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Literature Review of Cumulative Noise Metrics Relevant to X-59 Supersonic Overflights

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Nomenclature and Acronyms

ASEL	A-weighted sound equivalent level
b	Generalized day-night average sound level parameter
BDNL	B-weighted day-night average sound level
BSEL	B-weighted sound equivalent level
CDNL	C-weighted day-night average sound level
CHABA	Committee on Hearing, Bioacoustics and Biomechanics
CSEL	C-weighted sound equivalent level
DENL	Day-evening-night average sound level
DNL	Day-night average sound level
DSEL	D-weighted sound equivalent level
EDNL	E-weighted day-night average sound level
ESEL	E-weighted sound equivalent level
FAA	Federal Aviation Administration
FICON	Federal Interagency Committee on Noise
HUD	United States Department of Housing and Urban Development
ISBAP	Indoor sonic boom annoyance predictor
k	Decibel equivalent number
L_i	Single-event level of the ith event
L_{max}	Maximum sound level
L_{Aeq8hr}	A-weighted 8-hour average level
L_{Ieq100ms}	Impulsive A-weighted equivalent 100 ms level
LLZ	Zwicker's loudness level in phons
LLZd	Zwicker's loudness level in phons for frontal incidence
LLZf	Zwicker's loudness level in phons for diffuse incidence
n	number (of articles)
N	total number of events
NA	Number above
NA55L_{max}	Number above a maximum sound level of 55 dB
NA60L_{max}	Number above a maximum sound level of 60 dB
NFI	Noise-free interval
PL	Perceived level
psf	pounds per square foot
PNL	Perceived noise level
QSF18	Quiet Supersonic Flights 2018
SEL	Sound exposure level
TNO	Netherlands Organisation for Applied Scientific Research
UAM	Urban Air Mobility
WHO	World Health Organization
WSPR	Waveforms and Sonic Boom Perception and Response
ZDNL	Zero-weighted (or flat or unweighted) day-night average sound level
ZSEL	Zero-weighted (or flat or unweighted) sound equivalent level

Executive Summary

Upcoming studies with the X-59 aircraft will collect dose-response data to understand community response to en-route supersonic noise. This data collection effort will inform regulators in their efforts to potentially update the ban on commercial supersonic flight with acceptable noise standards. Part of the dataset will consist of end-of-day responses to the noise from multiple supersonic overflights. This document provides rationale from relevant literature surrounding which cumulative noise metric to pair with end-of-day survey responses for upcoming community studies with the X-59 aircraft. Despite its deficiencies, day-night average sound level (DNL) remains the most likely choice for a cumulative noise metric for multiple supersonic overflights because 1) it is widely used for other transportation noise sources and 2) its relevance for infrequent events is somewhat plausible, unlike some recent alternative metrics.

I. INTRODUCTION

NASA has recently developed the X-59 aircraft to demonstrate quieter supersonic flight. Community response studies are planned in which the X-59 aircraft will be flown over a community multiple times a day for several weeks (Rathsam et al., 2023). Annoyance responses will be collected from participants in the community after each overflight and at the end of each day. This data collection effort will inform regulators in their considerations to replace the supersonic speed limit with permissible noise standards. The purpose of this document is to review potential cumulative noise metrics that can be paired with the end-of-day survey responses to X-59 noise signatures.

Because of the outright ban on overland commercial supersonic flight in 1973,[1] there is no regulatory metric for sonic booms. Understanding how people respond in the long term to noise from multiple supersonic overflights and the appropriate noise metric to relate those responses are important for the approval of future supersonic operations. The most pervasive cumulative noise metric in the noise literature is the day-night-averaged sound level (DNL). This metric serves as a baseline since DNL with various frequency weightings is presently the planned cumulative noise metric for analysis of upcoming X-59 community studies (Rathsam et al., 2023).

