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Noise Data from Snowmobile Pass-bys: The Significance of Frequency Content

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ABSTRACT

This paper presents a summary of the results of noise measurements of various snow machines conducted by Harris Miller Miller & Hanson Inc. (HMMH) in 2002. Because the data were collected as part of an analysis including audibility and sound propagation over long distances in national parks, measurements included the frequency content of the snow machines as well as the A-weighted sound levels (dBA). Frequency data are given for some of the snow machine pass-bys at the SAE Clean Snowmobile Challenge 2002 and also for those measured under various operational conditions at Yellowstone National Park in February 2002. Measurements were conducted in substantial conformance with SAE J192. Comparisons are made of snow machines under acceleration and constant-speed conditions, and between those with two-stroke and four-stroke engines. The data show substantial differences in spectral content for some vehicles with similar A-weighted sound levels. A description of the significance of low-frequency tonal content on the audibility of noise in remote areas provides context for the spectral data presented.

BACKGROUND

In 2000, HMMH conducted a noise study for the National Park Service's Environmental Impact Statement on the Winter Use Plan for Yellowstone and Grand Teton National Parks.[1,2] This study incorporated measurements of over-snow vehicle emissions and of the existing sound environment in the parks, and followed with modeling of projected sound levels and vehicle audibility for different winter use alternatives. Since this study was conducted, the National Park Service has been conducting supplemental analyses of various alternatives. As part of these supplemental studies, NPS contracted with HMMH to conduct additional measurements of vehicle pass-by noise emissions, including those of the newer type of snowmobiles with four-stroke engines. Additional measurements conducted in February 2002 included some of the four-stroke machines as well as two-stroke snowmobiles and selected snow coaches. In addition to these supplemental measurements, HMMH also participated in the noise measurements at the 2002 SAE Clean Snowmobile Challenge.

NATIONAL PARK SERVICE PERSPECTIVES

The mission of the U.S. National Park Service (NPS) is to conserve park resources and to provide for their enjoyment by park visitors "in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."[3] In units of the U.S. National Park System, the term "natural soundscape" refers to the aggregate of all the natural sounds that occur in parks in the absence of human-caused sound.[4] Natural soundscapes are park natural resources subject to the NPS mission, and are also valued parts of the visitor experience in parks.[5] As it does with other park resources and values, the NPS strives to preserve or restore the natural soundscapes in parks[6] as well as provide opportunities for visitors to experience them. In the context of snow machines, NPS policy requires managers to carefully evaluate and manage how, when, and where all forms of motorized equipment are used in parks[5], and to avoid or minimize adverse impacts of such use on park resources, values, and visitor experiences.

In this context, the *audibility* of human-caused sounds, including motorized equipment such as snow machines, is important in evaluating impacts on park resources and on visitor experiences. The resource of particular concern is the natural soundscape, and the most affected visitor experiences include those that involve solitude, tranquility, and contemplation of nature and natural processes.

AUDIBILITY ASSESSMENT

Audibility (the detection of a sound) is simple in concept and easy for most people to understand, since it answers the simple question "Can you hear it?" However, audibility is more challenging to measure and compute than sound levels are. The audibility of a sound in a given background sound environment is dependent on both the sound's level and the background sound level. In very quiet environments, such as Yellowstone and Grand Teton National Parks in wintertime, the audibility of a sound is also dependent on the noise of the human auditory system (related to the threshold of hearing). Since human hearing discriminates roughly in 1/3-octave bands, such a frequency analysis is necessary for computing audibility.

The wintertime background sound levels at Yellowstone and Grand Teton National Parks are very low. During quiet daytime periods with low wind conditions, A-levels are as low as 10 to 20 dBA[2,7]. Figure 1 shows 1/3-octave band descriptors of the background sound levels acquired on digital audio tape in the Pelican Valley area north of Yellowstone Lake, during a relatively quiet 30-minute period of natural sounds from wind in the trees during the daytime. Low-noise measurement instrumentation was used at this and other sites to more accurately document the very low ambient sound levels in these remote areas. The instrumentation included the Brüel & Kjær 4179 microphone and 2660 preamplifier, which are capable of measuring sound levels below the threshold of hearing. Note that sound levels in the lowest frequency bands (125 Hz and below) are lower than those in the mid frequencies (250 Hz to 1000 Hz). This is a background spectral shape not commonly seen in more populated areas, where distant transportation sources dominate the low frequencies, which travel for long distances with little attenuation from the air or ground. Since the levels of ambient background sound are so low in the frequency range below 250 Hz, those sounds often cannot "mask" or cover up the low-frequency engine noise generated by some snow machines.

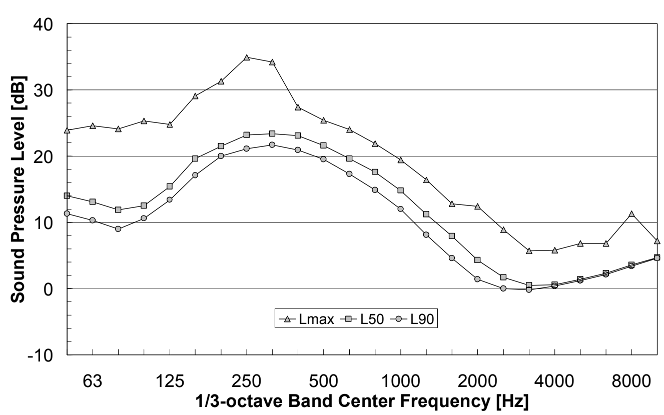

Figure 1. Ambient Spectra During a Quiet Daytime Period at Pelican Valley, Yellowstone NP

For the NPS Winter Use Plan analysis, audibility was computed from auditory signal detection calculations, which compare the computed vehicle sound levels to the background sound levels in 1/3-octave bands. The metric of audibility (detectability) used is called d′. A threshold for audibility derived from field observations occurs where 10 log d′ = 7 dB[8]. Because the background sound levels in the parks are so low, the equivalent human auditory system noise is higher than the background sound level over much of the frequency range. Therefore, auditory system noise must be added to the background noise to represent the total masking noise against which the vehicle noise signal should be compared for human detection calculations. (Auditory system noise in 1/3-octave bands has been estimated from the ISO pure-tone hearing threshold, and results in values that are numerically within about 2 dB of the threshold at 1/3-octave band center frequencies below 250 Hz.)

