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A Comparison of Operational Noise Conditions on the Denali Park Road

A grizzly bear pads along the Denali Park Road towards a group of visitors parked in the distance.
NPS / EMILY MESNER

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Abstract

In response to the Pretty Rocks Landslide and subsequent changes to Park Road operations in 2021, the Incident Commander of the Denali Road Lottery Incident Management Team requested an assessment of how traffic conditions affect the acoustic environment between the Teklanika River and East Fork Toklat River in Denali National Park and Preserve (Technical Assistance Request #19924). This study used previously collected data from Igloo Canyon (2013) to evaluate acoustic impacts associated with three operational states: the standard summer Vehicle Management Plan (VMP), the Road Lottery, and Administrative Access. Acoustic data were gathered using a canonical National Park Service Type-1 monitoring system. Five acoustic indicators—three duration-based (Event Duration, Time Audible, Noise-Free Interval) and two energy-based (Maximum Sound Level, Sound Exposure Level)—were used to characterize differences among operational states. Motion-activated cameras enabled identification of vehicle type and mechanical features, supporting a physical model of pass-by noise. Findings show that Road Lottery traffic significantly increases acoustic impacts. Time Audible rose by 12.3% (about three additional hours per day), while the median Noise-Free Interval fell by more than 50%. The energy-based metrics also revealed strong contrasts: noise energy per visitor was 21.2 dB under Road Lottery conditions versus 1.7 dB under VMP, due to the lower capacity of private vehicles. These results suggest that the VMP shuttle system not only reduces noise but also attenuates operational complexity—a key principle of Ashby's Law of Requisite Variety. The physical model accurately predicted maximum sound levels and may support scenario planning in Denali and other parks. Overall, this analysis demonstrates how acoustic monitoring can serve as both a resource indicator and a management diagnostic, revealing that vehicle management systems like the VMP can protect natural soundscapes while improving visitor access and experience.

List of Terms or Acronyms

Acoustic Environment: A combination of all the physical sound resources within a given area. This includes natural sounds and cultural sounds, and non-natural human-caused sounds. The acoustic environment of a park can be divided into two main categories: intrinsic and extrinsic.

Acoustic Resources: Includes both natural sounds like wind, water, and wildlife and cultural and historic sounds like tribal ceremonies, quiet reverence, and battle reenactments.

Amplitude: The relative strength of a sound wave, described in decibels (dB). Amplitude is related to what we commonly call loudness or volume.

Audibility: The ability of animals with normal hearing, including humans, to hear a given sound. It can vary depending upon the frequency content and amplitude of sound and by the hearing ability of individual animals.

Decibel (dB): A unit of sound energy. Sound levels are measured on a logarithmic scale relative to the reference sound pressure for atmospheric sources, 20 µPa. The logarithmic scale is a useful way to express the wide range of sound pressures perceived by the human ear. Every 10 dB increase represents a tenfold increase in energy. Therefore, a 20 dB increase represents a hundredfold increase in energy.

Energy Equivalent Sound Level (L_{Aeq}): The sound energy level averaged over the measurement period. Generally, refers to A-weighted 1-second time averaged sound levels measured between 12.5 Hz and 20 kHz. This is a standard measurement collected using the NPS acoustic monitoring protocol for sound level meters. Sound levels measured over 1 second intervals are used to calculate summary statistics, specifically percent of time a sound level of interest is exceeded.

Frequency: Related to the pitch of a sound. Defined as the number of times per second that the wave of sound repeats itself and expressed in terms of hertz (Hz). Sound levels are often adjusted (“weighted”) to match the hearing abilities of a given animal. In other words, different species of animals and humans are capable of hearing (or not hearing) at different frequencies. Humans with normal hearing can hear sounds between 20 Hz and 20,000 Hz, and as low as 0 dB at 1,000 Hz. Bats, on the other hand, can hear sounds between 20 Hz and 200,000 Hz.

Noise Free Interval (NFI): The length of a continuous period during which no human-caused sounds are audible.

Sound Exposure Level (SEL): The total sound energy of the actual sound during a specific time period. SEL is usually expressed using a time period of one second.

Sound Pressure: The minute change in atmospheric pressure due to passage of sound that can be detected by microphones.

Sound vs. Noise: Sound and noise are often used interchangeably to describe an acoustic source. A common definition of noise is unwanted sound or sounds that interfere with a signal of interest (Harris 1998; Templeton 1997). However, noise is not a purely subjective designation. Any sound that serves no function is noise. Most sounds produced by human transportation and other machinery are unintended and serve no function, therefore are noise regardless of the attitudes of the listener. While there are unintended sounds in nature, like the footfalls of an animal, these sounds provide vital cues for some receivers and are therefore considered sounds to the receiver, yet noise from the perception of the producer.

Soundscape: The human perception of physical sound resources.

Spectrogram: A visual, raster (matrix) representation of how the frequency of sound energy within a recording changes over time. The display shows time on the horizontal axis, frequency on the vertical axis, and uses shading or color to indicate amplitude. In the field of environmental sound monitoring, spectrograms are commonly used to identify sound sources, detect patterns, and study wildlife and environmental sounds.

Time Audible: The amount of time that various sound sources are audible to humans with normal hearing, commonly expressed in percent of day, or percent of daytime hours and nighttime hours. A sound may be above natural ambient sound pressure levels, but still not audible. Similarly, some sounds that are below the natural ambient level can be audible. Time Audible is useful because of its simplicity. It is a measure that correlates well with visitor complaints of excessive noise and annoyance. Most noise sources are audible to humans at lower levels than virtually all wildlife species. Therefore, time audible is a protective proxy for wildlife. These data can be collected either by a trained observer (on-site listening) or by making high-quality digital recordings for later playback (off-site listening).

Acknowledgments

The data we relied on for this report were originally collected during the Denali Hybrid Bus Project, 2012–2013. Many people helped contribute. Bennie Johnson, Joe Flower, Britta Schroeder, Scot Sharp, and Kim Arthur assisted with field data collection throughout the project.

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Introduction

After the Pretty Rocks Landslide altered Denali Park Road (Park Road) conditions, the Incident Commander of the Denali National Park and Preserve (DENA) Road Lottery Incident Management Team requested an assessment of differing operations on acoustic environments between the Teklanika River and the East Fork Toklat River within DENA (Figure 1; Technical Assistance Request #19924, *Quantifying Noise Impacts From Road Lottery Traffic*). This study was conducted using relevant data which had been previously collected in Igloo Canyon circa 2013.

