National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Modeling Noise from Snow Vehicles in Yellowstone National Park

Tools Utilized for the 2011 EIS and 2012 SEIS

DRAFT Natural Resource Technical Report NPS/XXXX/NRTR—2012/XXX

ON THE COVER
A train of snowmobiles getting underway on a snow road in Yellowstone
Photograph courtesy of Yellowstone National Park

Modeling Noise from Snow Vehicles in Yellowstone National Park

Tools Utilized for the 2011 EIS and 2012 SEIS

DRAFT Natural Resource Technical Report NPS/XXXX/NRTR—20XX/XXX

Kurt Fristrup, Damon Joyce

National Park Service
Natural Sounds and Night Skies Division
1201 Oakridge Drive, Suite 100
Fort Collins, CO 80525

Charlotte Formichella, Cecilia Leumas

Colorado State University
1201 Oakridge Drive, Suite 100
Fort Collins, CO 80525

August 2012

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service (NPS), Natural Resource Stewardship and Science office in Fort Collins, Colorado publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Technical Report Series is used to disseminate results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The series provides contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This draft report has been informally reviewed by subject matter experts who were not involved in the development of the results. The noise modeling presented in this report does not require formal peer review because it constitutes: "routine statistical data used to compute standard indicators and trends that are gathered using methods based on well-established, peer-reviewed protocols and are analyzed and interpreted within the guidelines of the protocols." Noise modeling was performed with the Noise Model Simulation package (NMSim). NMSim has undergone more rigorous testing than is mandated by the peer review requirements set forth in the OMB Guidance on Peer Review (The Office of Management and Budget (OMB) Final Information Quality Bulletin for Peer Review, December 16, 2004). NMSim has been in development and use for 20 years. In 1998 an interagency, multidisciplinary noise model validation study was initiated to empirically test the ability of four noise models to predict the audibility of aircraft noise at Grand Canyon. Forty seven scientists and engineers from ten federal agencies and engineering companies participated in the study design, execution, and review of the results. The final report (2003) concluded: "Overall, NMSim proved to be the best model for computing aircraft audibility, because it is shown to have the most consistent combination of low error, low bias, and low scatter for virtually all comparisons."

Consequently, in 2004 NPS issued a Federal Register notice (vol. 68, no. 216, p 63131) stating that NMSim would be the model for calculating aircraft audibility at Grand Canyon and other NPS units. A subsequent Federal Interagency Committee on Aircraft Noise (FICAN) report comparing NMSim and the Integrated Noise Model (INM: John A. Volpe National Transportation Systems Center) concluded that both models were based on well-established physics and had been field validated. The application of NMSim to snow vehicle noise mapping was performed in accordance with guidance from and discussions with the program's developer. NMSim output files were processed and condensed to provide noise summaries. These condensations involved routine algebraic summations of contributions from each vehicle on each route segment, using formulae derived from physical principles of conservation of energy and the statistics of random processes, as described in the methods. The latter were subject to an independent study by the Volpe Transportation Center (Boeker *et al.* 2012a, 2012b).

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the

This draft report is available from the Natural Sounds and Night Skies Division of Natural Resources Stewardship and Science, and the final version will be posted on the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Once the report is formally published, the appropriate citation for this publication will be of the form:

Fristrup, K., D. Joyce, C. Formichella, and C. Leumas. 2012. Modeling noise from snow vehicles in Yellowstone National Park: methods employed for Winter Use NEPA analyses for the 2011 EIS and 2012 SEIS. Natural Resource Technical Report NPS/XXXX/NRTR—20XX/XXX. National Park Service, Fort Collins, Colorado.

NPS XXXXXX, Month Year

Contents

Page

Figures

Tables

Page

Abstract

This report describes the computational tools that were utilized to evaluate snow vehicle noise impacts for the Yellowstone 2011 EIS and 2012 SEIS analyses. The Noise Model Simulation (NMSim) computer program was utilized to generate spatially explicit measures of noise exposure. These noise maps were summarized in terms of three measures of noise exposure: Peak 4 (a measure of highest received noise level), Percent Time Audible (a measure of the duration of perceptible noise exposure), and $L_{eq,\ audible}$ (a measure of average noise loudness when audible).

The Natural Sounds and Night Skies Division of NPS Natural Resources Stewardship and Science implemented software tools that ingested the NMSim model output and enabled flexible combination of these data to rapidly generate composite noise maps resulting from all snow vehicle traffic in the park. These tools also enabled creation of new graphical displays that depict several measures of noise exposure.

These noise analyses also utilized formulae for evaluating the aggregate noise generated by a group of snow vehicles as a multiple of the noise generated by a single vehicle. These formulae were exploited to speed noise modeling, and they informed discussions about the comparability of noise impacts from different types of tour groups.

Acknowledgments

NSNS is pleased to acknowledge several colleagues who helped orient and inform the models described in this report. John Sacklin and Wade Vagias (Yellowstone) and David Jacob (NRSS Environmental Quality Division) provided detailed guidance regarding management alternatives and analytical needs throughout the modeling process. Shan Burson (Yellowstone and Grand Teton) provided foundational data and shared insights from more than a decade of environmental sound monitoring and noise measurement. Among many supportive colleagues at the Volpe Transportation Center, Cynthia Lee, Aaron Hastings, Eric Boeker, and Gregg Fleming developed research results and guidance that elevated the winter use modeling process. Bruce Ikelheimer of Blue Ridge Consulting far exceeded any reasonable expectations in his prompt and unfailingly patient responses to our questions regarding NMSim use and interpretation of results.

List of Terms and Acronyms

EIS: Environmental Impact Statement

km: kilometer, or 1000 m, equal to 0.621371 mile

kph: kilometers per hour

$L_{Aeq,T}$: the equivalent A-weighted continuous sound level measured over a time interval of T, often abbreviated as L_{eq} when the time interval is understood. In Yellowstone Winter Use analyses, T is 8 hours when the duration of the average is not specified

$L_{Aeq,audible}$: the equivalent A-weighted continuous sound level measured over the time interval when the noise source is audible

log10(): the base 10 logarithm of the quantity inside the parentheses

m: meter, a unit of distance equal to 3.28084 feet

mph: miles per hour

NEPA: National Environmental Policy Act

NMSim: Noise Model Simulation, a program for modeling the spatial and temporal extent of noise as it propagates across the landscape. NMSim was developed by Wyle Laboratories, Inc. and Blue Ridge Consulting, Inc.

NSNS: The Natural Sounds and Night Skies Division of NPS Natural Resources Stewardship and Science, located in Fort Collins, CO (http://nature.nps.gov/sound/)

SEIS: Supplemental Environmental Impact Statement

Introduction

One of the most spatially extensive environmental effects of any transportation system is noise. Noise models are routinely used in airport and road projects to compare the acoustical consequences of different alternatives. In Yellowstone National Park, winter transportation on snow roads presents an unusual scenario: very light traffic (less than 500 vehicles per day), an eccentric mix of vehicles (best available technology snowmobiles and diverse snowcoaches), and an environment that under calm weather conditions can exhibit some of the lowest outdoor sound levels ever measured.

Noise modeling has been used in previous winter use planning for Yellowstone and Grand Teton National Parks to estimate the area affected by noise, and to evaluate differences in noise exposure that would result under a range of management alternatives (Hastings *et al.* 2006, Hastings *et al.* 2010).