Figure 2 shows an example of the spectra that contribute to the calculation of audibility, including that calculated for a snowmobile at a distance of 3000 ft over mostly open terrain. Spectra for both the auditory system noise and "quiet" (low-wind condition) open terrain background are shown adding together to a total masking spectrum (heavy solid line). The snowmobile spectrum is computed from the maximum pass-by sound spectrum of a 2000 Polaris 500cc machine at 35 mph measured at 50 ft. This spectrum is then propagated to 3000 ft using the sound propagation algorithms built into the Federal Highway Administration's 1998 Traffic Noise Model[9]. This model incorporates different ground types, including snow. The over-ground propagation algorithms derive from the widely accepted publications of Embleton[10], Delany[11] and Chessell[12]. The model allows for terrain variation and also incorporates attenuation due to dense foliage[13]. For the example in Figure 2, open and flat terrain was used. The snowmobile sound levels would be lower over flat forested terrain, and either lower or higher over hilly terrain, depending on the specific terrain and the locations of the source and receiver of sound. Also in the example, calm wind conditions are assumed; over long distances, sound levels from sources are usually higher downwind and lower upwind.

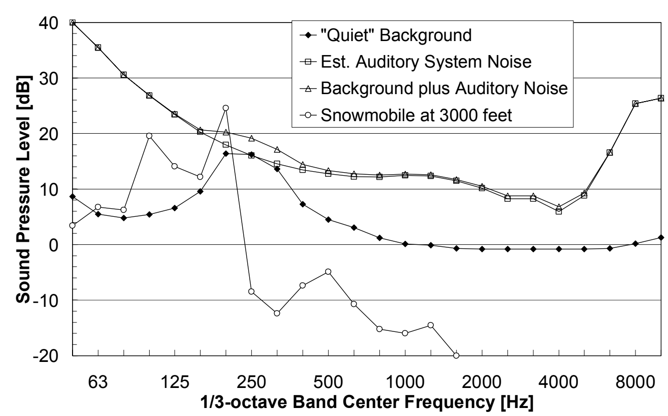

Figure 2. Spectra of Background, Auditory System Noise and Snowmobile computed at 3000 ft.

In Figure 2, the snowmobile noise spectrum exhibits a tonal peak at 200 Hz, which is consistent with its measured 50-ft spectrum shape in the low frequencies. Although the peak in the 1/3-octave band sound level is 5 dB higher than the masking curve at that frequency, the computed value for audibility is 10 log d′ = 9.4 dB, about 2 dB higher than the audibility threshold of 7 dB, which indicates that the tone would be audible.

A significant effect exhibited in Figure 2 is that the higher frequencies of the snowmobile noise are significantly attenuated over the long propagation distances. This reduction occurs from absorption by the air, and from ground-effect attenuation over the absorptive snow. Such effects are far more significant at frequencies above about 200 Hz than at the lower frequencies. Therefore, it is the low-frequency components of the source spectra that become the most significant with respect to audibility at the longer distances. An effect of this is that the overall A-weighted sound level loses its value as a metric for describing vehicle noise at longer distances, because the A-weighting network emphasizes mid and high frequencies, and de-emphasizes the low frequencies. This finding is consistent with HMMH's observations about noise from helicopter and propeller aircraft flights in Grand Canyon National Park at long distances[14,15]. However, it should be noted that confidence in these findings could be improved with spectral data from controlled measurements of snow machines at long distances in typical winter environments.

SNOW MACHINE MEASUREMENTS AT YELLOWSTONE NATIONAL PARK

On February 6, 2002, HMMH conducted vehicle pass-by measurements of many different over-snow vehicles on behalf of the National Park Service, in a cooperative endeavor with several local tour operators, who provided the snow machines for testing, and the Wyoming Trails Program, whose staff coordinated the pass-bys. Jackson Hole Scientific Investigations, Inc. also collected noise data in the test zone[16]. The purpose of the program was to supplement and update the initial data collected in 2000 for the Winter Use Plan EIS. The measurement site was an open area on the road just south of the south entrance to Yellowstone National Park. Snow machines traveled on the groomed road; the rest of the site was covered with soft, light unpacked snow 36 in. to 40 in. deep. Skies were clear to partly cloudy, temperatures were 0º F to 10º F, and winds were generally calm or less than 2 mph.

The measurements were conducted in substantial conformance with the SAE J192 and J1161 measurement standards for snowmobile pass-by noise measurements. Sound level meter "fast" response was used for consistency with J192 and because many of the vehicle pass-bys were at high enough speeds to require *fast* response for accurate readings. (J1161 recommends *slow* response, but pass-by speeds are limited to 15 mph.) The snowmobiles were run for four constant-speed pass-bys, two in each direction, at each of three targeted speeds: 20mph, 35mph and 45mph. Snow coaches were run similarly, but at target speeds of 20mph and 30mph. A calibrated radar gun measured the actual speed of each pass-by. In addition to these constant-speed tests, the full-throttle acceleration test specified in J192, and idle measurements were also performed.

The rationale for measuring constant-speed, or cruise condition pass-bys is that since snow machines are operated mostly under cruise conditions while traveling in the parks, those conditions are best for developing the emission levels needed for modeling purposes. In addition, the majority of emission level data collected for use in the Federal highway noise prediction models are for highway vehicles under cruise conditions.

HMMH's measurements were conducted with ANSI Type I (precision) instruments including microphone (B&K 4189), preamplifier (Larson-Davis 900B), sound level meter/monitor (Larson-Davis 870), sound-level calibrator (GenRad 1987), and Digital Audio Tape (DAT) recorder (Sony TCD-D8). A-weighted sound levels were stored every 1/8 second in the sound level meter; maximum values were taken from that data stream. All events were also recorded on DAT and were processed later to obtain the 1/3 octave band spectrum at the time when the A-weighted sound level reached its maximum.

Table 1 provides a summary of the measured maximum pass-by A-levels for most of the snow machines that were measured, grouped by vehicle type and target speed. New-model snowmobiles with four-stroke engines were tested, including the 660 cc Arctic Cat (2001 and 2002) and Polaris Frontier 2002; three vehicles of each kind were tested. Four different models of stock snowmobiles with traditional two-stroke engines were tested, including a 2001 Polaris Sport Touring 550, a 2000 Yamaha Mountain Max 600, a 2001 Polaris Wide-Track 500, and a 2002 Polaris RMK 800. All of the snow coaches are grouped together in the table. Those tested included a Bombardier with high exhaust (yellow), a Bombardier with low exhaust (red Alpen Guide), a 1998 Chevrolet diesel-powered van conversion with Mattrack treads on each wheel (see Figure 3), a 1996 Ford gasoline-powered van with Mattracks, and a 1999 Ford gasoline-powered van conversion with skis on the front axle and two long tread tracks on the rear (see Figure 4).