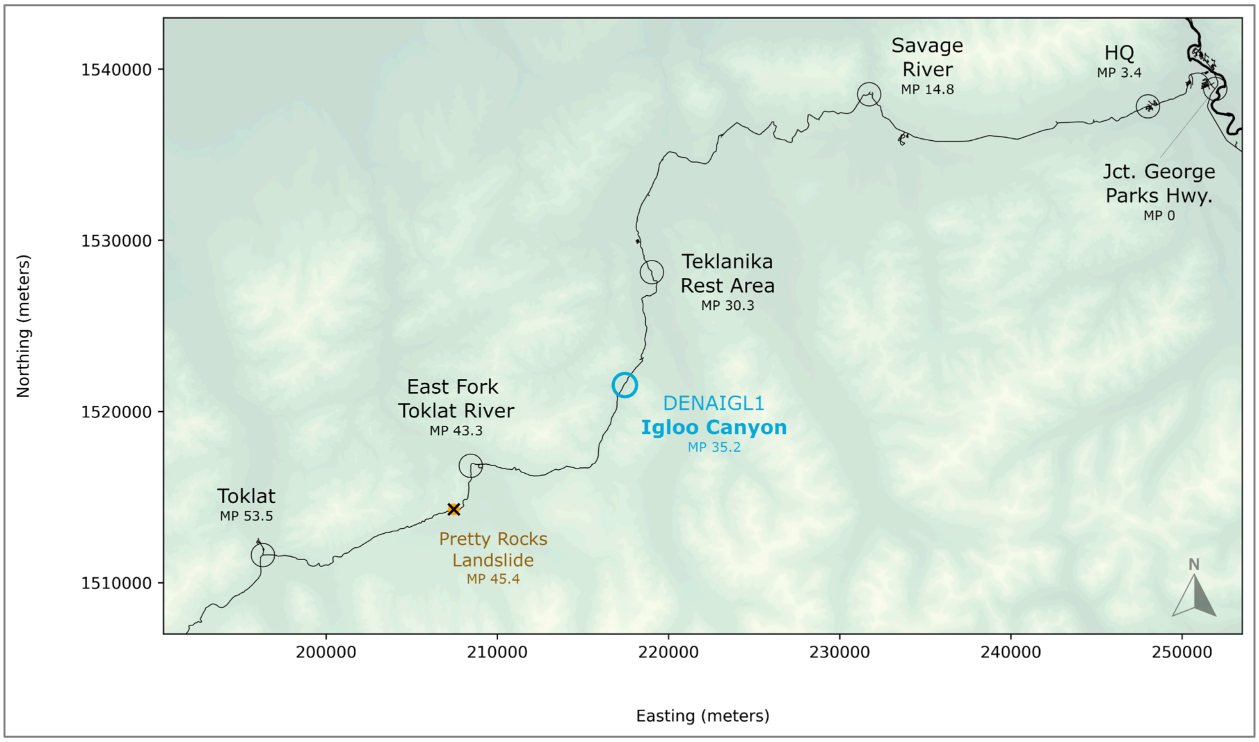

Figure 1. Locations of operational control along the Park Road (hollow, black circles). The park road begins at its junction with the George Parks Highway and continues beyond Toklat. Gates exist at HQ, Savage River, the Teklanika Rest Area and Toklat. At present, the road is impassible beyond the East Fork of the Toklat River due to the Pretty Rocks Landslide (orange “x”). The present study used data collected at the DENAIGL1 Igloo Canyon acoustic monitoring site (blue, hollow circle). “MP” is the abbreviation for Mile Post.

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Denali Park Road Operations

Management of DENA has historically had a primary focus on operations of the 92-mile-long Park Road. Current policy guidance for Park Road operations may be found in the Vehicle Management Plan (VMP; NPS 2012), with additional strategic thinking encapsulated within the Long Range Transportation Plan (NPS 2018).

The DENA summer shuttle bus system was instituted in 1972 as the proactive management solution to a “widely anticipated” influx of visitation via the newly completed George Parks Highway (Norris 2006; Goldfarb 2023). To accommodate local Alaskan communities as they adjusted to the change in management, visitors were allowed to drive a personal vehicle along the Park Road to Toklat (Figure 1) in spring before summer bus service began, and later in the fall after it concluded until snowfall rendered the road corridor fit for non-motorized winter recreation activities (Norris 2006).

As fall season visits became increasingly popular, they manifested in the exact type of vehicle management complexity the bus system sought to avoid. In 1990 a Road Lottery (Lottery) operation was implemented to reduce management complexity. A memorandum from Superintendent Ken Kehrer, Jr. on September 27th, 1991 (Kehrer 1991) offers insight into the types of events which led to the decision:

> *“The lottery system used for fall road opening came about after a chaotic 1989 fall season. On the first day alone, over 1600 vehicles drove the park road. The scene was bumper to bumper with several vehicles vandalized, 1 run off the road completely, dogs chasing sheep on the hillside, several motor vehicle accidents, wildlife being surrounded by crowds of visitors, and the road so blocked with vehicles that emergency vehicles had great difficulty responding to emergency situations.”*

Several management techniques were employed over the subsequent decades. Early DENA Lottery operations awarded entry to 300 private vehicles per day over the course of four days; 1,200 vehicles in all. In 1995, entry was increased to 400 vehicles per day; 1,600 vehicles in all. In 2004, an application fee began to be assessed for cost recovery related to the Lottery operation. In 2014, a “Military Appreciation Day” was added, lengthening the operation to five days; 2,000 vehicles in all. In 2014 the Lottery application was also transitioned to the Recreation.gov website to reduce the amount of processing time required for DENA staff. Finally, in 2020, DENA reduced entry back to 300 private vehicles per day over the course of five days; 1,500 vehicles in all (Hayes 2024).

In August 2021, landslide conditions at Pretty Rocks forced DENA managers to close the Park Road at the East Fork Toklat River (Mile Post [MP] 43.3), also calling DENA managers to question and ultimately cancel the Lottery operation into the foreseeable future. At the same time, the park reached out to the NPS Natural Sounds and Night Skies Division for technical assistance, requesting an assessment of the effects of the Lottery on acoustic environments between the Teklanika River (MP 30.3) and the East Fork Toklat River as compared to the park’s usual summertime Standard VMP operations.

Methods

Field Data Collection

To compare the Park Road operational conditions, we relied on an extensive archival acoustic dataset originally collected as part of the Denali Hybrid Bus Project, 2012–2013 (Flower 2013). The original project purposes were to contrast electric-hybrid and propane buses to the diesel fleet of the time, comparing noise emissions and fuel efficiency on the Park Road. The original study found hybrids were both louder and less fuel efficient than many diesel buses, while propane buses were both quieter and more fuel efficient under most operating conditions. The dataset was not restricted to buses alone. It includes observations of every vehicle category that traversed the Park Road during those seasons. The main categories considered here are the conventional bus fleet (owned by Concessionaire Doyon/Aramark), government vehicles including heavy equipment (GOV), and private vehicles.

To represent conditions between the Teklanika and East Fork Toklat Rivers, it was agreed that existing acoustic measurements from the 2013 Igloo Canyon deployment (DENAIGL1, 63.59589°N, −149.60706°W, MP 35.2) were sufficiently similar to current conditions to enable a useful comparison of Park Road operations (Betchkal 2015a; Figure 2). The microphone at DENAIGL1 was placed 47 meters (154 feet) from the centerline of the Park Road, where the grade at the closest point of approach was 1.1%. The acoustic record was collected using standard NPS protocols (Lynch et al. 2011). An omnidirectional microphone was paired with an American National Standards Institute (ANSI) type-1 sound level meter (Larson-Davis 831-A, Depew, NY). The system continuously logged unweighted, 1-second equivalent sound levels ($L_{Zeq,1s\ f}$) in each 1/3-octave frequency band, f, from 12.5 to 20,000 Hz. The overall sampling period for data collection was 06/05–09/17/2013 with intermittent equipment downtime.