This literature review focuses on rationale surrounding the use of DNL or any alternative metrics that may be better predictors of cumulative or end-of-day response to noise from multiple supersonic overflights. Other factors known to affect human response to sonic boom (e.g., rattle, vibration, and non-acoustic factors such as meaning associated with the sound) are not pursued here. The integration of single events is emphasized over the frequency weighting in this review. First, cumulative noise metrics are considered by sound source. Sonic boom studies are highlighted, and impulsive sounds and transportation noise are also reviewed. A focused description of DNL is provided with historical context and critiques. Lastly, a few alternative and supplemental metrics to DNL are included with special attention to the generalized DNL work of Vaughn and Christian (2024).

II. CUMULATIVE NOISE METRICS BY SOUND SOURCE

Sonic boom research is an obvious starting point for X-59 noise signatures as they are both concerned with the sound produced by an object traveling faster than the speed of sound. X-59 noise signatures differ from conventional sonic booms as they are generated by shaped-boom technology (Maglieri et al., 2014), producing significantly quieter sound, sometimes referred to as a “shaped boom,” “low boom,” or “sonic thump.” Expanding out from the topic of sonic booms, these quieter supersonic noise signatures fall into the category of impulsive sounds. Even more broadly, transportation noise provides a relevant discussion of DNL with particular emphasis on DNL application to subsonic, fixed-wing aircraft studies.

A. SONIC BOOMS

Since the Bell X-1 with pilot Chuck Yeager broke the sound barrier in 1947, there have been many decades of sonic boom research (Maglieri et al., 2014). Brief descriptions are provided of sonic boom community studies conducted by NASA with a focus on cumulative noise metrics and long-term response. Subsequently, select research from laboratory studies are summarized.

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[1] General Operating and Flight Rules, 38 Fed. Reg. 8,051, 8,051 (Mar. 28, 1973) (to be codified at 14 C.F.R. pt. 91).

1. St. Louis

Nixon and Borsky (1965) summarize the first community response study to sonic booms. Motivated by the anticipated emergence of commercial supersonic aircraft, such as the Concorde and the United States' supersonic transport (SST), the study was conducted in the St. Louis area from July 1961 to April 1962. A B-58 aircraft generated about 76 sonic booms with approximately 1,000 participants who were interviewed twice. Sonic booms were measured in overpressure with units of pounds per square foot (psf). They asserted that "there is no overpressure below which all sonic booms will be acceptable nor one below which no responses at all can be assured," and the results were unable to produce "firm predictive schemes nor inflexible exposure criteria." Additional reports related to this study are provided by Hubbard and Nixon (1965) and Borsky (1961).

2. Oklahoma City

In 1964, a more comprehensive study was conducted in the Oklahoma City area (Borsky, 1965; Hilton et al., 1964). A total of 1,253 sonic booms were generated by multiple aircraft with nearly 3,000 participants interviewed three times in person and once over the phone. Sonic booms were once again measured in overpressure given in psf. Over six months of testing, a larger percentage of participants reported annoyance to sonic booms as time went on. This is attributed to a combination of continued exposure and increased boom levels later in the study. Additionally, participants were asked to evaluate their long-term acceptability of eight booms a day. The reported acceptability fell from 90% after the first 11 weeks to 73% during the final 7 weeks of the study.

3. Western USA Sonic Boom Survey

Fields (1997) describes the first social survey with noise measurements of human response to long-term exposure to sonic booms. The study was conducted between 1992 and 1995 and consisted of 14 small communities in two regions: Region A in Nevada and Region B in California. These locations were identified as having regular or relatively frequent exposure to sonic booms from military training and aircraft testing. The least exposed communities had about one measurable boom in 20 days and the most exposed had an averaged of two booms per day. A total of 1,573 interviews were conducted in which participants evaluated their reaction to sonic booms over the past six months. Based on limited data, they suggest DNL with A-weighting is equal or better at predicting response than measures of averaged peak noise levels or C-weighted metrics.