Figure 3. Conversion van with Mattracks

Figure 4. Two-track conversion van

The measurement data in Table 1 show that the median pass-by levels of the two types of four-stroke snowmobiles measured were 3 to 5 dBA quieter than those of the four vehicles tested with two-stroke engines, depending on speed. The largest difference is seen at 20 mph, where the median L_{max} values for the four-stroke snowmobiles is 66 dBA, and the two-stroke snowmobiles are about 71 dBA, comparable to the snow coaches. The trends are similar but the differences smaller at speeds of 30 to 35 mph; average emissions of snow coaches were about 75 dBA, two-stroke snowmobiles approximately 74 dBA and four-stroke snowmobiles about 72 dBA. One observation during the testing of the snow coaches was that 30 mph appeared faster than normal for those vehicles. This observation was supported by comments from some of the snow coach drivers. Since most of these vehicles did not have functioning speedometers, a passenger operated a Global Positioning System unit to assist the driver in maintaining the target speeds for the tests.

Table 1. Comparison of measured sound levels of snow vehicle pass-bys at 50 ft, Yellowstone National Park, February 6, 2002

Vehicle Type	Target Speed (mph)	Average measured speed	Average L_{max} (dBA, fast)	Median L_{max} (dBA, fast)	Highest L_{max} (dBA, fast)	Lowest L_{max} (dBA, fast)	Number of Events
Snow coaches	20	20.9	70.7	71.6	75.8	63.6	24
Four-stroke snowmobiles	20	18.5	66.1	65.9	67.6	64.5	26
Two-stroke snowmobiles	20	18.4	71.0	71.3	73.1	68.9	12
Snow coaches	30*	29.0	74.8	75.3	80.5	68.8	20
Four-stroke snowmobiles	35	31.6	71.8	71.9	73.1	70.2	22
Two-stroke snowmobiles	35	31.9	74.0	74.2	76.8	71.3	14
Four-stroke snowmobiles	45	40.2	73.1	72.9	75.5	71.3	27
Two-stroke snowmobiles	45	40.3	75.8	76.3	77.2	73.3	14
Four-stroke snowmobiles	Accel	27.4**	73.1	72.7	77.0	69.6	24
Two-stroke snowmobiles	Accel	31.3**	78.7	79.1	80.2	76.2	12

*All snow coaches targeted 30 mph except the gas-powered Mattracks, which targeted 35 mph, but achieved 32 mph.
** Speed measured where vehicle was opposite microphone; an approximate measure.

Figure 5 presents a scatter plot of each of the stock vehicle pass-bys as a function of the speed measured by radar. The snowmobiles with 4-stroke engines are grouped separately from those with 2-stroke engines. The snow coaches are grouped into three categories: Bombardier, Mattracks and 2-track conversion van. The two-track conversion van was clearly the quietest snow coach, averaging 65.6 dBA at 20 mph, slightly quieter than the average four-stroke snowmobile. The red Alpen Guide Bombardier snow coach with low exhaust averaged 68.4 dBA. The gas and diesel-powered Mattracks snow coaches were comparable, at approximately 72 dBA. The yellow Bombardier snow coach with high exhaust was also about 72 dBA at 20 to 22 mph, but that test vehicle seemed to have higher exhaust noise levels than other yellow Bombardier snow coaches that passed by during the day. Interestingly, as a group, the two-stroke snowmobiles were the loudest vehicles at 20 mph, but the snow coaches (high-exhaust Bombardier and Mattracks) were the loudest at 30 mph.

It should be noted that much of the noise from some of the snow coaches (particularly the Mattracks) appeared to be generated from the interaction of the vehicle's treads with the snow, and the snow in the test zone had become fairly rough by the end of the day of testing. The rough snow probably caused the tests of some of the snow coaches later in the day to be somewhat higher in track-related noise levels than they would have been under smoother snow conditions. The snow conditions could also have affected the noise emissions of the later-tested snowmobiles as well.

Figure 6 through Figure 9 present examples of measured spectra for each of the vehicles tested. A typical pass-by was chosen to represent each vehicle; snowmobile spectra are shown for pass-bys at 30 to 35 mph. Snow coach spectra are shown for the 20 mph pass-bys, because the authors judged that to be a more typical travel speed for those vehicles. The spectrum shapes for the snow coaches at 30 mph are not substantially different.