In order to model the spread of noise across Yellowstone's landscape, standardized measurements of noise output were required of the vehicles being modeled. For the Yellowstone Winter Use plan, measurements were made of a wide range of vehicles on snow roads in the park (reference Volpe and Burson Reports). These noise measurements provided noise source spectral data that were used as input for the noise propagation modeling. "Spectral data" refers to sound levels measured for a range of 1/3rd octave bands that span the range of human hearing. Propagation and perception of noise vary with frequency (measured in cycles per second, or Hertz). Higher frequency components of vehicle noise lose energy more rapidly than lower frequency components as the noise spreads outwards from the source. However, higher frequency components of noise are more readily heard and identified by human listeners. Accordingly, any model that seeks to predict the spatial extent of audible noise must account for these frequency-specific effects.

Choice of Noise Model

Predicting the spatial extent of audible noise from snow vehicles in Yellowstone poses significant challenges, due to extremely low background sound levels and the numerous factors that affect the attenuation of noise energy at very long ranges. When the 2011 EIS process began, there were two noise propagation models available to the NPS that could model audibility: the Integrated Noise Model (INM) developed by the John A. Volpe National Transportation Systems Center (Volpe: Cambridge, MA), and the Noise Model Simulation (NMSim) developed by Wyle Laboratories (Arlington, VA) and Blue Ridge Consulting (Asheville, NC).

INM was used in the snow vehicle noise study conducted by Volpe in support of the 2007 Yellowstone EIS (Hastings *et al.* 2006, Hastings *et al.* 2010). The report found that the percent of the park area in which any snow vehicle noise would be audible varied from 10-15% for the modeled alternatives. However, the 2007 EIS noted that INM underestimated the measured sound level of snow vehicles at eight of twelve monitoring sites in the park and underestimated the percent time audible at seven of twelve sites (and overestimated audibility at one site).

The NPS Natural Sounds and Night Skies Division (NSNS) chose to utilize NMSim for the 2011 EIS and the 2012 SEIS, to explore how strongly the noise mapping results depended upon the model used, and to prepare for future use of some additional features in NMSim. NMSim can produce animated maps illustrating the temporal and spatial dynamics of noise exposure. These animations offer insights into the physics of noise propagation, and are suitable for a broader range of audiences than large tables of numbers. In addition, NSNS has worked with one of the developers of NMSim to integrate sound propagation code – Nord2000 – that can account for some effects of wind and temperature inversions into NMSim. Previous winter use NEPA documents have acknowledged the substantial effects of these atmospheric conditions on noise propagation in the park. For example, temperature inversions will cause snow vehicle noise to be audible at greater distances than would be predicted under neutral atmospheric conditions (when sound travels along straight ray paths). NMSim/Nord will provide the capacity to evaluate these effects in the near future.

INM and NMSim have been extensively tested. In 1998 an interagency, multidisciplinary noise model validation study was initiated to empirically test the ability of four noise models to predict the audibility of aircraft noise at Grand Canyon. Forty-seven scientists and engineers from ten federal agencies and engineering companies participated in the study design, execution, and review of the results. The final report (Miller *et al.* 2003) concluded: "Overall, NMSim proved to be the best model for computing aircraft audibility, because it is shown to have the most consistent combination of low error, low bias, and low scatter for virtually all comparisons." A subsequent review by the Federal Interagency Committee on Aircraft Noise (Fleming *et al.* 2005) included the following statements comparing INM and NMSim:

> *The components of both INM Version 6.2 and NMSim are based on well-established physics, and have been field validated.*
> *Substantial gains have been made with regard to understanding model-to-model differences; and many of those differences have been reduced or eliminated.*
> *However, when comparing INM Version 6.2 and NMSim, there still remain some differences, particularly with point-to-point comparisons.*
> *Both INM Version 6.2 and NMSim are performing equally well, on average, when compared with the "gold standard" audibility data measured in the GCNP MVS.*

GCNP MVS refers to Miller *et al.* 2003.

Study Area

The noise model results generated for the 2011 EIS and the 2012 SEIS encompassed a rectangular region that enclosed all of Yellowstone National Park that received measurable noise levels (small portions of the park lie outside of the rectangle). The southwest corner of this rectangle was at UTM zone 12 coordinates 4886890 (northing), 492457 (easting); the northeast corner of this rectangle was at 4990058, 580622 (all UTM coordinates reference the NAD83 datum). Noise exposure levels were computed on a regularly spaced grid of points within this rectangle; the grid contained 200 points per side. Accordingly, the spatial resolution of the noise maps was approximately 500 meters. A topographic raster file of the study area was ingested from the USGS Seamless Data Warehouse (www.seamless.usgs.gov).

Methods

NMSim Input Parameters

NSNS used NMSim (Noise Model Simulation; Wyle Laboratories) to simulate snow vehicles in Yellowstone National Park. These models were based on data from several sources. The acoustic ground impedance was set to 40 Rayls, corresponding to terrain covered with granular snow. Dry, unconsolidated powder snow can have ground impedance as low as 10 Rayls, which would result in greater absorption of noise, but granular snow was chosen as more representative of typical conditions. The air temperature and relative humidity were set to -8.4°C and 73.9% respectively, the seasonal averages for Yellowstone (Hastings *et al.* 2006). NMSim, like INM, can calculate several summary metrics of noise exposure at sites of interest. Thirteen sites were specified (Hastings *et al.* 2010, Figure 28), with a receiver height of four feet above ground level (AGL). All of these choices conformed to the values used for the previous INM modeling (*ibid.*).

One difference between the NMSim modeling and the previous INM models was the ambient sound level specification. The INM models designated two zones of ambient; these NMSim runs simplified the analysis by applying the 1/3 octave spectra data from the "Forested Area Acoustic Zone" (*ibid.* Table 1) throughout the park. The NMSim simulations ignored the effects of vegetation, to speed execution of the model, at the cost of introducing an upward bias in model results at locations whose line-of-sight paths to the snow road intersect a hundred meters or more of vegetation. Other sources of deviations from modeled attenuation – varying wind, humidity, and atmospheric temperature profiles – will be much larger than the bias introduced by omitting vegetation at most sites in the park.

Each NMS simulation required a trajectory file for the modeled vehicle. This trajectory file incorporated vehicle type, speed, direction of travel, and noise source height as parameters. The snow roads in the park were split into modeled road segments and saved as shapefiles using ArcGIS 9.3. Each segment shapefile was imported into NMSim as a base layer. This base layer was used as a frame of reference to digitize each trajectory. Snow vehicle noise source heights were 0.47 m above ground level (AGL) for snowmobiles and 0.91 m AGL for snowcoaches. Wheeled vehicles source heights were 0.47 m AGL for the car and 0.61 m AGL for the bus and medium truck sources.

The road segments that make up the West Entrance to Old Faithful route were modeled at 40 kph (25 mph) and 56 kph (35 mph) for the snowmobile and 40 kph (25 mph) for the snowcoaches. Every other route in the park was modeled using 56 kph (35 mph) and 72 kph (45 mph) for the snowmobile and 40 kph (25 mph) for the snowcoaches. All wheeled vehicles were modeled at 56 kph (35 mph). These speeds were based on local speed limits and park expert observations regarding typical operating speeds. When the modeled speeds do not match any speed at which vehicle noise levels were measured, NMSim interpolates to obtain the appropriate value. A 5-second time step was used for these simulations, resulting in spatial steps of 56 m (40 kph), 78 m (56 kph), and 100 m (72 kph).