4. WSPR

Waveforms and Sonic Boom Perception Response (WSPR) was conducted in 2011 at Edwards Air Force Base in California (Page et al., 2014; Fidell et al., 2012). The study consisted of 50 participants from base housing residents responding to 110 supersonic overflights over 10 days. The "low boom" noise signatures were produced by an F-18 performing a supersonic dive maneuver that enables sonic boom amplitudes to be much lower than those from level flight. The cumulative daily noise exposure was the primary controlling variable in the experimental design. Five distinct cumulative doses were targeted with each to be repeated once. Participants essentially received the same cumulative dose given the small test area (~1 sq mi).

Several cumulative noise metrics were included in this study. While overpressures in psf were noted, the primary metrics considered in the analyses are DNL calculated from Perceived Level (PL) (Stevens, 1972) and A- and C-weighted sound exposure level (SEL). Additionally, DNL variations using Zwicker's loudness level in phons for frontal (LLZf) and diffuse (LLZd) incidences (Zwicker and Fastl, 1990) as well as Perceived Noise Level (PNL) from Kryter (1959) were included. Results suggested that CDNL best explains variation in the percent highly annoyed for a linear piecewise regression. The utility or lack thereof for CDNL with quieter supersonic noise signatures is discussed later in Section B.1

An additional analysis of WSPR data by Fidell (2013) investigated multi-event annoyance predictions. An interesting question he poses for cumulative annoyance response prediction is whether subjects integrate their own judgments of the sounds rather than the sounds themselves. Therefore, rather than using the single-event doses, he first compares the highest single-event response with the end-of-day response. He then develops a conceptual model to relate single-event annoyance response to a cumulative annoyance response in an energy-like summation process. He asserts that because noise metrics are generally highly correlated, it is difficult to separate the effects of level, number, and duration of events from each other.

5. QSF18

Quiet Supersonic Flights 2018 (QSF18) was conducted in Galveston, Texas in 2018 (Page et al., 2020; Fidell et al., 2020). Like WSPR, the study consisted of an F-18 aircraft performing low-boom dive maneuvers to generate "low booms." A total of 52 events were produced over nine flight days, and there were 500 recruited participants. This study gradually acclimated the community to the noise from supersonic overflights by increasing single-event noise levels over the nine flight days. There was some negative feedback from the community during testing which prompted researchers to curb the highest planned levels.

Additional cumulative noise metrics were examined for QSF18 relative to WSPR. These metrics include A-, B-, C-, D-, E-, and F-weighted DNL (where F-weighted is unweighted), as well as DNL summed variants of LLZd, LLZf, PNL, and the Indoor Sonic Boom Annoyance Predictor (ISBAP). Despite the additional metrics, cumulative dose-response results are minimally informative as the percent highly annoyed is only 2% at the highest observed dose value (see Figure 3d in Vaughn et al., 2022).

6. Laboratory studies

Select laboratory studies relevant to cumulative noise exposure are summarized here. The Environmental Protection Agency (EPA) include a number and level relationship for sonic booms in Appendix G of the "Levels Document" (EPA, 1974). Citing earlier work on community and psychoacoustic sonic boom response to up to eight events per day (Kryter 1969; Kryter et al, 1968), the following is a proposed relationship between number of sonic booms (N) and peak overpressure (psf) to not annoy nor adversely affect the general health and welfare of a population: Daytime peak overpressure per day $= 35.91/\sqrt{N}$. This has not been utilized, especially since sonic boom metrics have moved beyond overpressures as rise time has been found to be an important factor for human response that is better captured by frequency-weighted metrics (Maglieri et al., 2014).

Mabry and Oncley (1974) sought to establish a threshold of acceptability for commercial aircraft sonic booms. They conducted an in-home study where simulated sonic booms were produced by a signal generation system that included a tape player and four loudspeakers. Twelve subject families were recruited in the Seattle area. Over six weeks, participants were exposed to 30 booms a day for four weeks and 15 booms a day for the final two weeks. In respect to establishing an acceptability threshold, they conclude that based on indoor measurements "87 dB using Stevens' Mark VI [(a precursor to PL)] should be seriously considered as a design/certification criteria for indoor living with not more than fifteen daily exposures."