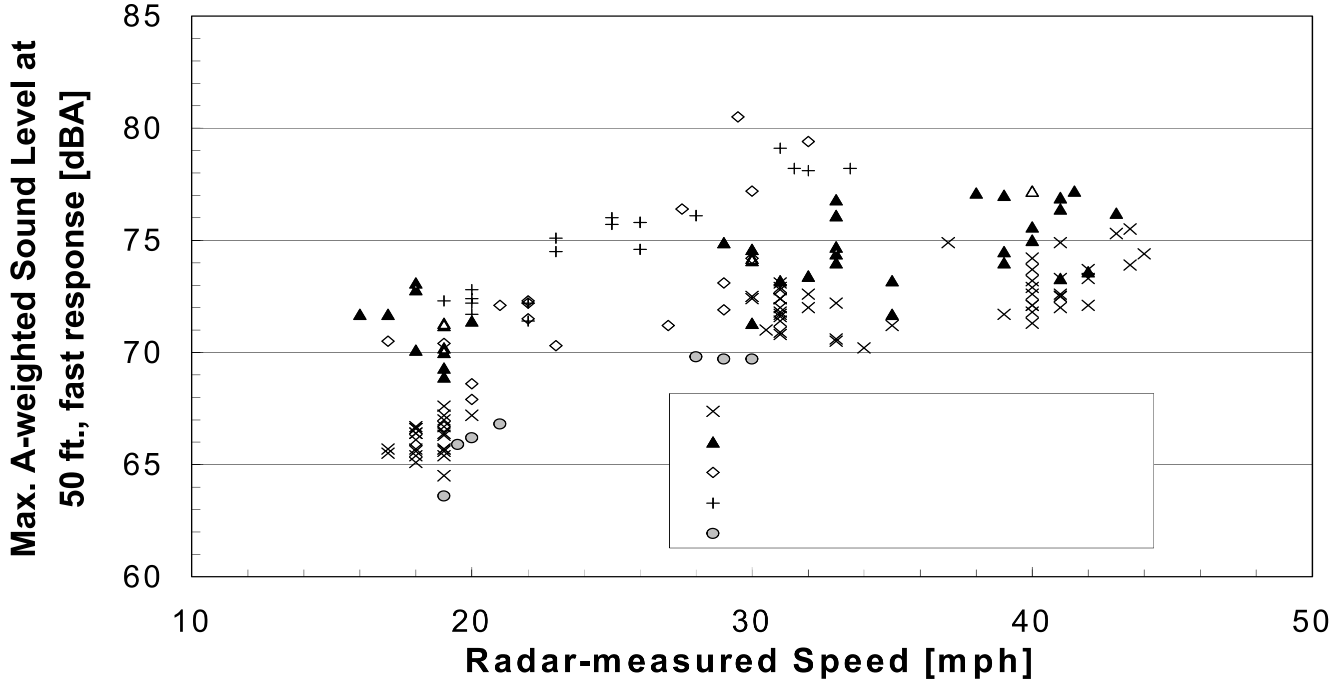

Figure 5. A-weighted Sound Levels of Snow Vehicles versus Speed

The spectrum shape for some vehicles is fairly smooth, without clear tonal peaks. The snow coaches that exhibit this characteristic are the 2-track conversion van (shown in Figure 8) and the Alpen Guide Bombardier with low exhaust (shown in Figure 9). Other vehicles exhibit strong tonal peaks, perhaps evident of engine firing frequency tones, exhaust resonance or track resonance. For example, the high-exhaust yellow Bombardier shows an engine/exhaust tone at 100 Hz. High-level tones in the low-frequency region below about 250 Hz will make

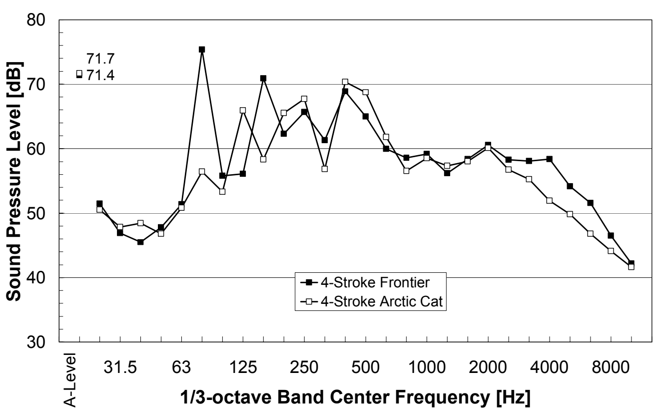

Figure 6. Sound Level Spectra of 4-Stroke Snowmobiles at 30 to 35 mph

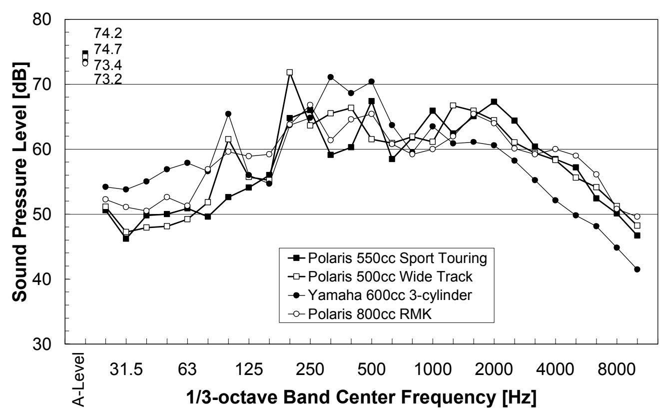

Figure 7. Sound Level Spectra of 2-Stroke Snowmobiles at 30 to 35 mph

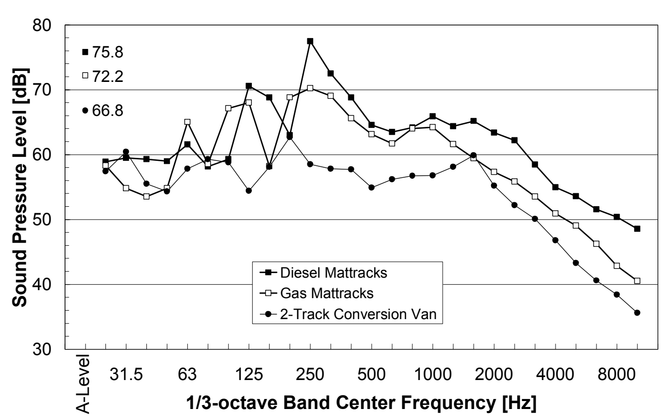

Figure 8. Sound Level Spectra of 4-track and 2-track Snow Coaches at 20 mph

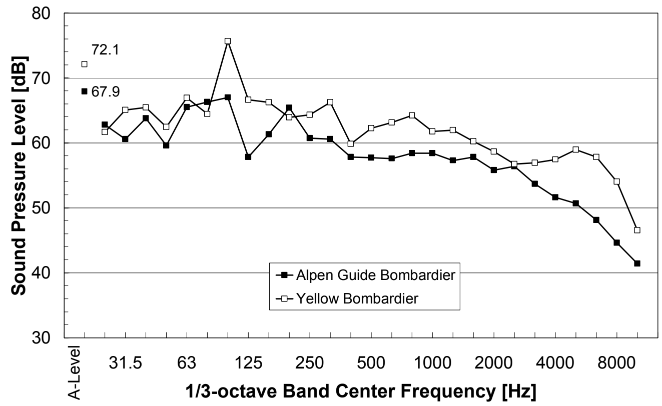

Figure 9. Sound Level Spectra of Bombardier Snow Coaches at 20 mph

a snow machine significantly more audible at longer distances as compared with machines with smoother spectra or less sound energy in the low frequencies. The diesel-powered conversion van with Mattracks shows a prominent tone at 250 Hz (Figure 8).

The snowmobiles with the lowest and smoothest low-frequency spectra were the (two-stroke) Polaris 550 cc Sport Touring and the Polaris 800 cc RMK. Between the two four-stroke machines shown in Figure 6, the Arctic Cat had a significantly lower and smoother low-frequency spectrum than the Polaris Frontier, which has a prominent 75 dB tone in the 80 Hz 1/3-octave band.