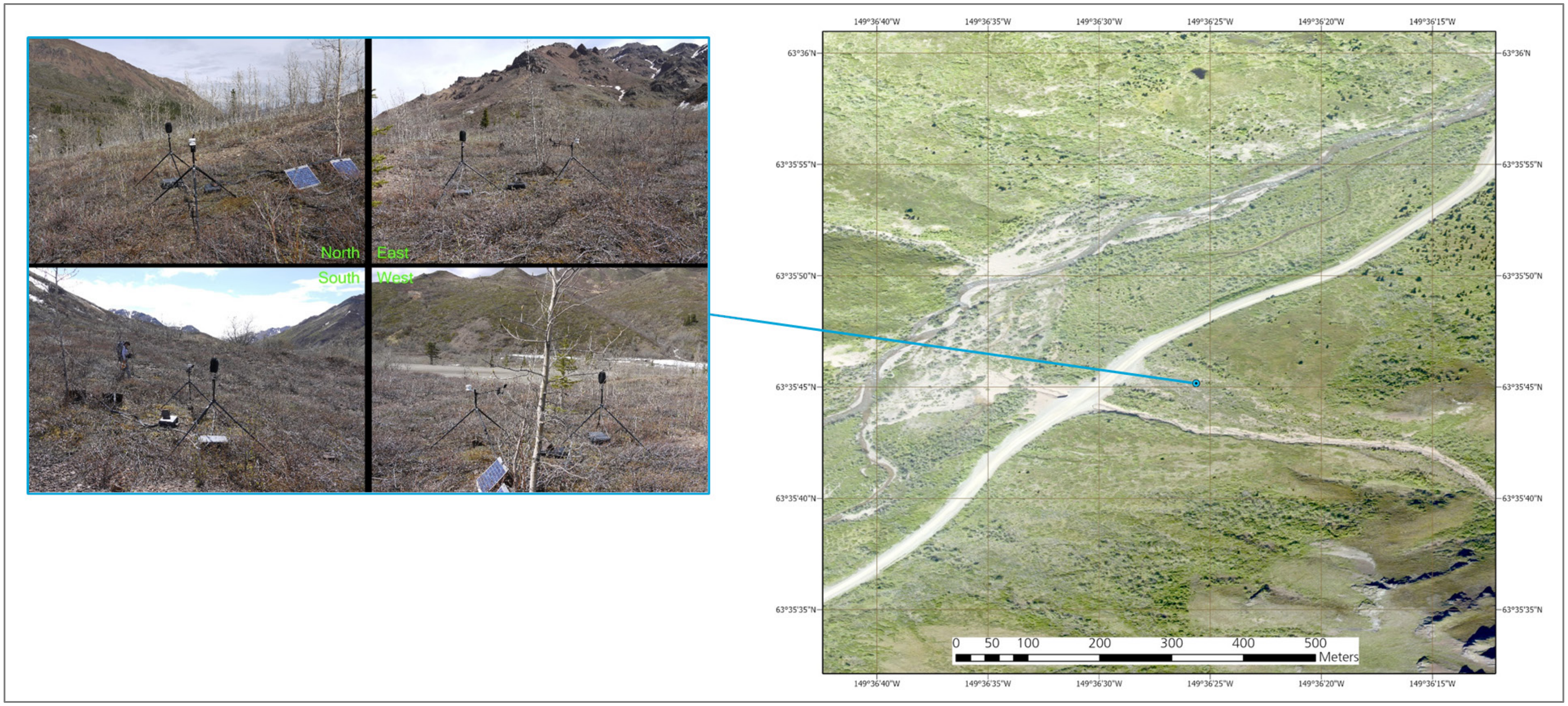

Figure 2. A composite of photographs taken in each cardinal direction from DENAIGL1 in 2013 (left) and a satellite imagery map indicating the local alignment of the Park Road with respect to the microphone (right).

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A pair of motion-activated cameras (Reconyx, Holmen, WI) oriented east and west captured images of vehicles traversing the Park Road past DENAIGL1 (Figure 3). The timestamp of each photograph was used to establish a causal linkage between the category of a given vehicle and its noise within the acoustic record. To perform the join, we used the NPS software program Sound Pressure Level Annotation Tool (SPLAT v1.0.7795; Joyce 2022). SPLAT allows an analyst to visualize the acoustic record as a series of spectrograms in search of road vehicle pass-by noise events. Such events are distinguished by relatively bright, vertical morphology which is temporally aligned with the vehicle's closest point of approach to the microphone (Figure 4). These forms tend to have shorter duration at higher frequency and can include prominent tones, which are visible as superposed horizontal lines. Examples across a variety of vehicle categories are provided in Appendix A. Whenever a vehicle pass-by noise event was identified, the analyst annotated the temporal extent of audibility. When the measured $L_{Zeq,1s\ f}$ of the noise in any one-third octave band exceeded both the threshold of human hearing (ISO 2003) and the co-occurring residual sound level (ANSI 2014) in the same band by ≥4 dB, the measurement was considered to be audible. Over an entire observation period, the annotated events form the set of noise intervals, I_n.

Figure 3. A pair of photographs looking eastbound (left) and westbound (right) along the Park Road adjacent to DENAIGL1.

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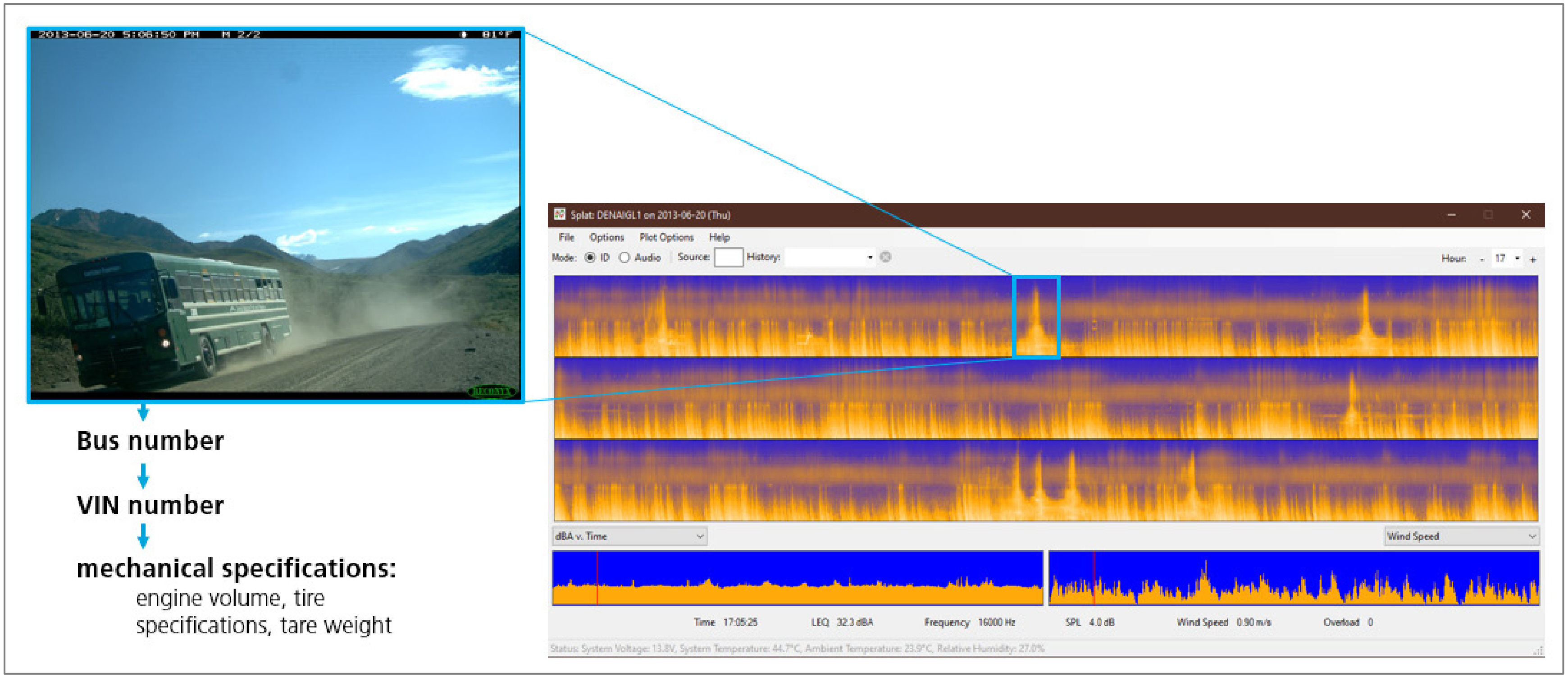

Figure 4. A causal linkage may be established between the photographic (left) and acoustic (right) records using a timestamp. A visual identifier (e.g., painted number) enabled detailed mechanical specifications to be linked to 93% of the pass-by events in the acoustic record.
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Vehicle photographs which included a visual identifier—especially numbers painted on the Concessionaire bus fleet—further enabled detailed mechanical specifications to be joined via their Vehicle Identification Number (VIN). Relevant mechanical attributes included engine volume, tire specifications, and tare weight (Figure 4). Categorical joins were established when the timestamp of the photograph could be unambiguously attributed to spectral morphology in the acoustic record as visible in SPLAT. Such joins were established for 93% of pass-by events in the acoustic record

During the time DENAIGL1 was deployed, 148 vehicles traversing the Park Road—estimated to represent 70% of the total traffic—were equipped with a GPS unit (McKenny et al. 2014). The data were served via an online platform (Fleet Management Solutions, Northbrook, IL USA) which also provided geofence services. A geofence bounding DENAIGL1 logged the time that GPS-equipped vehicles entered and exited the geofence, which allowed a pass-by speed to be determined. The median traffic speed was 27 MPH.