NMSim simulations utilized a grid size of 200x200 points to evaluate noise exposure throughout Yellowstone. This corresponded to a spatial resolution of approximately 500 m. The full grid and receiver location data for every run were saved to text files. The full grid data provided the raw material for subsequent summations of the aggregate noise exposure due to the full complement of snow vehicle traffic on each route for each of the proposed management alternatives. The receiver location data provided convenient summaries of noise exposure at specific locations. The full grid output is a text file containing all of the 1/3 octave band data at each time step for every grid point. The receiver location output contains the 1/3 octave band data at each time step and some additional summary metrics.

Noise source spectra

The noise source spectra for the simulations were obtained from the NMSim noise source library (wheeled vehicles), U. S. DOT Volpe Transportation Center (snow vehicles: Hastings *et al.* 2006) and unpublished snow vehicle measurements made in March 2012 by Shan Burson in Yellowstone National Park using standardized measurement procedures (*ibid*., SAE 2004). These source data were obtained at a standard measurement distance of 15 m (50 ft). These levels were reduced by 26 dB to account for NMSim's reference distance of 305 m (1000 ft), in accordance with instructions provided by the developers of NMSim. NMSim expects that input noise source levels incorporate spreading or divergence loss as the sole attenuating factor affecting these reference levels.

For the combined 2011 and 2012 modeling efforts, six snowcoaches, one snowmobile, and three wheeled vehicles were used as noise sources. Although noise models were run for all of these vehicles, some results were not used in either NEPA document.

Table 1. Vehicle types modeled in NMSim, with annotations to note the NEPA documents in which the results were used.

Vehicle Description	2011 EIS	2012 SEIS
Alpine Kitty snowcoach (AK)		+
Buffalo Bus Touring #3 snowcoach, Ford E-350, mattrack x4 (B3)		+
Buffalo Bus Touring #8 snowcoach, Ford F-550, griptrack (B8)		+
Volpe generic mattrack snowcoach (SCM)	+	+
Volpe generic Bombardier snowcoach (SCB)		
Volpe generic fulltrack snowcoach (composite energy average) (SCF)		
Volpe 4-stroke snowmobile (composite energy average) (SM4)	+	+
NMSim standard automobile (CAR)	+	
NMSim standard van (CAV)	+	
NMSim standard medium truck (MTK)	+	

Table 2. Modeled 1/3rd octave noise spectra in centibels (= 10*decibels) as a function of vehicle speed in miles per hour

Vehicle	SCB	SCB	SCB	SCF	SCF	SCF	SCF	SCM	SCM	SCM	AK	AK	AK	AK	AK	B3	B3	B8	B8	SM4	SM4	CAR	CAR	CAV	CAV	MTK	MTK
MPH	15	20	35	10	15	20	35	10	20	35	10	15	20	25	30	15	22	15	22	30	40	20	40	20	40	20	40
Hz																											
50	378	385	406	379	366	305	306	294	311	299	333	350	386	386	367	296	308	389	371	213	277	-72	-9	-68	-7	129	111
63	375	387	412	343	308	406	432	365	253	360	492	387	360	371	383	335	305	289	427	252	271	6	78	10	80	164	165
80	441	443	436	243	364	293	334	255	282	295	415	427	418	366	342	463	299	313	351	465	314	46	126	51	127	188	202
100	365	406	347	365	311	382	481	260	327	288	432	383	360	348	355	309	477	308	356	288	302	65	148	70	150	205	228
125	357	412	401	250	379	412	389	276	275	365	355	308	341	386	347	286	409	277	353	376	410	75	161	80	164	219	250
160	402	416	526	229	309	269	418	237	248	358	238	321	352	387	444	352	369	285	350	422	406	87	175	92	179	236	274
200	395	427	432	250	281	329	363	293	352	356	237	305	323	328	343	311	383	322	397	384	328	102	194	107	197	255	300
250	353	432	428	271	298	278	359	274	331	402	208	297	327	340	334	354	420	313	362	409	399	125	220	130	224	279	329
315	331	406	445	309	347	329	426	300	373	449	182	278	308	329	354	367	441	295	312	338	439	160	259	165	263	312	368
400	297	393	458	248	281	305	400	312	385	390	152	257	287	302	303	321	383	262	263	438	381	211	314	216	319	358	419
500	319	379	397	240	289	333	372	264	346	402	181	252	284	309	309	301	359	249	268	414	394	253	360	258	366	395	459
630	273	360	402	240	268	333	355	274	327	363	191	251	287	319	314	304	335	270	272	350	414	234	346	240	353	371	438
800	312	357	428	253	274	358	372	256	314	359	177	243	271	307	308	281	325	270	291	317	345	201	317	207	325	333	401
1000	295	338	406	378	285	339	397	247	331	350	207	250	270	305	304	281	315	260	290	329	324	180	299	187	309	310	378
1250	263	360	393	299	259	352	390	247	310	355	193	260	288	313	312	283	310	298	307	309	354	173	292	180	304	302	368
1600	250	311	391	223	251	326	364	246	293	319	182	222	246	282	290	267	297	286	310	323	350	189	308	197	321	320	383
2000	238	302	395	232	217	293	314	215	262	300	153	208	233	276	285	258	287	297	311	344	355	240	357	249	372	374	435
2500	232	307	367	224	268	295	331	202	234	285	141	215	232	262	283	247	277	276	289	316	355	147	259	155	275	284	342
3150	209	277	358	201	245	288	306	184	228	278	134	185	207	246	260	238	265	261	279	309	332	124	231	133	248	266	321
4000	191	268	338	194	227	288	293	197	224	267	102	155	177	214	233	212	249	237	257	303	297	130	230	140	247	275	328
5000	175	270	303	163	308	324	278	197	217	260	91	143	162	194	209	213	250	225	252	266	276	90	183	100	201	237	289
6300	172	273	281	145	172	208	230	202	196	247	120	129	141	177	197	197	223	190	224	238	264	34	122	45	140	184	234
8000	152	226	248	130	149	171	191	213	167	220	31	114	160	165	171	163	198	176	204	194	236	2	88	13	107	157	203
10000	110	188	213	99	144	162	156	220	148	190	26	93	115	137	149	150	175	157	194	159	201	-31	59	-20	80	133	173

Interactive Noise Mapping Framework

Noise modeling is a computationally intensive process. Modeling a full alternative can require more than one week of continuous processing on several computers. This delay inhibits development of intuitive understanding of the physics of noise that could be fostered through an interactive process of alternative modification and evaluation. Accordingly, NSNS developed an alternative approach to modeling that created opportunities for very rapid evaluation of alternatives. The key to this approach was the realization that all conceivable alternatives share common elements: the noise contributions of each type of vehicle as they traverse each unique segment of the snow road system at Yellowstone. These “elemental” noise footprints can be modeled individually and stored for inclusion in subsequent alternative analyses. For each new alternative, composite noise exposures due to all of the traffic can be computed as the sum of all contributions from each vehicle transiting each road segment.