MEASUREMENTS AT SAE CLEAN SNOWMOBILE CHALLENGE 2002

Harris Miller Miller & Hanson Inc. participated in the SAE Clean Snowmobile Challenge 2002. Noise measurements were conducted alongside Jackson Hole Scientific Investigations, Inc., who was performing the official contest measurements. References 17 through 26 provide much detail on the results of the SAE CSC 2002 and the specifics of the contestant snowmobiles. The noise measurement procedure conformed to SAE J192, the full-throttle acceleration test, which starts the vehicle acceleration at a point 75 ft down the track from the position nearest the microphone, 50 ft away. This test is different from the constant-speed pass-bys presented in the previous sections, so the results are not directly comparable. HMMH used the same instrumentation for the CSC measurements as for the February snow vehicle measurements described above. The data were similarly reduced to the A-level maximums and the associated 1/3-octave band spectra at those maximums. Figure 10 through Figure 25 present the spectra of the highest A-level L_{max} measured on each side (right and left) of each contestant snow machine. The overall A-weighted sound levels are shown at the left in each figure.

The only two machines to pass the combined SAE CSC 2002 Acceleration/Noise test were those submitted by Kettering University (71 dBA official test result) and the University of Idaho (73 dBA test result). These machines exhibited both noise emissions below 74 dBA and acceleration times of less than 10.5 seconds. The University of Buffalo machine had the lowest noise emissions (68 dBA test result), but failed the acceleration test at 11.7 seconds. No other machines passed the noise emissions test, since they had test results ranging from 75 dBA to 80 dBA.

As the figures show, there is significant variation in spectrum shape among the contestant snowmobiles. For example, the Clarkson University machine (Figure 10) exhibits few tonal peaks, and at frequencies below 200 Hz, levels are less than 65 dB. In contrast, the snowmobile from the Michigan Technological University (Figure 17) exhibits two strong tonal peaks above 75 dB at 50 Hz and 100 Hz, although the A-level of the Michigan machine (72 to 73 dBA) is lower than that of the Clarkson snowmobile (75 to 77 dBA). This comparison is a clear example of how the A-weighted sound level is not sufficient to describe noise from snow machines where audibility at long distances is of concern. The snowmobile from the Michigan Technological University would be audible at significantly greater distances than the machine submitted by Clarkson University.

Among all the contestant machines, while its A-levels were not the lowest, the Clarkson University snowmobile emitted the least sound energy with the smoothest spectrum below 250 Hz; sound levels were below 70 dB at all frequencies of 250 Hz and below. Some machines exhibited tonal peaks with 1/3-octave band sound levels between 70 dB and 75 dB in that frequency range. Those snowmobiles were from Kettering University, University at Buffalo, University of Idaho, University of Waterloo, and University of Wisconsin at Madison. These machines would be more audible at long distances than the Clarkson University machine, but less audible than the other contestant snowmobiles, which had one or more low-frequency tonal peaks between 75 dB and 80 dB.