A study by McCurdy et al. (2004) addressed long-term sonic boom exposure in a home setting. They provided 33 participants an in-home noise generation system to simulate 4 to 63 sonic booms throughout the day over eight weeks. Participants provided end-of-day annoyance responses to the events of the given day. Applying the work of Fields (1984), they determined the best “decibel equivalent number,” k, for various indoor-measured DNL-based metrics. The rank order results for the DNL variants of the single-event metrics are as follows: PL, ASEL, PNL, LLZd, LLZf, CSEL, and ZSEL. While k values ranged from 10 to 15, they were deemed to not be statistically different from $k = 10$, suggesting that the equal-energy 3-dB tradeoff for halving or doubling the number of events is applicable for evaluating human response to sonic booms.

While not directly addressing cumulative noise exposure, additional laboratory studies have indicated preferred frequency weighting schemes for sonic booms that can be applied to cumulative noise metrics. The work of Leatherwood et al. (2002) evaluated five metrics: ASEL, CSEL, ZSEL, PL, and ZLL (Zwicker Loudness level). Among them, PL was found to be the best choice for comparing booms with different shapes and amplitudes. It also was deemed a good metric for outdoor listening conditions that worked well indoors. Subsequently, Loubeau et al. (2015) established six candidate metrics for human response to single-event supersonic overflights: A-, B-, D-, E-weighting SEL, PL, and ISBAP. These likewise are candidate frequency weightings for cumulative noise metrics for noise from multiple supersonic overflights.

B. IMPULSIVE SOUND

Impulsive sounds are defined as having a duration less than one second and being clearly audible over ambient noise (ANSI S12-9-2005/Part 4). Impulsive sounds are further subdivided into three categories: high-energy, highly, and regular impulsive sounds. High-energy impulsive sound encompasses blasts, explosions, and sonic booms. Highly impulsive sounds consist of small-arms gunfire and various sounds common to a factory environment. Regular impulsive sounds cover any sound that is not a high-energy or highly impulsive sound. The following sections contain brief examples of high-energy and highly impulsive sounds with discussion of their relevance to en-route supersonic noise.

1. High-energy impulsive sound

Schomer et al. (1997) conducted a comparison study on human response to blast noise and sonic booms. Their study recommends outdoor-measured CSEL for predicting human and community response to high-energy impulsive sounds (i.e., blast noise and sonic booms). The use of C-weighting builds on the earlier impulse noise response research by the Committee on Hearing, Bioacoustics and Biomechanics (CHABA) (CHABA, 1981; CHABA 1996). Schomer et al. (1997) report that indoor C-weighted measurements neither predict building nor human response. For the same outdoor-level, sonic booms were considered more annoying. This work validated treating blast noise and sonic booms in a like manner as implemented in the 1996 iteration of the ANSI standard regarding impulsive sounds (ANSI S12-9-2005/Part 4).

Nykaza et al. (2012) conducted a cross-sectional and panel study of community response to blast noise from a military installation in the United States. Their results revealed that annoyance was weakly correlated to the following blast noise metrics: number of blasts above unweighted peak level of 110 dB, number of blasts above unweighted peak level of 115 dB, and CDNL. They report that vibration and rattle contribute to annoyance. The weak correlation between annoyance and the cumulative noise metrics is attributed to the sporadic nature of blast events throughout the year and that the metrics do not properly account for the number and level nor the spatial and temporal variation of events.

Despite the prevalence of C-weighting for high-energy impulse sounds, the utility of C-weighting is diminished for shaped booms. Maglieri et al. (2014) explain that C-weighted metrics do not reflect the reduced loudness of shaped booms that have increased shock rise times. Their example compares the levels of an N-wave with a shaped boom using PL and CSEL. For PL, the shaped boom is 9.9 dB lower whereas in CSEL, it is only 4.1 dB lower. Additionally, the weak correlation between annoyance and cumulative noise metrics observed by Nykaza et al. (2012) for blast noise is plausible for en-route supersonic noise due similarly to the number, level, and variation of events. Furthermore, quieter supersonic noise signatures may be at levels below the criteria for high-energy impulsive sound.