Operational States Observed

The full 2013 DENAIGL1 sampling period spans three distinct operational states (Table 1). Standard VMP operations are represented by two subsets of the overall record from 06/23–06/30 and 08/11–08/16. In this state, buses predominate over GOV traffic, but both are present. Private vehicles represent a negligible proportion of the overall traffic during Standard VMP operations. During Lottery operations from 09/14–09/17, private vehicles predominate over GOV traffic, and buses are absent. During the final operational state from 09/17–09/18 only Administrative Access by GOV was authorized as various facilities were winterized. The monitoring equipment was also removed from the area at the end of this period. The two Standard VMP observation periods serve as an internal control (i.e., the baseline condition which we can compare against), as we expect the traffic volume and mixture to be very similar. Because Administrative Access has very low traffic volume compared to either of the other two states, it serves as a negative control.

Table 1. Periods of observation for three distinct operational states of the Park Road, DENAIGL1 2013.

Observation Period	**Operational State**	**Generalized Traffic Mixture**
06/23–06/30	Standard VMP operations	Bus > GOV
08/11–08/16	Standard VMP operations	Bus > GOV
09/14–09/17	Road Lottery	Private Vehicle > GOV
09/17–09/18	Administrative Access	GOV only

Acoustic Indicators

Managers use acoustic indicators to monitor environmental quality of backcountry (NPS 2006) and frontcountry (Ferguson et al. 2023) areas of DENA. Once detected, every noise event has definitive timing as well as quantifiable energy and duration attributes (Betchkal and Ward 2018). Acoustic indicators possess distinct properties that enable managers to track the aggregate timing, energy, and duration attributes of a sequence of noise events that are detected over an entire observation period.

For this study, we selected five indicators to form a comprehensive comparison of the three operational states on the Park Road. To calculate the indicators, only the set of noise event intervals, I_n, as annotated in SPLAT are necessary (Betchkal 2023). The length of a typical noise event is simply the median duration of the set of events. A complementary metric is the median Noise-Free

Interval (NFI)—the typical duration between successive events. As such, the median NFI describes an important indicator of park enjoyment and wildlife recovery from noise (Poling and Betchkal 2023). Time audible is the sum of the durations of all events expressed as a proportion of the overall period of observation. The sound exposure level (SEL) of each event describes its total energy content, so the arithmetic mean over all events describes the amount of energy radiated into Igloo Canyon per event. Because road vehicle positions are constrained to the roadway, the most energetic 1-second observation within an event, maximum $L_{Aeq,1s\ [12.5–20000\ Hz]}$ (L_{max}), is associated with the vehicle's closest approach to the microphone. In the case of pass-by events, it is also a mathematical fact that the median L_{max} of many events converges on the continuous equivalent sound level ($L_{eq,*}$) of the vehicle in a reference frame moving along with it (Betchkal 2015b). The five selected indicators are summarized in Table 2.

Table 2. Acoustic indicators used to compare operational states of the Park Road.

Acoustic Indicator	Event Attribute(s) Summarized	Domain	Unit	Management Question
Median Event Duration	Duration	Event	Minutes	How long is a typical noise event?
Median Noise-Free Interval	Duration, Timing	Synoptic	Minutes	How long, typically, between events?
Time Audible	Duration	Synoptic	%	During what proportion of the observation period was noise present?
Mean Sound Exposure Level	Energy	Event	Sound level (dB)	What is the average amount of noise radiated into the local environment per event?
Median L_{max}	Energy	Event	Sound level (dB)	How energetic is the traffic mixture?

Physical Model of Road Vehicle Noise

Among the most practical attributes of a road are the mechanical specifications of each vehicle category present. The same mechanical attributes predict noise output of the traffic flow. Decisions about transportation management often hinge on design attributes of the vehicles moving along the roadway. For example, "what are the dimensions of the vehicle?", or "how many seats?" The bridge from transportation management into noise management is also via mechanical specification. Such a strategy allows managers to design a transportation system that integrates physical properties of the traffic flow into their overall decision-making.

The Denali Hybrid Bus Project study "found clear evidence in support of the physical theory that buses with larger engine volume are quieter than buses with smaller engines on the same road grade" (Betchkal 2015a). This result was only possible because bus VIN information allowed the engine type of each pass-by to be specified. Because it is useful for reasoning and has not yet been published, we elaborate the physical model here. The foundation is from Priede's 1971 "Origins of automotive vehicle noise", where he writes,

"… the main criterion which determines [automotive vehicle] noise is the operational speed or how short the time interval is within which the operation of one cycle of events is being performed by the machine …"

To build upon this foundation, we consider the physical work, W, performed by a vehicle traversing a section of a road. First, we equate the pressure-volume work of the engine to the force-distance work that allows the bus to move forward, writing,

$$Fd = W = pV$$

On the left-hand side work is represented by the product of force, F, and distance, d, while the right-hand side represents the same work as the product of pressure, p, and volume, V. Although these expressions are theoretically equivalent, it is important to recognize that inefficiencies in real-world systems necessitate that the actual pressure-volume work is greater than or equal to the force-distance work. This inequality will be resolved later in this section, as we discuss radiation efficiency.

Next, we expand the main forces opposing the forward motion of the bus. A reasonable approximation of the total force is to sum the force of gravity ($F_{gravity}$), the force of drag (e.g., from air resistance; F_{drag}) and the force of friction (e.g., rolling resistance of the tires in contact with the gravel; F_{roll}). Given our noise context, we notice that Priede's "operation of one cycle" refers to each explosion of the gas which creates pressure within a cylinder of the combustion engine. So, we are specifically concerned with cylinder pressure, p_{cyl}, and the total volume of the cylinders, commonly referred to as engine volume, V_{engine}. The expanded equality becomes:

$$\left(F_{gravity} + F_{drag} + F_{roll}\right)d = p_{cyl}V_{engine}$$

We rearrange to find a formula for cylinder pressure:

$$p_{cyl} = \frac{\left(F_{gravity} + F_{drag} + F_{roll}\right)d}{V_{engine}}$$

This cylinder pressure is responsible for actuating the motion of the vehicle. A tiny proportion of this pressure is also responsible for the noise radiated from the engine. Due to the structural complexity of an engine, this proportion is often expressed by an empirical quantity, radiation efficiency, ε, which describes how well structural vibrations of the engine are conveyed into the surrounding environment (cf. Kvist et al. 2025; Fahy and Gardonio 2007; Vér 2005). By incorporating the mechanical efficiency of the vehicle into the radiation efficiency term ε, we effectively address the earlier inequality. In the present model ε is treated as a band-averaged, empirical calibration constant, with a unitless value of approximately 1×10^{-18} chosen to match typical pass-by data across different vehicle types. Then we may estimate acoustic pressure in the engine as follows:

$$p_{acoustic} = \varepsilon\, p_{cyl}$$

Finally, to compare our estimated acoustic pressure to a sound level measurement, we use a formula that converts the pressure value into a sound level in decibels. This is done by taking the logarithm of the ratio of our estimated acoustic pressure to a reference pressure. By convention, the reference pressure in air is set at 20 micro Pascals (µPa), which is considered the threshold of hearing for humans. To calculate the sound level, we use the following equation:

$$L_p = 10 \log_{10} \frac{{p_{acoustic}}^2}{{p_{ref}}^2}$$

A full implementation as Python code is available within the public domain (Betchkal 2025). The function estimates the maximum sound level, L_{max}, of a road vehicle pass-by at distance using mechanical specifications of the vehicle. It requires the following inputs:

