emphasizes stop-and-go operation, which consumes much of the fuel and is the operating mode we measure at the entrance gates.

The National Park Service records the number of vehicles entering the park on a daily basis. Visitor vehicle counts obtained for 1999 listed the numbers of cars, self-powered campers (RVs), buses, snowmobiles, and snow coaches that entered the park (*22*). At the entrance gates, no distinction is made by the park service attendant as to the types of automobiles entering. It is necessary to supply this distinction for inventory purposes because, in the U.S., light-duty vehicle on-road emissions limits are different for cars than for trucks. We have defined light-duty cars and trucks based on their U.S. emissions certification, which for trucks will include minivans, four-wheel drive automobiles, and sport utility vehicles, many of which may not necessarily look like trucks.

Light-duty vehicle fleet emissions and fuel economy estimates were constructed from on-road emission databases collected in Riverside, CA (July 1999) and Chicago, IL (September 1999) using the same instrument and measurement techniques that were used to collect the snowmobile emissions (*10, 23*). Data from these two cities provide reasonable upper and lower limits for light-duty fleet age (Chicago's fleet is approximately 2 years newer and therefore lower emitting than Riverside), emissions, and vehicle type (western states have a higher percentage of light-duty trucks than eastern) found throughout the U.S. Despite the age differences between the Chicago and Riverside fleets, light-duty vehicle fuel economy values have changed little over the last 10 years, and the on-road fuel economies used came from combining the Chicago and Riverside fleets by model year and applying model year fuel economies provided by

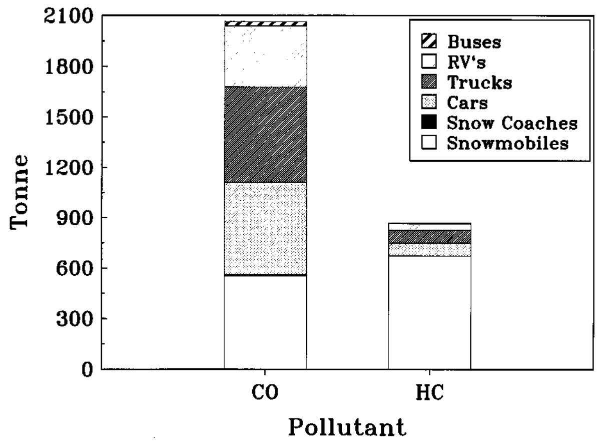

FIGURE 5. A stacked bar chart by vehicle type showing the best estimate in metric tons of CO and HC for the 1999 visitor mobile-source inventory for Yellowstone National Park.

Singer and Harley (*18*). Recreational vehicle fuel economies were further reduced by 10% to account for generator usage (the exact magnitude of this adjustment is unimportant to the final result but is expressed to emphasize an activity known to occur). The high emissions estimate for on-road vehicles uses the Riverside emission factors, the low estimate uses the Chicago data, and the best estimate uses a combined fleet from the two cities. To reduce the number of variables carried through the calculations, we have fixed the percentages of cars and trucks for all of the estimates to the proportions found in Riverside where light-duty trucks make up 45% of the fleet. This is the larger fraction of the two cities used for this inventory, but is still smaller than some western fleets we have measured in Denver and Phoenix (*10, 23*). It is reasonable to expect a higher fraction of trucks in the Yellowstone fleet as many smaller commuting cars found on-road in major cities will not be used for vacation purposes. The emissions certification (for car and truck designation) for vehicles in Riverside and Chicago has been inferred from each vehicle's identification number (vin) and manufacturer information provided by the National Insurance Crime Bureau in its annual Passenger Vehicle Identification Manual (*24*).

Emission factors for RVs were estimated from on-road remote-sensing data collected in 1999 in Riverside, CA, Phoenix, AZ, Chicago, IL, and Denver, CO for 642 gasoline vehicles with gross vehicle weights greater than 4536 kg (*10, 23, 25*). Diesel bus emissions were estimated from on-road remote-sensing measurements of over-the-road heavy-duty diesel trucks measured in the U.S. and Europe (*26*). Currently, there are two types of snow coaches operating in the park: those manufactured by Bombardier Corp. before 1970 which have no emissions controls (emission factors from pre-1974 model year vehicles (*23*)) and conversions of modern light-duty passenger vans which meet current federal emission standards (emission factors from averaged light-duty trucks, Table 3). For the purposes of this inventory, we have assumed that the snow coach fleet was composed of 60% pre-emissions control Bombardier coaches and 40% modern conversions.