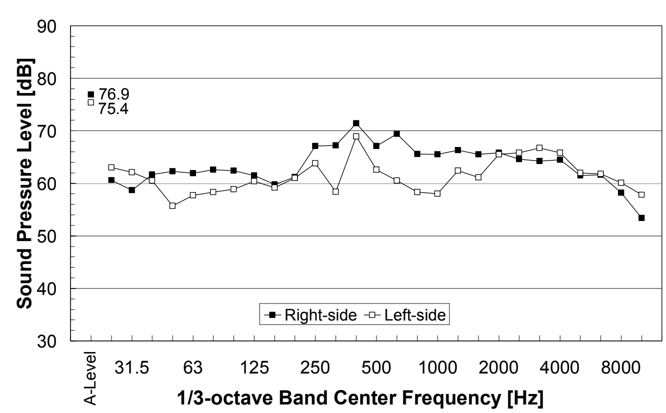

Figure 10. Clarkson University Snowmobile Sound Level Spectra

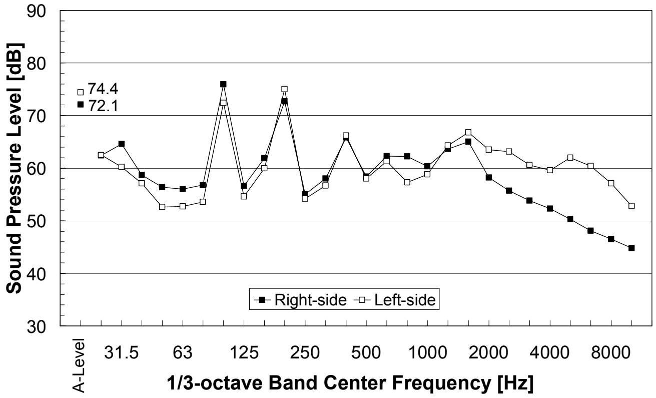

Figure 11. Colorado School of Mines Snowmobile Sound Level Spectra

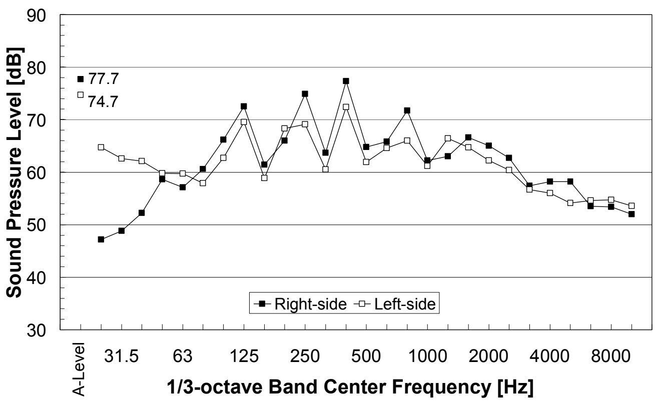

Figure 12. Colorado State University Snowmobile Sound Level Spectra

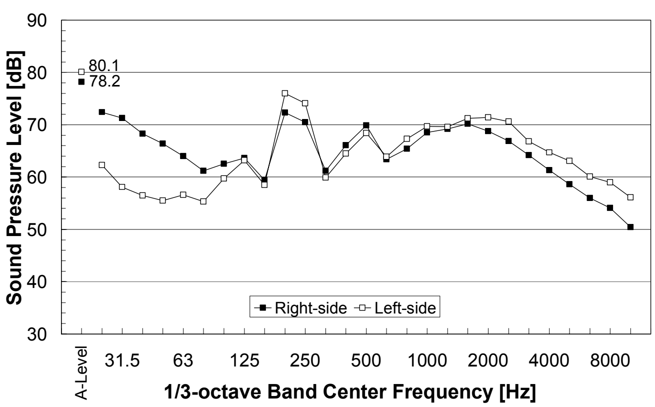

Figure 13. Control Snowmobile Sound Level Spectra

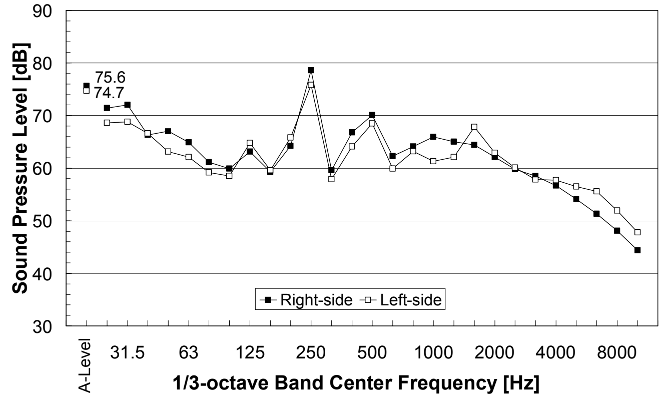

Figure 14. Idaho State University Snowmobile Sound Level Spectra

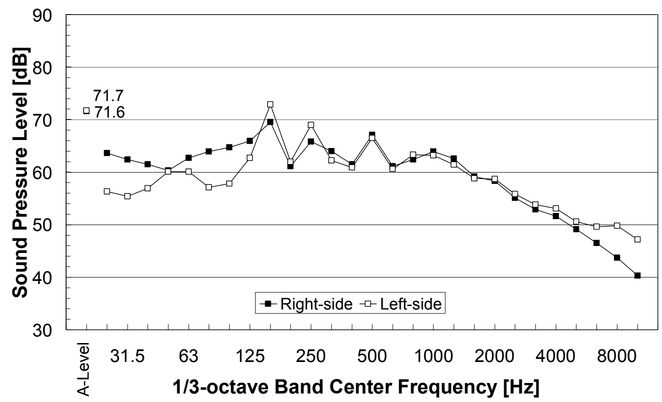

Figure 15. Kettering University Snowmobile Sound Level Spectra

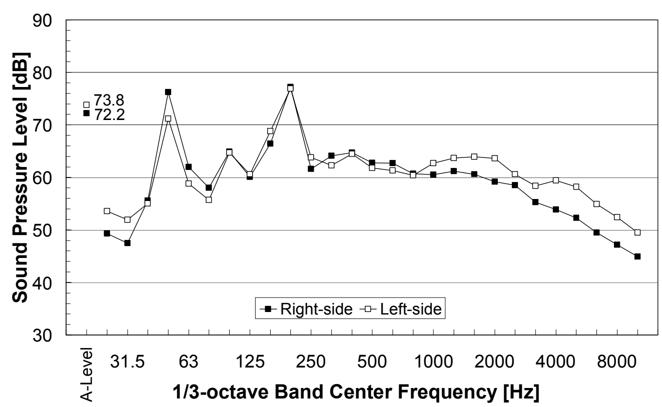

Figure 16. Minnesota State Univeristy - Mankato Snowmobile Sound Level Spectra

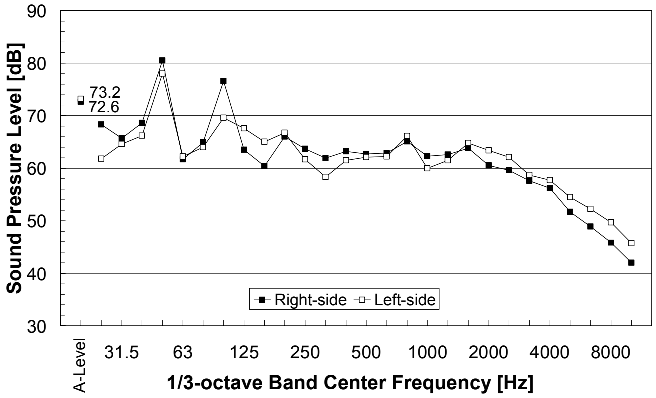

Figure 17. Michigan Technological University Snowmobile Sound Level Spectra

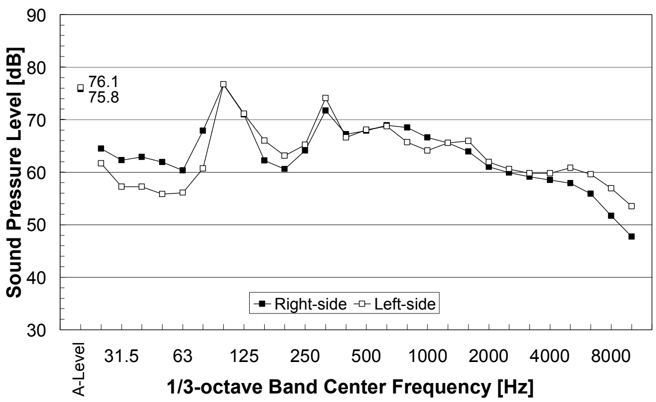

Figure 18. University of Alaska at Fairbanks Snowmobile Sound Level Spectra

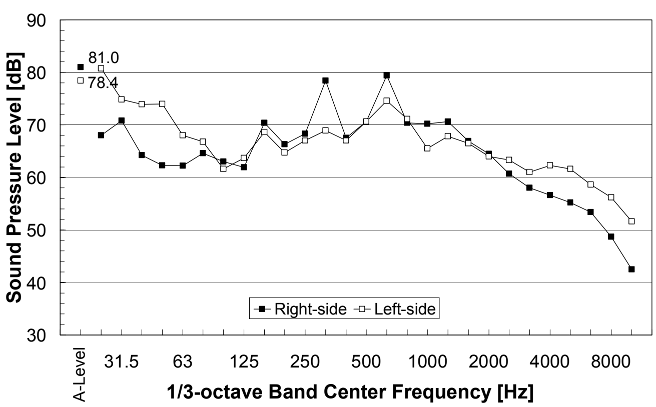

Figure 19. University of Alberta Snowmobile Sound Level Spectra

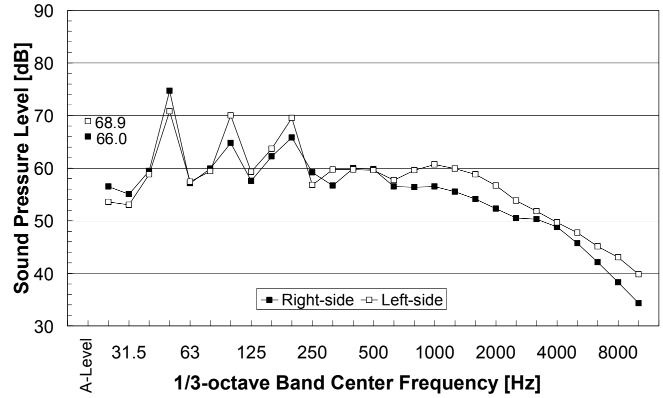

Figure 20. University at Buffalo Snowmobile Sound Level Spectra

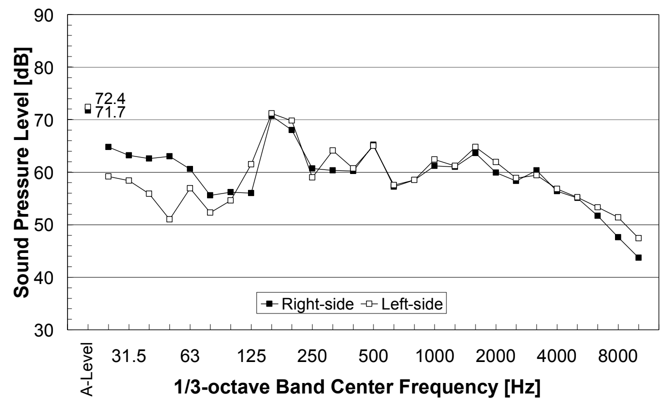

Figure 21. University of Idaho Snowmobile Sound Level Spectra

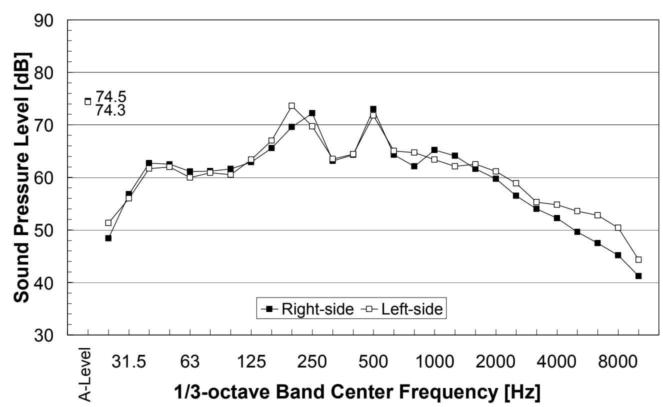

Figure 22. University of Waterloo Snowmobile Sound Level Spectra

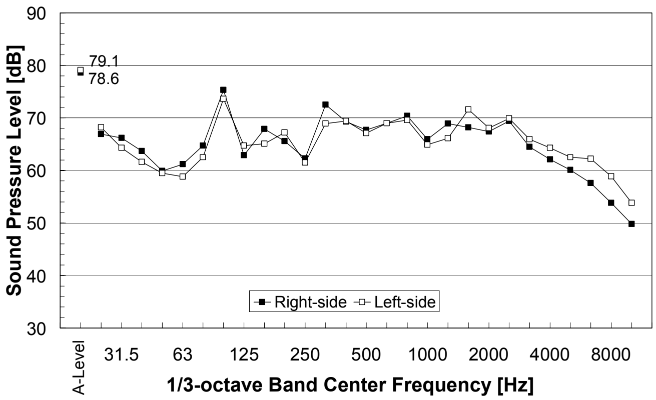

Figure 23. University of Wisconsin at Plattsville Snowmobile Sound Level Spectra

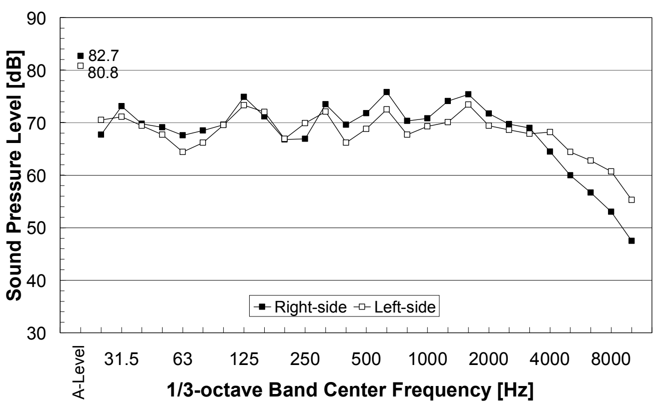

Figure 24. Sound Level Spectra of University of Wisconsin at Madison Snowmobile

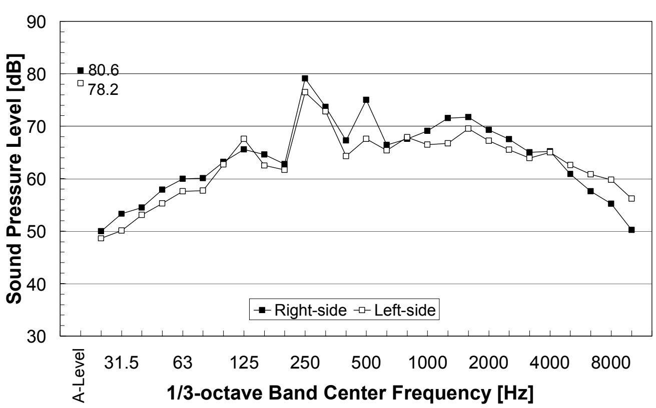

Figure 25. University of Wyoming Snowmobile Sound Level Spectra

CONCLUSIONS