2. Highly impulsive sound

Malowski et al. (2022) provide a literature review on firearm noise exposure. Peak single-event sound pressure levels of firearms are between roughly 130 and 175 dB. The general focus of these articles is on noise-induced hearing loss for occupational, recreational, and/or military operations. While the levels are far higher than anticipated for en-route supersonic noise from X-59, a study on developing a cumulative noise exposure model for outdoor shooting ranges lends another perspective to consider for cumulative noise exposure to en-route supersonic noise.

Wall et al. (2019) developed a cumulative noise exposure model for outdoor shooting ranges with military rifle data collected at the Weapons Training Battalion in Quantico, Virginia. This work is motivated by concern for hearing loss among military personnel following basic training. Their cumulative metric is an 8-hour A-weighted average level (L_{Aeq8hr}). They note that A-weighting may not be optimal for impulse damage risk assessment. Single-event levels are calculated as impulsive A-weighted equivalent 100 ms level ($L_{\mathrm{IAeq100ms}}$). Single-event and cumulative levels are related as follows: $L_{\mathrm{Aeq8hr}} = L_{\mathrm{IAeq100ms}} - 54.6$ dBA.

While the extreme difference in levels and number of events make the direct utilization of the Wall et al. (2019) model to en-route supersonic noise unpragmatic, the consideration of a different time scale (8 hours as opposed to 24 hours) could be further explored as future supersonic operations are limited to daytime hours in X-59 community studies and a metric that describes only those hours may be clearer to the public.

C. TRANSPORTATION NOISE

The Schultz curve is a common starting point within the literature of community response to transportation noise (Schultz, 1978). Schultz's work was motivated by efforts of the United States Department of Housing and Urban Development (HUD) to develop noise standards for a suitable living environment to help define compatible land use (HUD, 1971). He performed a meta-analysis using data consisting of community response to aircraft, road traffic, and railway noise from around the world. The resultant dose-response curve consisted of high annoyance as the response, given in percent highly annoyed, and A-weighted DNL as a measure of the long-term noise exposure for the dose.

Schultz subsequently published a book that further depicts his insight into community noise research (Schultz, 1982). He notes that the community response to transportation noise is more complex than suggested by his curve, specifically noting the importance of the frequency content, time variation of the sound, and the time of day and year of occurrence. Schultz's work set the foundation for much of the following community noise literature, including the prevalence of the DNL metric.

Ensuing research built upon the work of Schultz, as encapsulated by Fidell (2003) in his 25-year review on the subject. Fidell and Mestre (2020) provide a thorough review of aircraft noise through the lens of regulatory policy in the United States. Select research is summarized, showing strengths and deficiencies of DNL. Kryter (1982) differentiates between aircraft and road traffic noise. He claims that Schultz underestimated annoyance due to aircraft. Still using DNL as the cumulative noise metric, Kryter found aircraft to be more annoying than road traffic for the same noise level, demonstrating that DNL does not distinguish among transportation noise sources, which seems to be an important factor in annoyance. He also found high correlation between DNL and percent highly annoyed by aircraft for both broad (35 dB) and restricted (20 dB) dose ranges. Fidell et al. (1991) provide an update to the Schulz curve with results of an additional dozen social surveys. They continue to use DNL and conclude that the Schultz curve still provides a reasonable fit to the datasets.

In 1992, the United States Federal Interagency Committee on Noise (FICON) dictated their preferred metrics to measure dose-response relationships in community noise assessments (FICON 1992). For the response, annoyance was its preferred "summary measure of the general adverse reaction of people to noise," and that percent "'highly annoyed' by long-term exposure to noise" was its preferred measure of annoyance. For the dose, they indicate "the DNL methodology" for their noise metric of choice, particularly in the context of evaluating land use compatibility.

Miedema and Oudshoorn (2001) likewise conducted a meta-analysis of transportation noise for the Netherlands Organisation for Applied Scientific Research (TNO). The TNO study considered both DNL and day-evening-night averaged sound level (DENL) as cumulative metrics. Transportation noise was examined by source for aircraft, road traffic, and railway. Datasets spanned from 1965 to 1993 and were primarily from Europe with a handful of studies from the United States, Canada, and Australia. Their results include confidence intervals with the dose-response curves. For the same level, aircraft were found to be most annoying, followed by road traffic and then railway.

The World Health Organization (WHO) similarly performed a meta-analysis of transportation noise (WHO, 2018). Their goal was to provide guidelines protecting human health from exposure to environmental noise, including transportation noise. Each noise source (e.g., aircraft, road traffic, railway, etc.) is considered individually and include data from studies conducted around the world (including Asia). They focus their work on DENL as it is one of the most used cumulative noise metrics. In their justification for recommending reduced noise levels for communities, the WHO link cumulative noise exposure to health risks, including annoyance, sleep disturbance, and hypertension.

In the United States, the FAA conducted the Neighborhood Environmental Study (NES) to evaluate annoyance to aircraft noise near airports (Miller et al. 2021). Annoyance response data were collected from participants living near 20 randomly sampled airports across the United States. The FAA Integrated Noise Model computed DNL for the cumulative dose. A major takeaway from the NES study is that the national dose-response curve depicts greater annoyance relative to previous studies at the same levels, suggesting that, based on DNL, community annoyance to aircraft noise has increased over time.

Schreckenberg and Hong (2021) recently reviewed literature on community response to noise from 2017 to 2021. They narrowed their focus to 156 publications. Most studies use cumulative noise metrics that are A-weighted and equal-energy based, such as DNL and DENL. Noise annoyance is the most common response studied to noise ($n = 97$). Transportation noise is the most studied sound source, particularly aircraft noise ($n = 59$), road traffic ($n = 39$), and railway ($n = 23$).

III. DAY-NIGHT AVERAGE SOUND LEVEL

The widespread usage of DNL in community noise research, as noted in the transportation literature cited above, traces back to the EPA document, colloquially known as the "Levels Document" (EPA, 1974). The "Levels Document" resulted from the United States Noise Control Act of 1972. From the document emerged what became DNL, a time-weighted average measure of sound level, a single-valued measure of long-term noise exposure. The document also set forth guidance for predicting community reaction to noise using DNL. Stewart (2000) provides a historical review of DNL from the 1970s to 2000, largely overlapping the transportation noise literature above.

By definition, DNL is the 24-hour average frequency-weighted sound level with a 10-dB penalty added to nighttime levels from 10 p.m. to 7 a.m. A 5-dB penalty is added to evening levels from 7 to 10 p.m. for DENL (see Miedema et al., 2000 as an example validating evening and nighttime penalties for aircraft noise). For N single events, DNL can be calculated as follows:

$$L_{dn} = 10\log_{10}\left[\sum_{i=1}^{N} 10^{L_i/10}\right] - 49.4 \tag{1}$$

where L_i is the sound exposure level of the ith event and 49.4 dB results from integrating over the number of seconds in a day. A-weighting is the default frequency weighting for DNL unless otherwise specified.

DNL follows the equal-energy hypothesis with a prescribed tradeoff between level, duration, and number of events. A 10-dB level increase corresponds to a tenfold increase in number of events. For example, the DNL for a day with one noise event at 85 dB would be equivalent to a day with 10 events at 75 dB. Let us assume that a person's end-of-day response is not at all annoyed in a day with one event at 75 dB and highly annoyed by one event at 85 dB. Utilizing DNL would suggest that 10 events at 75 dB would produce the same high annoyance as one event at 85 dB. Upcoming community studies with the X-59 aircraft will have a maximum of 6 events per day, which may limit some ability to test the equal-energy hypothesis, making difficult to prove or disprove in general the tradeoff assumed with DNL for en-route supersonic noise.

Mestre et al. (2011) reviews DNL in the context of commercial, subsonic, fixed-wing aircraft and lists several pragmatic limitations, particularly when communicating to the public. A 24-hour, time-weighted average level is an abstract concept. People do not have common experience with DNL and may be unfamiliar with logarithmic units. Logarithmic arithmetic is non-intuitive to those of a non-technical background. The same DNL level can represent many different combinations of operations. The name "day-night average sound level" suggests insensitivity to events with high levels. Also, the name seemingly implies daytime and nighttime events.

In a similar vein, the Government Accountability Office (GAO, 2021) further recommends supplemental information and metrics beyond DNL for aircraft noise. Because DNL combines the effects of several components of noise (i.e., level, number, duration) into a single metric, DNL does not clearly express potential operational changes. They advocate for including additional metrics, such as changes in number of events, to help identify and address possible noise concerns, especially in communication with the public.

IV. ALTERNATIVE AND SUPPLEMENTAL CUMULATIVE NOISE METRICS

Alternative and supplemental metrics[2] are drawn from literature within the last five years and are discussed in relation to their potential utility for evaluating cumulative response to noise from multiple supersonic overflights. The metrics brought forward in the literature have limited utility for en-route supersonic noise, mainly because X-59 overflights will be infrequent compared with other noise sources studied with these metrics.

A. Generalized DNL

Vaughn and Christian (2024) provide background on, describe methodology for, and demonstrate a generalized DNL metric. The metric was developed with application to en-route supersonic noise in mind while also influenced by work from Urban Air Mobility (UAM) vehicle noise. Much of the background literature focuses on the “noise and number” problem, which addresses how to combine the noise from individual events into a single metric. One metric related to this work is the “decibel equivalent number,” k, from a meta-analysis by Fields (1984). More detail on the background literature supporting the generalized DNL formulation and on the “noise and number” topic can be found in Section II of Vaughn and Christian (2024).

This generalized DNL methodology uses a parameter b (previous references used ב, the Hebrew letter “bet”) to vary the cumulative noise metric. The generalized DNL metric is expressed as follows:

$$L_{dn,b} = 20\log_{10}\left[\left(\sum_{i=1}^{N}\left(10^{L_i/20}\right)^{b^{-1}}\right)^{b}\right] - 49.4 \tag{2}$$

where L_i is the sound level of the ith of N single events. To implement this analysis for a given dataset, with annoyance values fixed, the parameter b is varied from 0 to 1 to vary the resultant cumulative dose. When b equals 0, the formula returns the greatest/highest single event value. When b equals 0.5, the formula performs an equal-energy summation and outputs DNL. When b equals 1, greater weighting is given to the number of events than prescribed by DNL. Comparing the cumulative dose-response fits as a function of b provides insight into how well the data support the equal energy hypothesis.

Vaughn and Christian (2024) demonstrate this “b-analysis” on two datasets; one is simulated and the other was measured in QSF18. The simulated datasets exemplify when the analysis performs well and some potential limitations. Application to QSF18 data was not conclusive but establishes a framework for future application to data from X-59 community studies and other community noise studies.

Vaughn et al. (2023) further explored simulated datasets based on plans for X-59 community studies. (Note that the analysis with QSF18 data was performed prior to X-59 simulated datasets, despite the later publication date). Four preliminary dose designs for X-59 community studies were examined with the b-analysis. An association was found between experimental dose design and confidence in the b estimate. Two of the designs enabled a more

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[2] The terminology of alternative and supplemental metrics is loosely borrowed from Mestre et al. (2011). They state that alternative metrics to DNL are those that improve the ability to predict noise impacts and should not correlate well with DNL, while supplemental metrics are intended to improve communication with the public and their correlation to DNL does not matter. The metrics here are not differentiated between whether they are alternative or supplemental but are included as additional metrics to consider.

precise estimate of b than the other two designs, which indicates that it may be possible to optimize an experimental dose design for precision estimates of b.

The X-59 community studies are apt for application of the b-analysis. Given the larger dataset due to a combination of more participants and more days, X-59 community studies are more likely to produce greater precision in estimating b than QSF18, though limitations may still exist. Additionally, cumulative dose may be a secondary or tertiary concern for the final dose design schedule. Even if the b-analysis is not utilized in producing the final dose design for X-59 community studies, the framework is established to apply the analysis and leverage results to increase the interpretability of cumulative dose-response results. Ultimately, the simple description of the loudest single event or number of events relative to DNL as a predictor of cumulative annoyance response can help more clearly disseminate results than DNL alone.

B. Number Above

Number above (NA) is a metric gaining attention in the realm of fixed-wing aircraft noise. This metric simply counts the number of events above a given noise threshold, often a maximum sound level ($L_{\max}$). Newer technologies enable aircraft to efficiently fly precise flight tracks, which concentrates flight paths and increases the number of overflights for certain parts of a community. Motivated by this concern, Yu (2019) examined NA to reflect the impact of increased operations more accurately on the community. Scholten and Scata (2022) included NA in an update by the FAA on the NES. The NA55$L_{\max}$ and especially the NA60$L_{\max}$ show consistent responses in percent highly annoyed when plotted over equivalent ranges of the NES national curve, which "shows that the number above is also a very good predictor of annoyance that is pretty consistent with DNL results."

The applicability of NA to en-route supersonic noise appears limited. There are only up to six events per day planned for X-59 community studies (Rathsam et al., 2023) and future projections for commercial operations are a maximum of 10 events per day (Rachami and Page, 2010). With relatively few events, each event can contribute more significantly to the cumulative noise exposure; however, NA likely has limited utility for en-route supersonic noise given the few events in X-59 studies.

C. Kurtosis

Xin et al. (2023) recently recommended to use kurtosis to help assess occupational noise induced hearing loss in a factory setting associated with intermittent (or highly) impulsive noise. This newer recommendation of kurtosis echoes earlier work of Erdreich (1986). Kurtosis is a statistical measure of extreme values in a distribution relative to a normal or Gaussian distribution. When describing noise, kurtosis characterizes the "peakedness" of the pressure waveform (not to be confused with the "peakedness" of the pressure distribution) (Qiu et al., 2020). Peaks in the pressure waveform correspond to impulsive events.

Direct application of kurtosis as used by Xin et al. (2023) might not be relevant to en-route supersonic noise. Acceptability and annoyance are the concerns for en-route supersonic noise, not occupational noise induced hearing loss. The frequency and number of impulsive events in a factory setting are quite different from the two to six supersonic overflights per day in the X-59 community studies. It may be of interest in the future to look at kurtosis to characterize and compare conventional sonic booms with shaped booms in a listener study setting, or even in a post-hoc analysis of community response data.

D. Noise-Free Interval

Poling and Betchkal (2023) describe the noise-free interval (NFI) metric to assess human-generated noise in a national park. This metric describes the amount of time between the end of one audible noise event and the start of another. Much of the human-generated noise in national parks is from vehicles that enable visitors to access various parts the parks. The NFI can be used to assess vehicle management and the potential noise impact as national parks seek to restore and protect natural sounds as a resource.

The NFI could be used in post-hoc analysis of community studies with the X-59. Though there are few operations, understanding any potential changes in response due to their timing could help guide future commercial supersonic operations. In particular, the NFI could inform future commercial supersonic operations to limit supersonic flight paths over national parks.

V. CONCLUDING REMARKS

This document reviewed literature on cumulative noise metrics to consider for evaluating human response to en-route supersonic noise. Despite its deficiencies, DNL remains the most likely choice for a cumulative noise metric for multiple supersonic overflights because 1) it is widely used for impulsive, aircraft, and other transportation noise sources and 2) its relevance for infrequent events is somewhat plausible, unlike recent alternative metrics like NA, kurtosis, and NFI. DNL being well-established within the context of transportation noise allows for potential comparison with community response to various sound sources. Critics of DNL claim it is not easily understood by the public and that the prescribed tradeoff between level and number may not be as evidently established for relatively few, short-duration events. One recommendation is to supplement DNL with analysis performed using the generalized DNL formulation by Vaughn and Christian (2024). This formulation, though more complicated than DNL, may result in a simple description of whether people are more responsive to the single loudest event or the number of events relative to DNL. This analysis can be performed post hoc on X-59 community study data.

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