Yellowstone National Park has 7 service stations (upper and lower Old Faithful, Canyon Village, Grant Village, Mammoth, Fishing Bridge, and Tower Junction) four of which are also open during the winter season (upper Old Faithful, Canyon Village, Mammoth, and Fishing Bridge). Summer and winter retail fuel sales were kindly provided by the Yellowstone Park Service Station Company for 1998 and 1999 (*27*). The fuel sales from these stations account for only a portion of the fuel used by visitors to the park, but we will use them to provide a basis for estimating the overall fuel usage.

The Yellowstone Park Service Station Company has estimated from a survey of credit card sales receipts that only 20% of the gasoline used by summer visitors in the park is purchased from the park service stations (*27*). Using this information, we have estimated the high-range of summer gasoline usage at 34254 t (~39 L/vehicle). For the low-range fuel estimate we used a National Park Service travel activity estimate of 120 miles per visitor vehicle (*2*), and when this estimate was combined with vehicle counts and their fuel economies, it resulted in a gasoline usage of 18568 t (~21 L/vehicle). The best light-duty emissions estimate was constructed using the arithmetic mean of these two estimates. The low-range diesel fuel use estimates for the buses were made using the low-range gasoline formula and then scaled proportionately using the high/low range gasoline estimates to provide a high-range diesel fuel usage.

The winter refueling scenario is a little simpler than summer because all but one of the stations (Mammoth) can be reached only after extensive drives from the entrances (Figure 1). As all of the over-the-snow vehicles enter the park with full fuel tanks, any fuel sales that occur at the interior service stations are to vehicles which have already consumed an amount of fuel equal to the amount of fuel purchased within the park. We have assumed that these vehicles will consume at least the same amount of fuel purchased on its return trip. For this reason, we have constructed the low-range gasoline estimate for over-the-snow vehicles by doubling the amount of fuel sold at the Old Faithful, Fishing Bridge, and Canyon Village service stations and adding that to the amount sold at the Mammoth station for a low-range estimate of 1086 t (~23 L/vehicle). The high-range estimate was based on the National Park Service's estimate that each snowmobile used 37.85 L/visit (*2*) and when this same consumption rate is apportioned for snow coaches it results in a high-range fuel use estimate of 1857 t (~39 L/vehicle). Winter light-duty on-road vehicle fuel usage via the North entrance was estimated between 85 t (~3 L/vehicle) and 199 t (~7 L/vehicle).

Figure 5 is a stacked bar chart of the results for the best estimate of CO and HC emissions during 1999 in Yellowstone National Park by vehicle type. Snowmobiles account for 27% of the total carbon monoxide and 77% of the hydrocarbons emissions. The best-estimate ratio between summer and winter emissions is 2.6:1 for CO (the range is 3:1 to 2.2:1) and 1:3.5 for HC (the range is 1:3.3 to 1:3.7). The differences in the summer and winter inventories are not as lopsided as some have claimed (*1*). The large differences in emission rates between the over-the-snow vehicles and the on-road vehicles is balanced by the large excess of fuel which is consumed in the park during the summer. However, the difference in HC emissions speaks to the need for the snowmobile industry to move away from 2-stroke designs to more fuel efficient 4-stroke engines.

Acknowledgments

The authors would like to acknowledge the financial support provided for this work from the U.S. Department of Energy's Western Regional Bioenergy Program award #5011, the National Park Service, the International Snowmobile Manufacturers Association, the West Yellowstone Chamber of Commerce, the Town of West Yellowstone, MT, Environmental Systems Products, Inc., the Montana Department of Environmental Quality, and the Yellowstone Foundation. We would also like to acknowledge the invaluable help provided by John Sacklin, Mary Hektner, John Ray, Julie Hannaford, Kitty Eneboe, Christi Phelps, Christine Langland, Hellen Atwell, Tom Barr, Alex Moldenhaue, Helena Mayo, Daniel "Boone" Vandzura, Pat Navaille, Rick Mossman, Kathleen O'Leary, and Dave Phillips of the National Park Service, as well as Howard Haines of the Montana Department of

Environmental Quality, Dave McClintock of Rentals 2 Play, and Chris Wright of Arctic Cat.

Literature Cited

(1) 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*; National Park Service: Denver, CO, 2000; http://www.nps.gov/planning/yell/winterfinal/frames.htm.

(2) National Park Service. *Air quality concerns related to snowmobile usage in National Parks*; National Park Service Air Resources Division: Denver, CO, 2000; http://www.aqd.nps.gov/ARD/pubs/snowmobilereport.pdf.