This paper has demonstrated the significance of the frequency content in the noise emissions of snow vehicles as it pertains to the audibility of such vehicles in quiet background environments. Data were presented from controlled constant-speed pass-by measurements of sixteen snowmobiles and snow coaches from February 2002. In terms of the A-weighted sound levels at a 50-ft distance, the snowmobiles with four-stroke engines and the two-track conversion van snow coach were the quietest vehicles at all speeds. As groups, snow coaches and two-stroke snowmobiles produced similar average A-weighted sound level emissions, but there was significantly greater variation among the snow coaches.

Vehicles that produce prominent low-frequency tones and/or significant low-frequency sound energy (at frequencies of about 250 Hz and below) can be heard at significantly longer distances than vehicles with less low-frequency noise emissions. The machines exhibiting the least low-frequency energy were the two-track conversion van snow coach and two Polaris snowmobiles with two-stroke engines.

Measurements of spectral content at the SAE Clean Snowmobile Challenge 2002 also revealed significant differences among the contestant snowmobiles, tested under full acceleration. The Clarkson University snowmobile produced the least low-frequency energy, with no prominent tones, although it's A-weighted sound level was only average. Some contestant machines with lower A-levels had significant low-frequency tones that would be heard at much longer distances.

The data show that there is great variation in low-frequency sound energy among over-snow vehicles, and that the low-frequency content is not correlated with the A-weighted sound level. Therefore, close-in measurements of A-levels are not sufficient to describe the noise characteristics of over-snow vehicles, when audibility at long distances is at issue.