- The distance offset from the microphone to the roadway (m, must be ≤150 m or 492 ft)
- The engine volume of the vehicle (L, liters)
- The speed of the vehicle (MPH, miles per hour)
- The number of tires
- The radius of the tires (m, meters)
- The frontal area of the vehicle (m^2)
- The mass of the vehicle (kg, kilograms)
- The vehicle’s expected Coefficient of Drag (dimensionless, default = 0.8)
- The density of the air the vehicle is driving through (kg/m^3, default = 1.1)
- The road surface condition (either “dry” or “wet”, default = “dry”)
- The grade of the road (%)

This physical model was used to predict the L_{max} indicator for two important vehicle categories on the Park Road, a bus and a generic sport utility vehicle (SUV), each of which typify the main component of a traffic mixture listed in Table 1. The median GPS-based speed of 27 MPH was used to model both vehicles. The local percent grade of the Park Road at the point of closest approach to the microphone was 1.1%. The defaults for air density and road surface condition were used. The distinguishing set of operational and mechanical specifications for the two vehicle categories are provided in Table 3.

Table 3. The mechanical specifications used to predict pass-by L_{max} for buses and private vehicles.

Mechanical Specification	Bus	Private Vehicle (SUV)
Engine Volume (L)	6.5	2.3
Number of Tires	6	4
Radius of Tires (m)	1.07	0.35

Table 3 (continued). The mechanical specifications used to predict pass-by L_{max} for buses and private vehicles.

Mechanical Specification	Bus	Private Vehicle (SUV)
Frontal Area (m^2)	7.5	3.0
Vehicle Mass (kg)	19400	2000
Coefficient of Drag	0.8	0.4

Results

The selected acoustic indicators of quality were highly sensitive to changes in operational state. Each of the two main indicator types reveal a different attribute of the operational state—the duration-based indicators reveal shifts in traffic volume, while the energy-based indicators reveal shifts in traffic mixture. The indicator values over each observation period are provided in Table 4.

Table 4. Observed values of each acoustic indicator under various operational states of the Park Road.

Observation Period	Operational State	Median NFI (mins)	Median Event Duration (mins)	Time Audible	Average SEL (dB)	Noise Budget (dB/visitor)	Median L_{max} (dB)
06/23–06/30	Standard VMP operations	4.0	1.4	17.7%	67.3	1.7	55.4
08/11–08/16	Standard VMP operations	3.7	1.5	17.1%	68.5	1.7	55.0
09/14–09/17	Road Lottery	1.3	1.3	29.7%	63.7	21.2	50.7
09/17–09/18	Administrative Access	14.2	1.1	4.3%	65.3	–	54.4

Duration-Based Indicators

The duration-based indicators reveal changes in traffic volume. The median noise event duration was found to be similar under every operational state. For example, the duration of events during Standard VMP operations exceeded the Lottery by only +0.15 minutes (+9 seconds). Despite this, the Lottery reduced NFI by over half due to a 127% increase in traffic volume. During the Administrative Access control period which followed, traffic volume on the Park Road dropped by 84%, and the corresponding median NFI was triple that of Standard VMP operations.

A comparison of the two periods of Standard VMP operations reveals a high level of consistency for the NFI and Time Audible duration metrics. This is especially true of Time Audible, which differs by only 0.6% over the two observation periods.

A comparison between the operational conditions reveals that Time Audible increases by +12.3% (3 additional hours of noise per day) during Lottery operations as compared to the Standard VMP operations. During the Administrative Access period there is a similarly large reduction in noise as compared to Standard VMP operations, −13.1% (3 fewer hours of noise per day).

Energy-Based Indicators

The energy-based indicators reveal changes in traffic mixture. Comparisons of SEL and L_{max} reinforce the physical reality that buses must perform significantly more pressure-volume work than private vehicles to traverse the Park Road. Again, the comparison of the two sets of the Standard VMP data reveal a high level of consistency.

A comparison between the operational conditions reveals that, on the logarithmic scale, both indicators show energy decreases by more than half during Lottery operations, with differences of −4.2 and −4.5 dB, respectively. During Administrative Access operations the observed indicator values are in between the other two states, likely due to the GOV composition of both heavy equipment and smaller vehicles used to complete winterization duties.

Another salient result involves expressing SEL per passenger. By estimate, a bus on the Park Road typically carries 40 people, while a Lottery vehicle carries 3 (Clark et al. 2021). The noise energy radiated into Igloo Canyon becomes 1.7 and 21.2 dB per visitor for Standard VMP and Lottery operations, respectively.

Physical Model

Given the mechanical specifications in Table 3, the physical model predicts an L_{max} of 55.7 dB for a bus and 51.0 dB for an SUV. The difference between these two values is −4.7 dB, which is close to the −4.5 dB change in indicator observed between Standard VMP and Lottery operations. This validates the fact that the change in sound level was caused by a near-total shift in traffic mixture. For both vehicle types the model slightly overpredicts the observed values of L_{max} as a direct function of mass; for buses by +0.5 dB and for private vehicles by +0.3 dB.

Conclusions and Future Work

Operational complexity has long been a concern central to the management of the remote Denali Park Road. Superintendent Kerher Jr. responded pragmatically to this challenge in 1991, instituting the Road Lottery to regain control after a chaotic fall season. More broadly, this managerial concern aligns with Ashby's Law of Requisite Variety (Ashby 1956; Raadt 1987; Schneider et al. 2017; Dale et al. 2023), which states that a system can only be effectively managed if the range of responses available to the manager matches or exceeds the complexity of the system itself. When this condition is not met, instability or unintended outcomes are inevitable. In this study, acoustic indices such as Noise-Free Interval, Time Audible, Sound Exposure Level, and Maximum Sound Level serve as measurable indicators of roadway complexity, linking visitor traffic patterns to both operational management and resource protection.

This study suggests that the Standard Vehicle Management Plan (VMP) operational condition offers advantages not only for maintaining a manageable roadway, but also for acoustic resource protection. Duration-based indicators (Noise-Free Interval and Time Audible) revealed a substantial reduction in overall noise under VMP operations, primarily due to its high-efficiency transport and corresponding decrease in traffic volume. Energy-based metrics (Sound Exposure Level and Maximum Sound Level) similarly demonstrated that changes in traffic composition under the VMP contributed to a lower per-visitor acoustic footprint. These paired indicators should offer a reliable and precise means of monitoring the effects of operational decisions on the Park Road. By consolidating visitors into high-occupancy vehicles and controlling traffic volume, the VMP effectively reduces the system's operational variety to a level manageable by park staff—demonstrating Ashby's Law in practice and helping prevent the kind of system instability evidenced by the Lottery's intense, short-term traffic surges.