The first step in developing interactive noise mapping capability was to identify all of the unique combinations of vehicle type, operating parameters, and route segment that might be evaluated in the alternatives development process. For Yellowstone, this involved identifying the segments of the snow road network that could have different traffic levels. The following table lists the junctions that defined the endpoints of the road segments that were modeled:

Table 3. Snow road segments utilized in winter use noise modeling

Location	UTM Zone 12 Northing	UTM Zone 12 Easting
Upper Terrace, Mammoth Hot Springs	4979168	523012
Norris Junction	4952698	524029
Canyon Village	4953710	540066
West Entrance	4945036	492293
Madison Junction	4943549	511224
Fishing Bridge	4935133	548580
East Entrance	4926736	579388
Five Mile (not labeled on the map)	4924052	573938
Old Faithful	4923077	512355
West Thumb	4917937	533563
South Entrance	4886683	526837

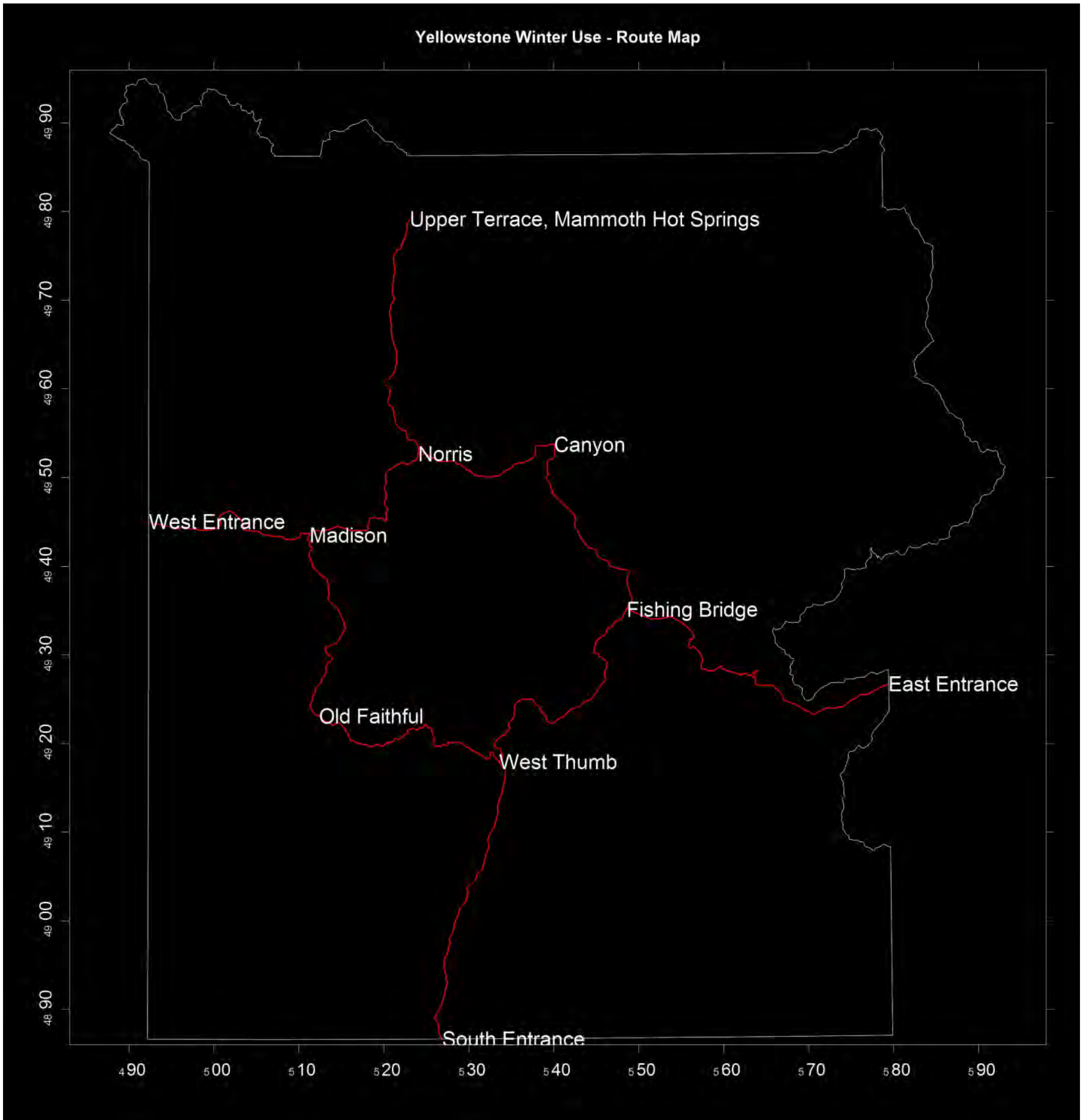

Figure 1. Schematic map of snow road segments used for winter use modeling. The horizontal axis is UTM Easting. The vertical axis is UTM Northing. The "Five Mile" point just west of the East Entrance is not shown in this map.

Note that typical tour routes involved a combination of two or more segments. A trip from Mammoth Hot Springs to Old Faithful would involve a combination of the Mammoth-Norris, Norris-Madison, and Madison-Old Faithful segments.

Each segment was modeled in both directions of travel. NMSim accounts for the change in engine loading with the slope of the road. Hundreds of NMSim simulations were computed. At the beginning of the 2011 modeling effort, each round of noise modeling took more than a week, with several machines running continuously. They generated nearly one terabyte of output data. These data were processed by software developed by NSNS to compress and index the data for faster loading by a subsequent program. This compression required about one day of continuous processing time. By the end of the 2012 effort, improvements in NMSim and in NSNS hardware configurations enabled each round of modeling and output data compression took less than a day.

The interactive software developed by NSNS ingests two files: a comma separated value (CSV) file containing the traffic levels for each vehicle, operating condition, and route segment, and the large data file with the NMSim noise data for each combination of vehicle and road segment. This program generates several maps that graphically summarize the spatial extent of noise exposure, as well as tables providing numerical summaries of noise.

The NSNS iterative mapping framework has several benefits. New kinds of noise maps and tabular summaries can be rapidly implemented, thanks to the flexible structure of this software. All of the NSNS code was implemented in R, an open source software environment that is available for free (R Development Core Team, 2010). More importantly, the consequences of revised alternatives can be evaluated in a few minutes, or about 1000 times quicker than would be possible if the revised alternative had to be modeled by computing a full set of noise models.

The computations in this iterative framework utilize the exact same computations that the models would employ if they were used to process the composite alternatives as a whole. For peak noise exposure levels, the iterative framework simply identifies the component of the local traffic that generated the loudest event. Aggregate noise energy is very simple to compute, as noise energy from multiple sources can be summed. This simple approach to summing noise energy assumes that the noise signals of different sources are incoherent, and it represents an example of the general physical principle of conservation of energy. For temporal metrics, like the duration of audibility, this framework utilizes a statistical formula that accounts for the probable overlap between adjacent noise events. This formula is adapted from Tanner (1951). Tests of this formula by the U. S. DOT Volpe Transportation Center (Boeker *et al.* 2012a, Boeker *et al.* 2012b) using data from the interagency model validation study at Grand Canyon (Miller *et al.* 2003) have proven this formula to provide the most accurate fit to the field data of the methods tested thus far.

Noise Metrics

The choice of noise metrics was motivated by three considerations: sustaining connections to previous noise impact analyses for Yellowstone and other NPS park units, incorporating knowledge gained from recent research and engineering developments, and improving the robustness of the results by diminishing the potential effects of modeling idiosyncrasies.