(3) Nuti, M. *Emissions from Two-Stroke Engines*; Society of Automotive Engineers, Inc.: Warrendale, PA, 1998.

(4) Bishop, G. A.; Stedman, D. H.; Hektner, M.; Ray, J. D. *Environ. Sci. Technol.* **1999**, *33*, 3924−3926.

(5) Bishop, G. A.; Stedman, D. H. *Acc. Chem. Res.* **1996**, *29*, 489−495.

(6) Lawson, D. R.; Groblicki, P. J.; Stedman, D. H.; Bishop, G. A.; Guenther, P. L. *J. Air Waste Manage. Assoc.* **1990**, *40*, 1096−1105.

(7) Ashbaugh, L. L.; Lawson, D. R.; Bishop, G. A.; Guenther, P. L.; Stedman, D. H.; Stephens, R. D.; Groblicki, P. J.; Johnson, B. J.; Huang, S. C. *On-road remote sensing of carbon monoxide and hydrocarbon emissions during several vehicle operating conditions*; Presented at Air and Waste Management Association, International Specialty Conference on PM10 Standards and Nontraditional Source Control, Phoenix, AZ, 1992.

(8) Popp, P. J.; Bishop, G. A.; Stedman, D. H. *J. Air Waste Manage. Assoc.* **1999**, *49*, 1463−1468.

(9) Morris, J. A. Master of Science Thesis, University of Denver, Denver, CO, 1999.

(10) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Chicago area: Year 3*; Coordinating Research Council, Inc.: Alpharetta, GA, 2000; Contract No. E-23-4; http:\\www.feat.biochem.du.edu\reports.html.

(11) Singer, B. C.; Harley, R. A.; Littlejohn, D.; Ho, J.; Vo, T. *Environ. Sci. Technol.* **1998**, *32*, 3241−3248.

(12) Wright, C. Arctic Cat, Inc. Personal communication, 2000.

(13) White, J. J.; Carroll, J. N.; Haines, H. E. *Soc. Automot. Eng.* **1997**, 972108.

(14) Wright, C. W.; White, J. J. *Soc. Automot. Eng.* **1998**, 982017.

(15) Baum, M. M.; Kiyomiya, E. S.; Kumar, S.; Lappas, A. M.; Lord, H. C., III. *Environ. Sci. Technol.* **2000**, *34*, 2851−2858.

(16) Desert Research Institute. *Real-world automotive emissions − Results of studies in the Fort McHenry and Tuscarora Mountain Tunnels*; Desert Research Institute: Reno, NV, 1994; Vol. 6480-1D1.

(17) Singer, B. C.; Harley, R. A. *J. Air Waste Manage. Assoc.* **1996**, *46*, 581−593.

(18) Singer, B. C.; Harley, R. A. *Atmos. Environ.* **2000**, *34*, 1783−1795.

(19) Singer, B. C.; Kirchstetter, T. W.; Harley, R. A.; Kendall, G. R.; Hesson, J. M. *J. Air Waste Manage. Assoc.* **1999**, *49*, 125−135.

(20) Singer, B. C. Doctor of Philosophy Thesis, University of California, Berkeley, CA, 1998.

(21) Pierson, W. R.; Gertler, A. W.; Robinson, N. F.; Sagebiel, J. C.; Zielinska, B.; Bishop, G. A.; Stedman, D. H.; Zweidinger, R. B.; Ray, W. D. *Atmos. Environ.* **1996**, *30*, 2233−2256.

(22) National Park Service. Public Use Statistics Office. Personal communication, 2000.

(23) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Los Angeles qjarea: Year 1*; Coordinating Research Council, Inc.: Alpharetta GA, 2000; Contract No. E-23-4; http:\\www.feat.biochem.du.edu\reports.html.

(24) National Insurance Crime Bureau. *Passenger Vehicle Identification Manual*; National Insurance Crime Bureau: Palos Hills, IL, 2000.

(25) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. *On-road remote sensing of automobile emissions in the Phoenix area: Year 2*; Coordinating Research Council, Inc: Alpharetta GA, 2000; Contract No. E-23-4; http:\\www.feat.biochem.du.edu\reports.html.

(26) Bishop, G. A.; Morris, J. A.; Stedman, D. H.; Cohen, L. H.; Countess, R. J.; Countess, S. J.; Maly, P.; Scherer, S. *Environ. Sci. Technol.* **2001**, *35*, 1574−1578.

(27) Broadhead, H. Yellowstone Park Service Stations. Personal communication, 2000.

Received for review January 8, 2001. Accepted April 3, 2001.

ES010513L