Finally, it must be noted that the issues surrounding sound propagation and the audibility of sound sources over long distances are complex ones. Further research is needed in both the measurement and modeling of sound at long distances in remote environments.

REFERENCES

1. "Winter Use Plans Final Environmental Impact Statement for the Yellowstone and Grand Teton National Parks and John D. Rockefeller Jr., Memorial Parkway," U.S. Department of the Interior, National Park Service, October 2000
2. "Technical Report on Noise: Winter Use Plan Final Environmental Impact Statement for the Yellowstone and Grand Teton National Parks and John D. Rockefeller Jr., Memorial Parkway," Harris Miller Miller & Hanson Inc. Report No. 295860.18, June 2001.
3. Title 16, US Code, Section 1.
4. The term "natural soundscape" is equivalent to the terms "natural quiet," "natural sound environment" and "natural ambient."
5. For example, see National Park Service Management Policies 2001, Sections 1.4.6, 4.9 and 8.2.3.
6. National Park Service Management Policies 2001,

Section 8.2.3.
7. Menge, C.W., and J.Ross, “Measurement and Modeling of Snowmobile Noise and Audibility at Yellowstone and Grand Teton National Parks,” Proceedings of Noise-Con 2000, Newport Beach, CA, December, 2000.
8. Fidell, Sanford, et al., “Evaluation of the effectiveness of SFAR 50-2 in restoring natural quiet to Grand Canyon National Park,” NPOA Report No. 93-1, June 23, 1994, p. 55.
9. Menge, C. W., C. F. Rossano, G. S. Anderson, and C. J. Bajdek, “FHWA Traffic Noise Model (FHWA-TNM), Version 1.0, Technical Manual” Report No. DOT-VNTSC-FHWA-98-2, February 1998.
10. Embleton, Tony F. W., J. E. Piercy, and G. A. Daigle, “Effective flow resistivity of ground surfaces determined by acoustical measurements,” *J. Acoust. Soc. Am.,* vol. 74, pp. 1239-1244, 1983.
11. Delany, M. E., and E. N. Bazley, “Acoustical Properties of Fibrous Absorbent Materials,” *Applied Acoustics,* vol. 3, pp. 105-116, 1970.
12. Chessell, C. I. “Propagation of Noise Along a Finite Impedance Boundary,” *J. Acoust. Soc. Am.*, vol. 62, no. 4, pp. 825-834, 1977.
13. ISO 9613-2:1996 Acoustics -- Attenuation of sound during propagation outdoors -- Part 2: General method of calculation.
14. Miller, N.P., Menge, C.W., "Status of the I-INCE Initiative on Recreation Noise and Progress on Quantifying Noise Intrusions In Parks", paper nc01_061, Proceedings of Noise-Con 01, Portland, Maine - 2001 October 29 -31.
15. National Park Service, "Review of Scientific Basis for Change in Noise Impact Assessment Method Used at Grand Canyon National Park," Appendix E, "A-Weighted Level Differences Compared with Detectability," January 2000.
16. Daily, J., Raap, K., “Supplemental Over-Snow Vehicle Sound Level Measurements,” Society of Automotive Engineers, SAE 2002-01-2766, October 2002.
17. Fussell, L.M., Bishop, G.A., Daily, J., Haines, H., and Roseberry, S., “The SAE Clean Snowmobile Challenge 2002 – Summary and Results”, Society of Automotive Engineers, SAE 2002-01-2775, October 2002.
18. Auth, P.S., Chin, M.A., Hess, P.S., and Den Braven, K.R., “University of Idaho Clean Snowmobile Refinements”, Society of Automotive Engineers, SAE 2002-01-2756, October 2002.
19. Schwulst, K., Burton, T., Taylor, J.E., Kampman, E., and Davis, G.W., “Kettering University’s Design and Refinement of an Automotive Based Four-Stroke Powered Clean Snowmobile”, Society of Automotive Engineers, SAE 2002-01-2757, October 2002.
20. Wilson, B., Fitshorn, P., Schaeffer, S., Bauer, T., Duncan, M., Lornez, N., Mastbergen, D., Nelson, S., Peterson, N., Rupp, J., Wedryk, B., Mathis, T., “Colorado State University Clean Snowmobile Challenge 2002”, Society of Automotive Engineers, SAE 2002-01-2758, October 2002.
21. Mills, N.A., Bratek, A.P., Cline, D.R., Wetzel, M.J., “Reducing the Emissions and Noise of a Turbocharged, Four-Stroke Snowmobile”, Society of Automotive Engineers, SAE 2002-01-2759, October 2002.
22. Peterson, R. and Benning, C., “The University of Alberta Four Stroke Ski-Doo MXZ-X Conversion”, Society of Automotive Engineers, SAE 2002-01-2760, October 2002.
23. Marchaus, J.G., Allen, J., Bauer, T., Martink, C., Boyarski, N., Mauerann, F., Tevis, L., Trettin, D., and Bower, G.R., “A Clean, Quiet, Environmentally Friendly Snowmobile”, Society of Automotive Engineers, SAE 2002-01-2763, October 2002.
24. Wegleitner, J.A., Miers, S.A., Hayes, R.D., Heim, S.P, Hoffman, D.P., and Bettig, B., “Design and Testing of a Single Cylinder, Turbocharged, Four-Stroke Snowmobile with E.F.I. and Catalytic Exhaust Aftertreatment”, Society of Automotive Engineers, SAE 2002-01-2761, October 2002.
25. Boutilier, C., Davidson, A., Derks, M., Flynn, K., Horne, B., Irvine, M., Kuntz, M., Lothian, A., Olsen, D., Van Driel, T., and Fraser, R., “Development Solutions to a Cleaner, Quieter, Two-Stroke Snowmobile”, Society of Automotive Engineers, SAE 2002-01-2762, October 2002.
26. Anderson, T., Brandl, M.T., Gillen, J.C., Ranweiler, C., Smith, J., Swanson, N.J., Utes, D.R., Bock, W., Bredemus, N., Dobesh, D., Hanson, T., Kellander, J., Laconic, A.J., Losinski, J.L., Mohrfeld, J., Poylio, M., Sandlin, M.D., Wilkie, J.R., Jones, B., and Ready, K., “Thorough Analysis of a Two-Stroke Cycle Engine Versus a Four-Stroke Cycle Engine: Minnesota State University Mankato’s Entry for the SAE Clean Snowmobile Challenge 2002”, Society of Automotive Engineers, SAE 2002-01-2764, October 2002.