The percent time that vehicle noise is audible was retained; it has been the foundation of all NPS noise impact assessments. Peak noise levels were modeled by Hastings *et al.* (2006), and a very similar metric was retained in this modeling effort. Instead of using the peak noise level, this analysis used the energy average (L_{eq}) of the four loudest noise levels (“peak 4”). This slight modification offered two benefits. First, it reduced the variation in estimated peak level that results from the precise locations that the model happened to select when projecting vehicle noise along a road. Second, it provides an indication of the duration of this high noise level: 15 seconds. The third metric modeled was audibility L_{eq}.

L_{eq} metrics have been extensively studied for more than four decades in relation to transportation noise. The World Health Organization (WHO 1999) recommends that: “Where there are no clear reasons for using other measures, it is recommended that $L_{Aeq,T}$ be used to evaluate more-or-less continuous environmental noises.” In the quoted text, the “A” refers to A-weighted integration of acoustic power spectra, and the “T” refers to the interval over which energy is averaged. FICON (1992) noted that criticism of L_{dn} (and other L_{eq} metrics) often stems from “lack of understanding of the basis for the measurement, calculation, and application of that metric.” Many people have difficulty relating an aggregate of perceived noise events to an average noise level, especially when the time interval for averaging extends over long periods. Hourly, daily, and even annual L_{Aeq} metrics have been used by some U. S. Federal Agencies.

Noise due to snow vehicle traffic at Yellowstone is not continuous. There can be substantial intervals of silence, especially on snow roads that experience light traffic. Therefore, a daily L_{eq} is not the best metric for explaining noise exposures, even though it enjoys support from decades of research into the effects of noise in communities. NMSim predicts when noise will be audible, so a modified L_{eq} metric was devised to represent the average noise level when noise can be heard: $L_{Aeq,audible}$. Instead of dividing the integrated noise energy by the entire modeling interval (0800-1600), this formula divides the energy by the total time audible. $L_{Aeq,audible}$ does not discount the average level because there are intervals of silence in the modeled day. Therefore, $L_{Aeq,audible}$ is logically and statistically independent of percent time audible, one of the other metrics used to characterize noise impacts in Yellowstone (as well as other National Park units). One metric addresses noise intensity when present; the other addresses how often noise is present. This approach is derived from the recommendation of Miller (1999) for NPS noise analyses, and it has the property of converging on the familiar L_{eq} metric used in community noise analyses when noise is audible all of the time.

Note that $L_{Aeq,T}$ can be calculated from percent time audible and $LA_{eq,audible}$ **:**

$L_{Aeq,T} = L_{Aeq,audible} + 10*\log10(\text{percent time audible}/100)$

Evaluating the composite noise levels produced by groups

One of the salient characteristics of snow vehicle tour traffic is the organization of snowmobiles into guided groups. The acoustical effects of grouping vehicles can be approximated algebraically, so it is possible to scale up the NMSim results for a single vehicle traveling down a snow road to estimate the effects of a group of similar vehicles. The key concept is that the noise energy contributed by each vehicle is diminished by the square of the distance from the vehicle to the listener. When the listener is far enough away from the road that the distances to all of the vehicles is about the same, then the noise energy from the group will be equal to the noise energy from one vehicle multiplied by the number of vehicles in the group. In terms of decibels:

$L_{group} = L_{vehicle} + 10 \log10(\text{number of vehicles})$

The following table shows the noise level increase of a group relative to a single vehicle. Note that this applies regardless of the single vehicle noise level. For example, a maximum group size of 11 BAT snowmobiles, each of which generates a noise level of 53 dB(A) at 150 meters, will generate an aggregate noise level of 54.4 dB(A) at 150 meters.

Table 4. Examples of group noise level increase in decibels (dB) relative to the noise level of a single vehicle

Number of vehicles	Group increase above single vehicle level in dB	Approximate percentage increase in maximum audible distance
2	3.0	41%
3	4.8	73%
4	6.0	100%
5	7.0	124%
6	7.8	145%
7	8.5	165%
8	9.0	183%
9	9.5	200%
10	10.0	216%
11	10.4	232%

The third column in Table 4 illustrates two effects of grouping snow vehicle traffic. A group of eleven snowmobiles can potentially be heard a bit more than three times as far away from the snow road as a single vehicle. This means that any concentration of traffic, whether organized as guided tours or as an accident of visitor stopping patterns due to scenery and wildlife, will cause noise to be audible farther from the snow road corridor. This effect is significantly mitigated by a related benefit. A group of eleven vehicles will generally be audible approximately three times as long as a solitary vehicle, or less than one third as much time as the summed audibility of eleven solitary vehicles. Grouping vehicles has significant benefits in terms of percent time audible and the duration of intervals free from noise.

When the listener is close enough to the line of vehicles that some vehicles are noticeably closer than others, Table 4 overestimates the aggregate noise level. This is because the nearest vehicles are much louder than the most distant vehicles, so all of the vehicles no longer make equal contributions to the total. The following table illustrates the effect of increasing distance for a group of 11 snowmobiles distributed evenly along 200 m of road (20 m between snowmobiles). The table presents these effects in terms of the largest increase in group noise level – which occurs when the middle vehicle is nearest to the listener – in terms of the increase in peak decibel level and also in terms of the equivalent number of vehicles this represents.

This table offers another interpretation. Consider two types of vehicles, one of which is 9 dB quieter than the other. A group of eight of the quieter vehicles, riding in close formation, will present the same noise impact to the park as one of the noisier vehicles.

Table 5. The effect of increasing distance from a group of 11 snowmobiles distributed along 200 m of road.

meters from group center	# vehicle equivalents	Group dB increase
5	1.2	0.7
10	1.6	2.1
20	2.8	4.5
50	5.7	7.6
100	8.3	9.2
200	10.1	10.0
400	10.7	10.3
800	10.9	10.4
1600	11.0	10.4

This table shows that a listener 5 m from the line of snowmobiles would experience peak noise level just 20 percent higher than the noise generated by a single vehicle. At 200 m from the road, a distance equal to the length of the line of snowmobiles, the peak noise level is equivalent to 10.1 vehicles, or 92% of the eleven-fold increase predicted by the long-distance approximation presented in Table 4.

One interpretive note regarding the decibel levels reported in the preceding two tables. The Type 1 sound level meters used by NPS to monitor acoustical conditions in parks are accurate to +/- 1 decibel, so differences in the tables of less than a decibel have no practical significance. Noise modeling is even less precise, and at long ranges experts would be pleased to have modeled noise levels that were within 2-3 decibels of the true value.

In closing this section, it is worth noting a unique property of daily L_{eq} as a metric. It does not matter how vehicles are grouped, or what the daily schedule of traffic is: L_{eq} is only affected by the number of vehicles, the amount of noise they generate, and the distance the travel in the park. The effects of grouping vehicles are confined to peak noise level, $L_{eq,audible}$, percent time audible, noise-free intervals, and the percent of park area receiving audible snow vehicle noise.

Modeling the effects of potential quiet technology

The preceding discussion of the effects of grouping vehicles provides a clue to the method used to estimate the benefits of requiring quieter snow vehicles in Yellowstone. For snowmobiles, the calculation was quite simple. The generic noise source level of for a four-stroke BAT snowmobile developed by Volpe was about 72 dB(A) at 30 mph, and 73 dB(A) at 40 mph, both measured at 50 feet from the road. In order to evaluate the benefits of an improved BAT snowmobile generating 67 dB(A) at 30 mph, the alternatives were set up to have 1/3rd as many snowmobiles per group, and 1/3rd as many snowmobiles overall. This kept the number of snowmobile groups constant, and reduced the noise radiated by each group of Volpe generic snowmobiles to the same level that would be achieved by the improved BAT snowmobiles. To evaluate the benefits of further noise reductions to 65 dB(A), the group size and total number of snowmobiles was reduced by a factor of five.