The DENA Road Lottery historically served as a transitional accommodation—helping buffer the expectations of local Alaskan communities as the Parks Highway system intensified fall-season visitation. With the Lottery currently on hiatus, this study offers a neutral, resource-focused lens to review the event's future. Awareness of the Lottery has evolved since 1990, and given the documented acoustic and operational burdens, its scope may no longer align with its original intent. To complement the operational insights of this report, it would be beneficial to clarify the purpose of the Lottery through social science survey methods similar to those used by Drage (2021), who examined stakeholder perspectives surrounding aviation tourism in Talkeetna.

More broadly, the findings of this report may be instructive for other parks contemplating vehicle management strategies. Systems that reduce traffic volume, congestion, and parking pressure—such as shuttle-based access—may also yield substantial ancillary benefits for the natural acoustic environments of parks. In this context, acoustic monitoring and modelling emerge as valuable diagnostic tools that can simultaneously reflect the enjoyment of a protected resource and the resilience of the system that sustains it.

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Appendix A: Causal Linkages—Visual and Acoustic Records of Vehicle Pass-By Events

This appendix presents additional examples of the numerous causal linkages established between the photographic and acoustic record at DENAIGL1 Igloo Canyon. Included are a representative selection of the vehicle categories passing the acoustic monitoring system—specifically buses, trucks/SUVs, heavy maintenance vehicles, and semi tractor-trailers. Each figure in this Appendix resembles Figure 4, above, with a motion-activated photograph in the left panel paired with an hour-long spectrogram in the right panel (Figures 5–12). The spectrogram is wrapped across three rows, each depicting 20 minutes of elapsed time. The vertical axis of each row spans an identical frequency range, from 12.5 to 20,000 Hertz.

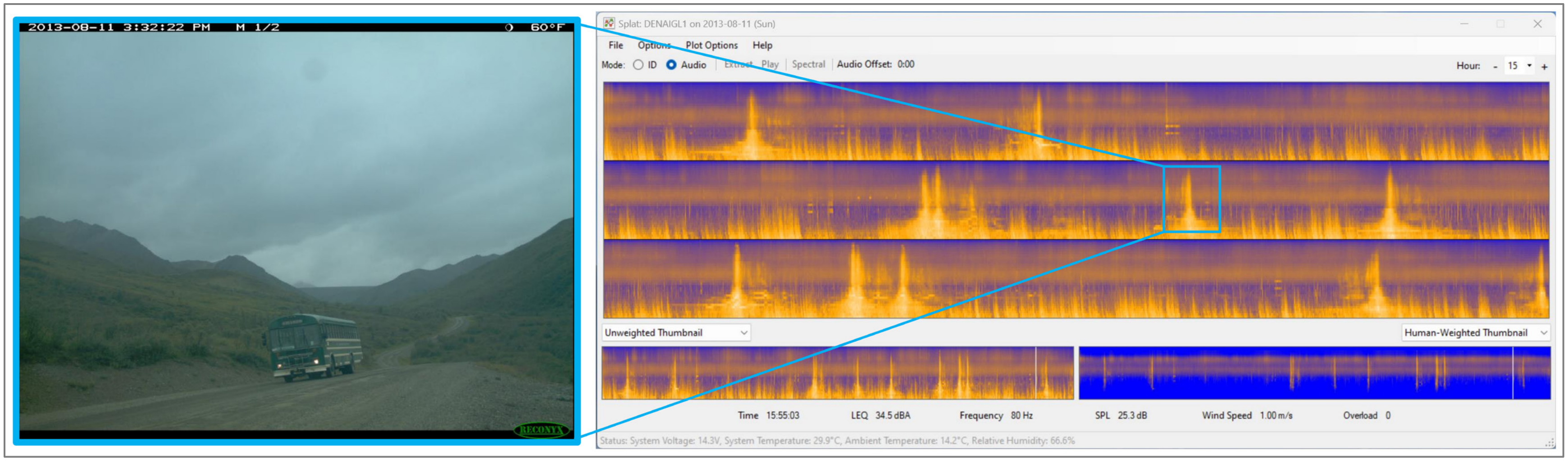

Figure 5. An eastbound bus passes DENAIGL1 Igloo Canyon at 15:32 on 2013-08-11. Tonal noise from the forward-mounted engine is apparent in the 80 Hz 1/3rd-octave band as a horizontal line, especially as the bus approaches the microphone.
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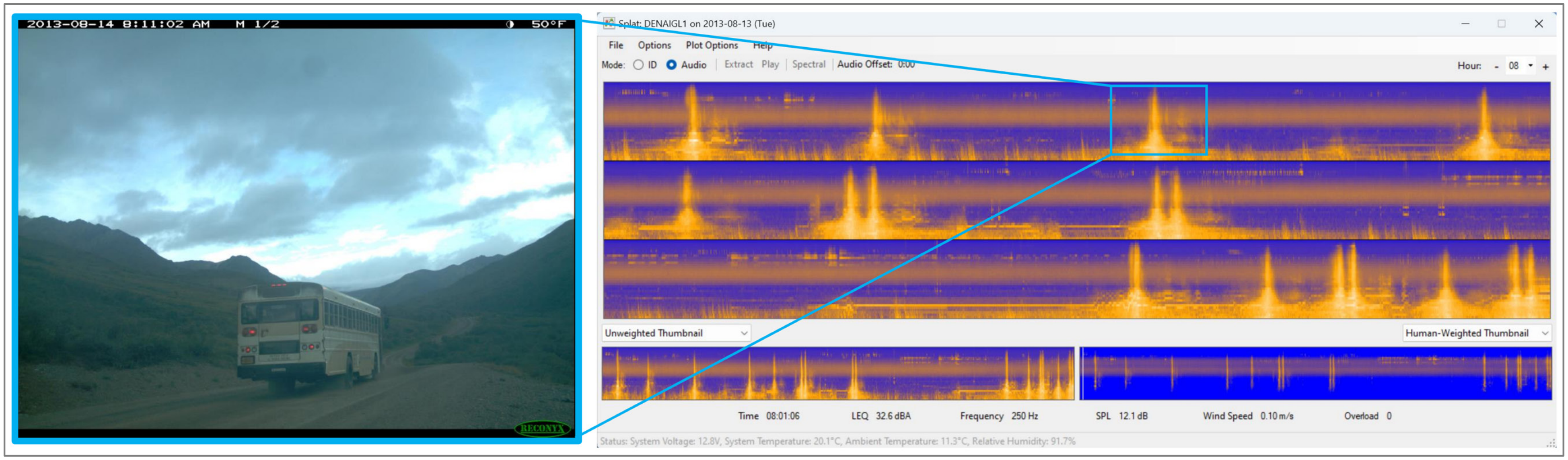

Figure 6. A westbound bus passes DENAIGL1 Igloo Canyon at 08:11 on 2013-08-14. The asymmetrical morphology of the pass-by noise event is shared by events throughout the hour. Sustained sound level from the rear of passing westbound vehicles is causally consistent with the light, steady wind from up valley (180 ± 8° relative to true north) that was measured during this particular hour.