To analyze the benefits of BAT requirements for snowcoaches, the primary challenge was to assess the potential for future improvements by examining variation in the current fleet. The next table displays the noise level at a cruising speed of 25 mph at 50' distance for a selection of snowcoaches measured in 2008, 2009, and 2012 (Hastings, Scarpone, Burson 2012 unpublished).

Table 6. Cruising (25 mph) noise levels for snowcoaches at 50 feet

Vehicle	Year and Model	Track type	dB(A)
Yellowstone Expeditions	1994 Dodge B-350	18" Snowbusters	64
AlpineGuide	1979 Bombardier B-12	Bombardier	67
YellowstoneExpedition_Hayden	1994 Dodge B-350	24" Snowbusters	69
Xantera165	2001 GMS Conversion Van	Snowbusters	70
Yellowstone Snowcoach	2002 Ford Van	Mattrack x4	71
SeeYellowstoneTours_#4	2000 Ford Econoline	Mattrack 150 x2	71
Rocky Mountain Snowcoach	1999 Ford Econoline	Mattrack x4	71
YellowstoneExpedition_Eleanor	1997 E-170 Ford Van	18" Snowbusters	71
GooseWing	2006 Ford Size Van	Mattrack x4	72
XanteraMattTrack_430	2008 Chevrolet Express Van	Mattrack x4	73
YellowstoneSnowcoach_SNOVAN5	2001 Ford Econoline Van	Mattrack x4	73
YellowstoneSnowcoach_SNOVAN4	2000 Ford Econoline Van	Mattrack x4	73
Xantera431	2004 Chevrolet Express Van	Mattrack x4	73
BuffaloBusTouring_#4	2009 Ford F-550	Grip Tracks	73
Xantera_Bombardier_710	1966 Bombardier B-12	Bombardier	74
BuffaloBusTouring_#T2	2005 For E-350 'Vanterra' Minibus	Mattrack x4	75
BuffaloBusTouringCo_#3	2006 Ford E-350 Comm-Trans	Mattrack x4	75
Xantera_713	1968 Bombardier B-12	Bombardier	75
National Park Service Yellow Bus	2003 International Yellow Bus	Grip Tracks	76
SeeYellowstoneTours_#6	2004 Fort E-450 'Vanterra' Minibus	Mattrack 150 x2	76
Xantera_707	1966 Bombardier B12	Bombardier	77
Xantera_709	1966 Bombardier B12	Bombardier	78
SeeYellowstoneTours_#9	2007 Ford E-450 'Odyssey' Minibus	Tank tracks x2	80
Prinoth_537	1988 Prinoth Powder Tour Cat	Rubber tracks x4	83

The range in noise levels and overall patterns in the ordering of vehicle types suggest that there is substantial opportunity for the fleet to evolve towards quieter vehicles. The energy averaged noise level for the current fleet is 75.4 dB(A), with each vehicle counted equally. The operational average of the current fleet, given the actual proportions of each vehicle used, is 72.4 dB(A). If all vehicles with noise output above the current fleet average were eliminated – all the vehicles below the thick black line – the energy averaged noise level for the fleet would drop to 71.6 dB(A). If all vehicles with noise output above 71 dB(A) were eliminated, what might be termed enhanced BAT, the energy averaged noise level would fall to 68.4 dB(A). Three values – 72.4, 71.6, and 68.4 dB(A) – were used to guide the simulation of snowcoach contributions to the aggregate noise exposures of each alternative.

Unlike the snowmobile modeling, where just one source spectrum was available, there were several snowcoach noise spectra available from which to build up a representative fleet. The 2012 SEIS simulations utilized noise spectra from the Alpine Kitty, Buffalo Bus #3, Buffalo Bus #8, and the Volpe generic mattrack vehicles, with the proportions of these vehicles adjusted to generate a snowcoach fleet with the desired aggregate noise output. The following table indicates the proportions of these vehicles that were utilized to simulate the snowcoach noise contributions under current conditions, future BAT requirements, and enhanced BAT requirements (which allow a pair of snowcoaches to travel in each tour group),

Table 7. Proportions of modeled snowcoach types included in alternative modeling scenarios

Vehicle	dB(A)	Current operations	BAT fleet	Enhanced BAT fleet
Alpine Kitty	60.6	4%		20%
Buffalo Bus #8	66.7	3%	22%	19%
Buffalo Bus #3	69.8	10%	18%	61%
Volpe Mattrack	72.9	83%	60%	

Note that the Enhanced BAT snowcoach fleet scenario assumed that all snowcoach tours consisted of a pair of vehicles.

Results

A variety of noise model results are reported and explained in the 2011 EIS and the 2012 SEIS, and little purpose would be served by recapitulating that discussion here. Instead, this section will focus on a pair of images that provide some insight into the interactive noise mapping framework implemented by NSNS to provide opportunities for rapid assessment of changes in traffic allotments to road segments and vehicle types. The next figure illustrates the maximum noise levels generated from one type of vehicle travelling on the road segment from South Entrance to West Thumb. This image, which is generated directly from NMSim, includes topographic contour intervals in the background map, which provides examples of how terrain shapes the transmission of noise.

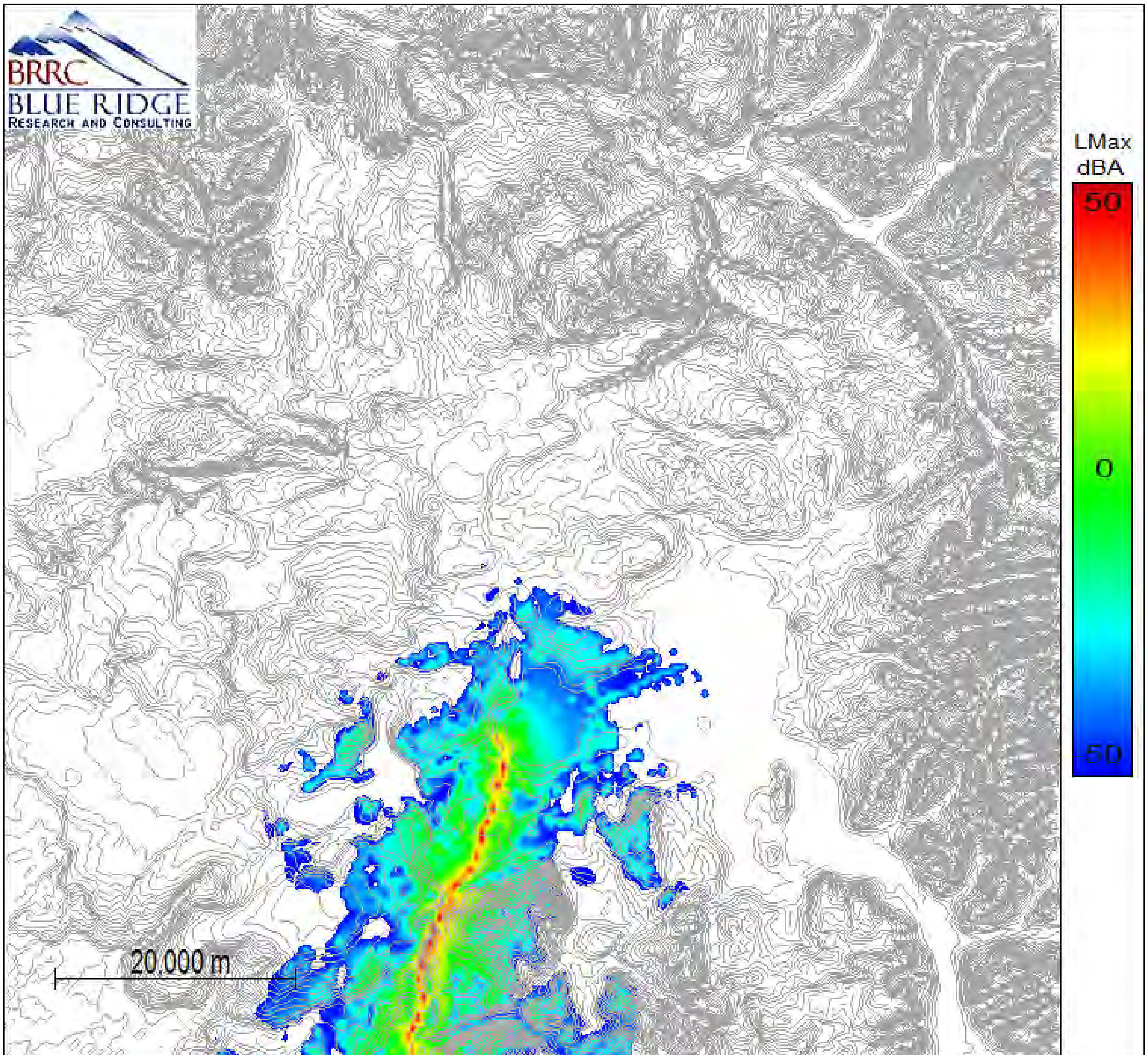

Figure 2. Example output of maximum noise level output from a single snow vehicle traveling on the snow road segment from South Entrance to West Thumb. This road corridor follows a relatively low path through the terrain. Areas of dense elevation contours (grey lines) indicate regions of high topographic relief.

The aggregate noise exposure from all snow vehicle traffic is created as a composite of these individual simulation results. For the Peak 4 noise metric, which is closely related to L_{max}, the maximum traffic levels permitted under the Interim Winter Use plan result in the following noise map.

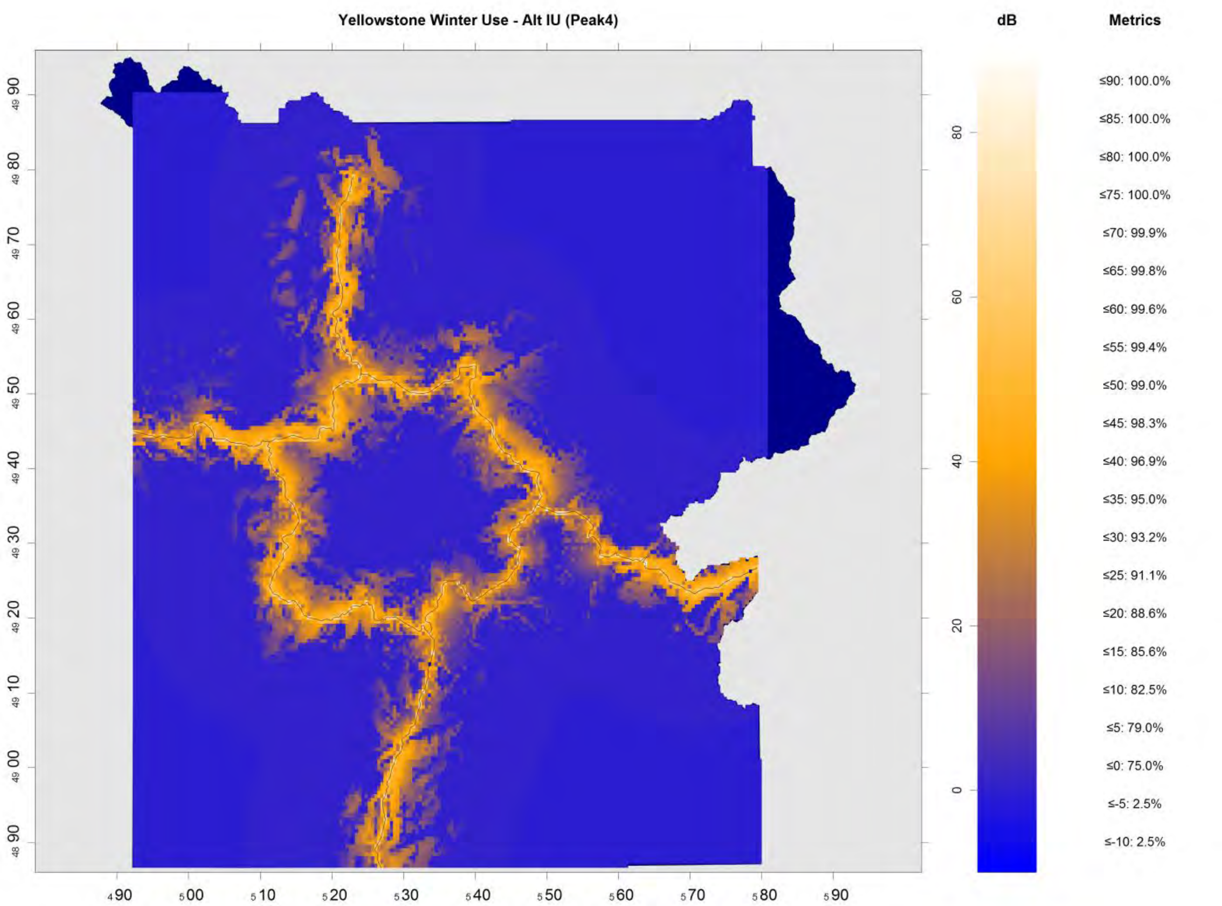

Figure 3. Example of Peak 4 noise exposures modeled under the maximum traffic levels allowed under the Interim Winter Use rule. The colorbar on the right depict the colors associated with Peak 4 decibel levels. The Metrics column indicates the percent of park area that has Peak 4 noise levels lower than the specified values. For example, 75% of the park experiences Peak 4 levels less than 0 dB(A). The lighter blue shading indicates the area inside the park boundary that was covered within the rectangular study area for the noise modeling. The darker blue areas excluded from modeling do not receive any measureable noise from snow vehicles inside the park.

One last map – which displays percent time audible for the same Interim Rule scenario – helps to illustrate some of the similarities and differences between measures of the intensity and duration of noise exposure. Note that Peak 4 does not vary with traffic intensity, but Percent Time Audible does.