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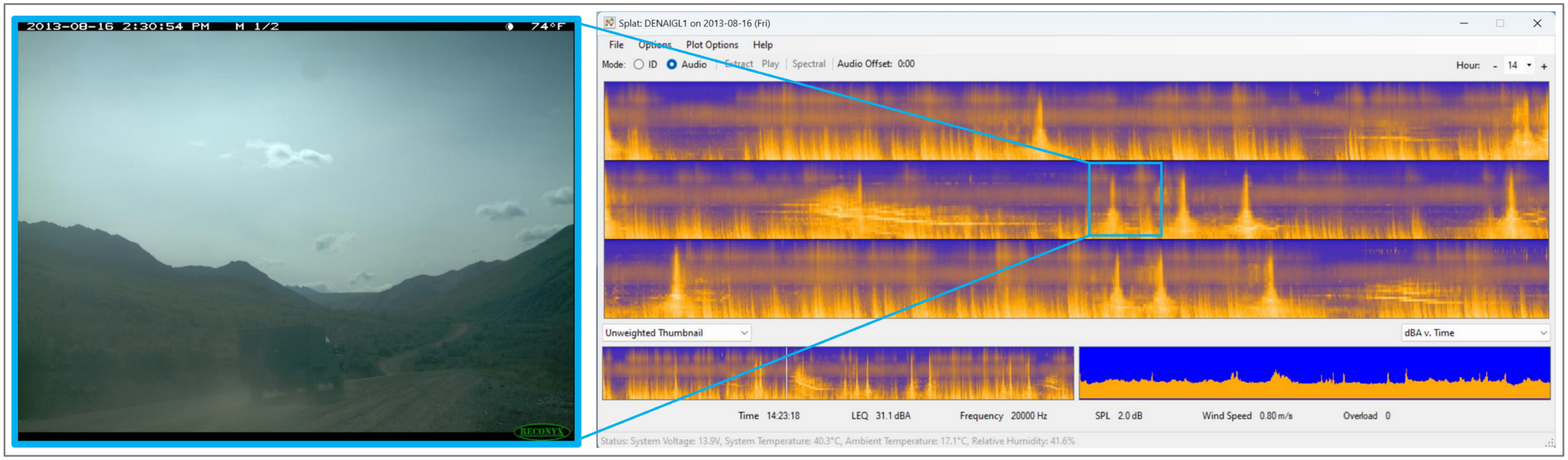

Figure 7. A westbound pickup truck passes DENAIGL1 Igloo Canyon at 14:31 on 2013-08-16. Tonal noise from the engine is apparent in the 125 Hz 1/3rd-octave band as a horizontal line, especially as the truck approaches the microphone.

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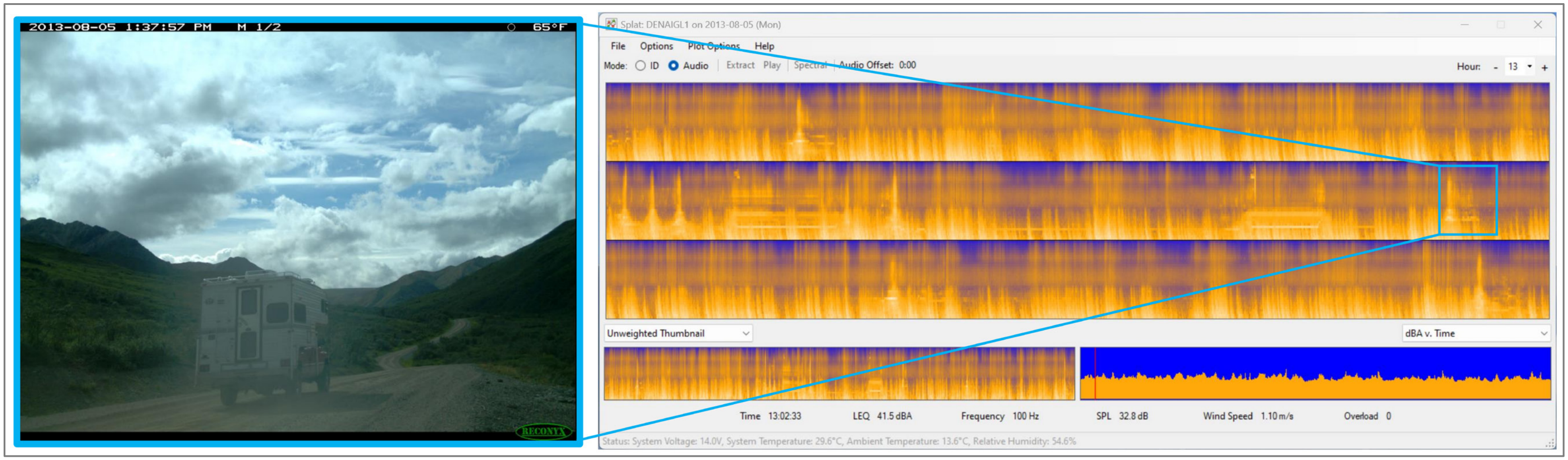

Figure 8. A westbound pickup truck with a camper passes DENAIGL1 Igloo Canyon at 13:38 on 2013-08-05. Despite strong winds during this hour, the duration of the pass-by noise event remains clearly distinguishable.

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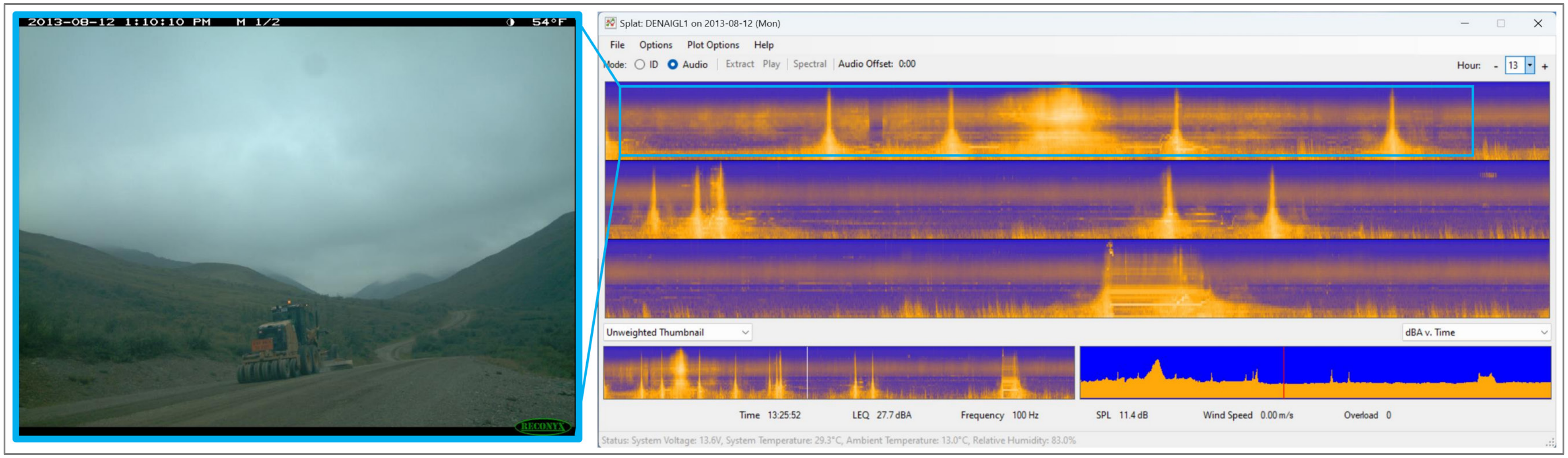

Figure 9. A westbound NPS road grader passes DENAIGL1 Igloo Canyon at 13:10 on 2013-08-12. Due to the low operating speed (3–5 MPH) required for grading, the resulting pass-by noise event lasts nearly 20 minutes. Morphological features on the spectrogram are scaled proportionally to speed, leading to a time dilation of the features typically observed for vehicles traveling at a median speed of 27 MPH. In this instance, the morphological scaling factor of 5 corresponds with the 6.75-fold ratio of speeds.

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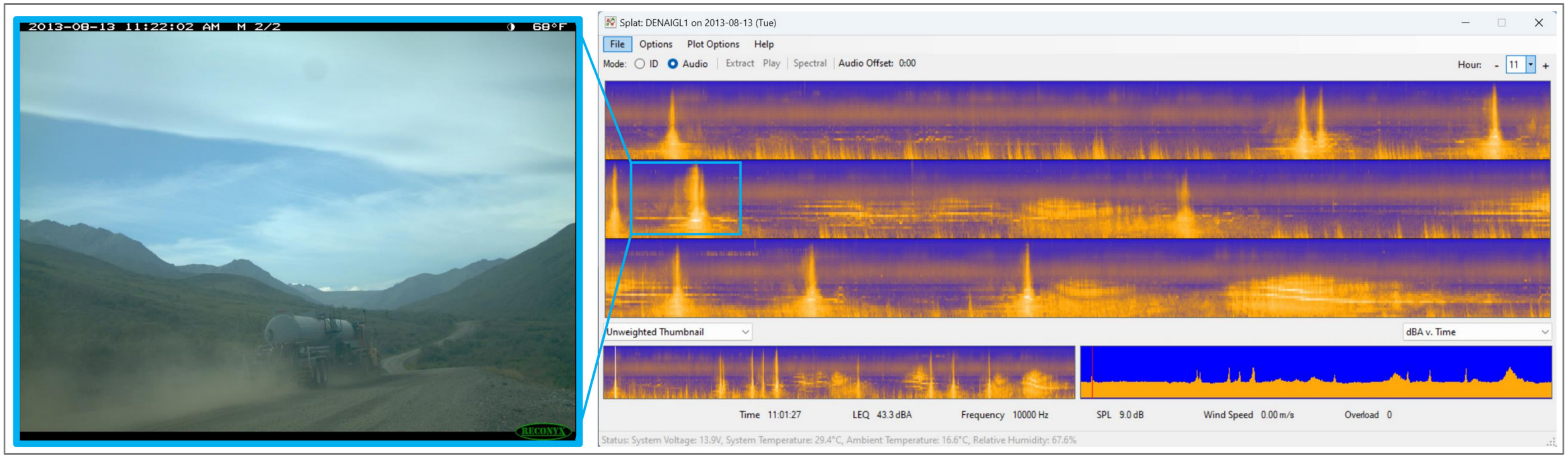

Figure 10. A westbound NPS tank truck passes DENAIGL1 Igloo Canyon at 11:22 on 2013-08-13. Prominent tonal noise from the engine is apparent in both the 40 and 80 Hz 1/3rd-octave bands as a pair of horizontal lines.

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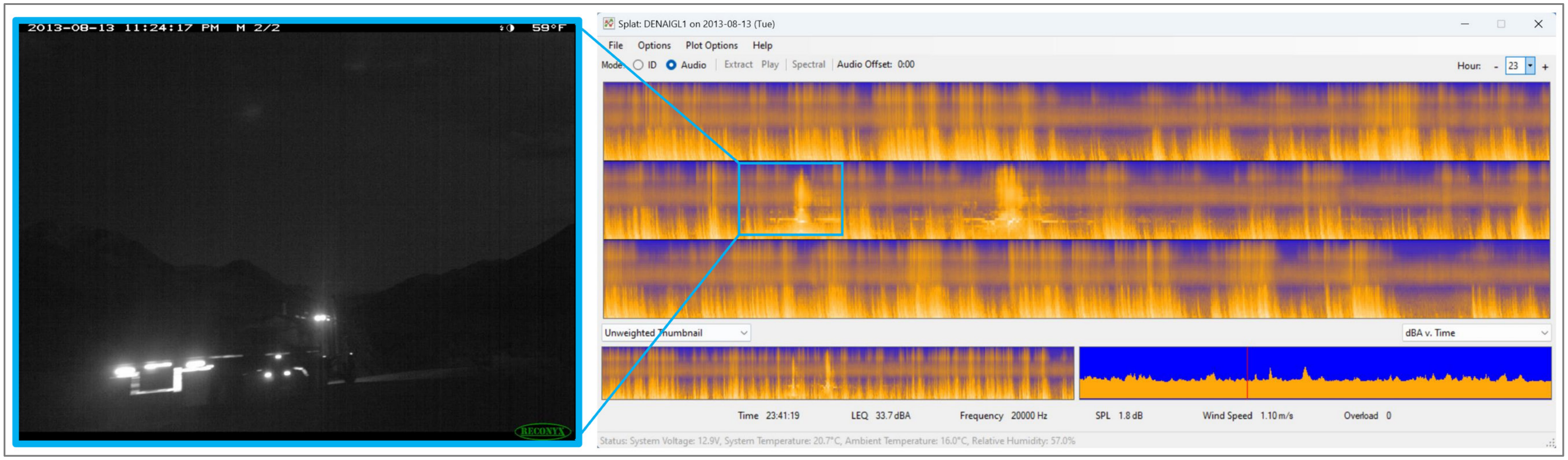

Figure 11. A westbound semi tractor pulling a flatbed trailer past DENAIGL1 Igloo Canyon at 23:24 on 2013-08-13. The trailer has equipment strapped onto it, occupying less than 25% of the bed.

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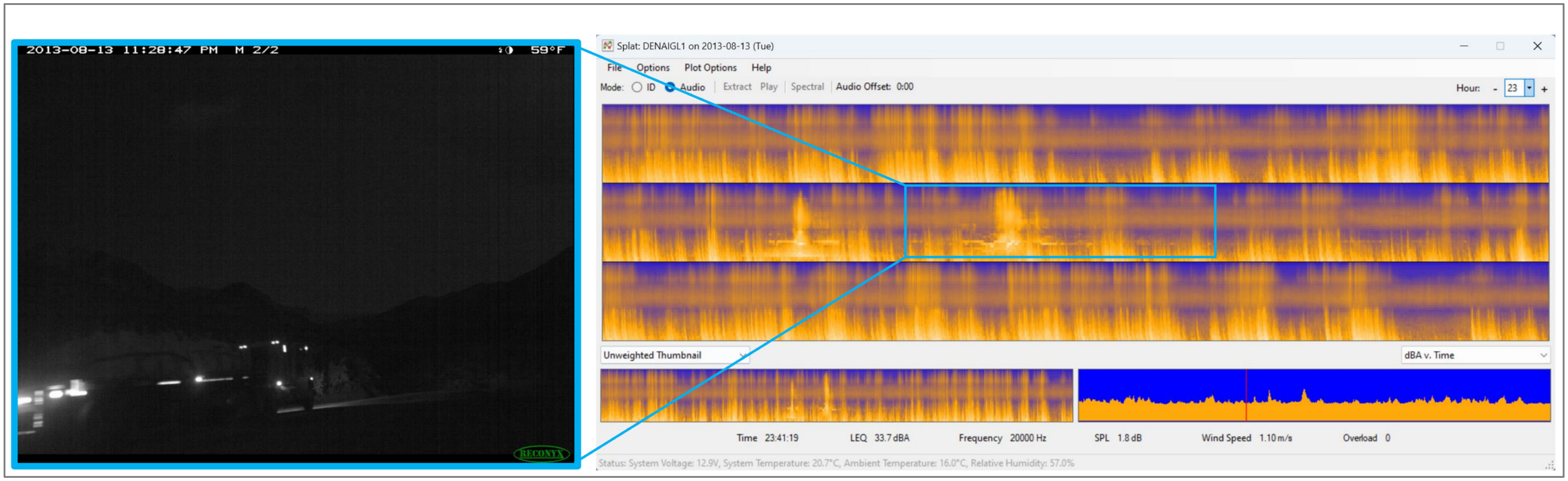

Figure 12. A westbound semi tractor pulling a flatbed trailer through Igloo Canyon at 23:29 on 2013-08-13. The trailer is loaded with construction gravel bags weighing 2,000–4,000 pounds apiece. Although identical in configuration to the truck in the previous figure, the relatively massive payload is causally consistent with the visibly brighter (e.g., louder), longer duration morphology on the spectrogram.

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