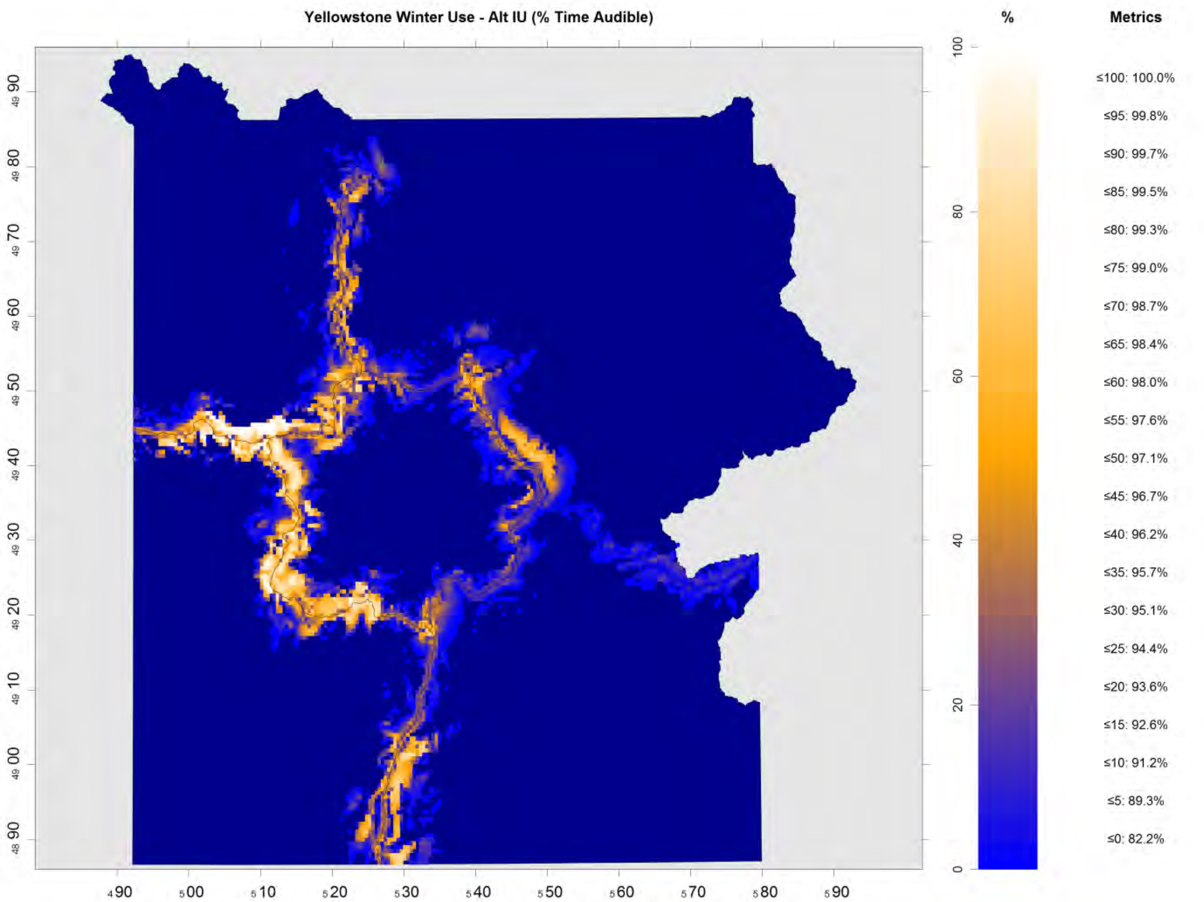

Figure 4. Example of Percent Time Audible noise exposures modeled under the maximum traffic levels allowed under the Interim Winter Use rule. The colorbar on the right depict the colors associated with audibility levels. The Metrics column indicates the percent of park area that has audibility levels lower than the specified values. For example, 16.8% of the park experiences audible noise from snow vehicles. This is slightly higher than results for any alternative analyzed using INM modeling conducted for the 2007 EIS. Accordingly, it is likely that the more recent NMSim results will more closely match the data collected during recent acoustical monitoring in the park.

Conclusion

The wide range of snow vehicle measurements offered by previous noise measurement studies combined with the interactive noise mapping scripts implemented by NSNS to offer the Yellowstone Winter Use planning team a rapid and flexible tool for assessing the effects of changes to potential management alternatives. Systematic analysis of the effects of snow vehicle grouping also supported evaluations the composite noise footprints of tour events, which supported the development of an approach to transportation management that focuses on impacts to acoustic resources rather than the identities of the vehicles.

Improvements in NMSim/Nord2000 modeling capability have created opportunities to investigate the effects of temperature inversions and other atmospheric conditions that markedly affect the spread of snow vehicle noise in the park. At the beginning of this modeling effort, it was infeasible to pursue model replicates that explored these atmospheric effects because of the compute time that was required. Incremental improvements in the speed of each model run and new capabilities to exploit multicore computational capacity have removed this obstacle, and future analyses will be able to generate quantitative comparisons of noise propagation under different weather conditions.

Literature Cited

Boeker, E. R., M. Ahearn, C. S. Y. Lee, C. J. Roof, G. G. Fleming 2012a. Analysis of Modeling Cumulative Noise from Simultaneous Flights, Volume 1: Analysis at Four National Parks. John A. Volpe National Transportation Systems Center, Cambridge, MA (draft).

Boeker, E. R., N. E. Schulz, C. S. Y. Lee, C. J. Roof, G. G. Fleming 2012b. Analysis of Modeling Cumulative Noise from Simultaneous Flights, Volume 2: Supplemental Analysis.: John A. Volpe National Transportation Systems Center, Cambridge, MA (draft).

Fleming, G. G., K.J. Plotkin, C. J. Roof, B. J. Ikelheimer, and D. A. Senzig 2005. Assessment of tools for modeling aircraft noise

Hastings, A. L., G.G. Fleming, and C. S. Y. Lee 2006. Modeling sound due to over-snow vehicles in Yellowstone and Grand Teton national parks. Report DOT-VNTSC-NPS-06-06, Volpe Transportation Center, Cambridge, MA.

Hastings, A. L., C. Lee, P. Gerbi, G. G. Fleming, and S. Burson 2010. Development of a tool for modeling snowmobile and snowcoach noise in Yellowstone and Grand Teton National Parks. Noise Control Eng. J. 58: 591-600.

Miller, N. P. 1999. The effects of aircraft overflights on visitors to U.S. National Parks. Noise Control Eng. J. 47: 112-117.

Miller, N. P. and G.S. Anderson, R. D. Horonjeff, C. W. Menge, J. C. Ross, and M. Newmark 2003. Aircraft noise model validation study. HMMH Report No. 295860.29, Harris, Miller, Miller, and Hanson Inc., Burlington, MA.

R Development Core Team 2010. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org.

SAE 2004. Operational sound level measurement procedure for snow vehicles. Society of Automotive Engineers Standard J1161-2004. Available at http://webstore.ansi.org/ (accessed 7 August 2012).

Tanner, J. C. 1951. The delay to pedestrians crossing a road. Biometrika 38: 383-392.

World Health Organization (WHO). 1999. Guidelines for Community Noise (edited by B. Berglund, T. Lindvall, D. Schwela, K-T. Goh). The World Health Organization, Geneva, Switzerland. ISBN: 9971: 9971-88-770-3.

National Park Service. 2010. Instructions to authors — Natural Resource Report, Natural Resource Technical Report, and Natural Resource Data Series: version 3.1. Natural Resource Report. NPS/NPRC/IMD/NRR—2010/256. National Park Service, Fort Collins, Colorado.

U.S. Forest Service (USFS). 1993. ECOMAP. National hierarchical framework of ecological units. U. S. Forest Service, Washington, D.C.

Figure 5. The senior author contemplates the challenges of noise mapping during a lull in traffic censusing at the Mary Mountain trailhead.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS XXXXXX, Month Year

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov