NOISE-CON 2024
TRUMPETING NOISE CONTROL
New Orleans, LA - June 10-12, 2024

Forecasting community response to low-frequency noise

David Nelson[1]
Nelson Acoustics
PO Box 5216
Bella Vista, AR 72714

ABSTRACT

The most common approach to managing environmental noise is by reference to A-weighted sound levels deemed appropriate for the community. These criteria are usually derived from transportation noise studies for which the relative proportion of low-frequency noise is implicit. Very different community reactions can arise when source spectra don't represent those studied. Responses diverge even further when the listeners' context also differs from that originally studied. This is nowhere more evident than in the case of large industrial equipment (such as power plants and gas compressor stations) sited in rural areas, due in large part to strong Low-Frequency Noise (LFN). Guidance for forecasting community reaction to LFN is scattered throughout the literature as individual studies employing a diverse assortment of approaches and noise descriptors. The purpose of the present paper is to demonstrate a straightforward, comprehensive, and unified forecasting approach suitable for inclusion in ANSI S12.9 Part 4 "Noise Assessment and Prediction of Long-Term Community Response", similar in many respects to the method recently deleted from this standard (2005 Annex D).

1. INTRODUCTION

It has been 51 years since Robert M. Hoover, then of Bolt Beranek and Newman, published "Beware low-frequency gas-turbine noise" [1]. He pointed out that a "sound pressure level of 75 dB in the 31.5 Hz octave will produce complaints from house dwellers whose windows, doors, and even china and flower pots are set into vibration", and explained that this frequency band shouldn't be ignored in design specifications. He was both preceded and followed by many others who correctly identified low-frequency noise (LFN) as a significant factor [see for example 2,3,4].

In spite of this, community noise criteria in the US are still commonly expressed in terms of Day-Night Sound Level (L_{dn}), an A-weighted average sound level with day-night weighting. The L_{dn} contribution from a house-rattling 75 dB at 31.5 Hz is only 43, which could lead to insufficient low-frequency noise control on the mistaken belief that LFN is not a factor. Unanticipated complaints from neighbors may then be regarded as spurious by the project owner, which can have the effect of supercharging the dispute. Failure to anticipate this type of situation contributes to mistrust of the noise control engineering profession by both owners and the public, as well as increased resistance to future projects from communities.

---

[1] david@nelsonacoustical.com

This "blind spot" comes about because of an incomplete reading of the 1974 US EPA "Levels Document" [5], which explored compatible levels of transportation noise in residential communities. The simple A-weighted sound level metric could be interpreted as suggesting that LFN is never a factor, but the relative LFN strength of transportation sources is well understood and therefore included implicitly.

The Levels Document goes on to specify 55 L_{dn} as compatible, and 60 L_{dn} as marginally compatible, with residential living in an urban environment. Normalization factors are included to address different contexts, characteristics, and operational factors (e.g., rural environment, tones, intermittent operation) without which the intended correlation with community response does not converge. These factors are often omitted and, unfortunately, LFN is *not* one of them.

It should not be surprising that the common, unadjusted 55 L_{dn} may be too high in situations where substantial LFN is present, and especially in rural areas. This warning has appeared in the literature repeatedly over roughly the last 70 years. It's time for the lesson it conveys to take a permanent place in our collective professional memory and in our acoustical standards.

2. NOISE ASSESSMENT AND PREDICTION OF LONG-TERM COMMUNITY RESPONSE

ANSI S12.9 Part 4 [6] addresses "Noise Assessment and Prediction of Long-Term Community Response". It formalizes the EPA approach, slightly modifies the Day-Night weighting, and provides additional detail about Adjustment Factors. An additional feature in the 1996 and 2005 versions is the "Schultz curve" which correlates the "adjusted day-night average sound level" L_{Ndn} with the percentage of the community "highly annoyed".

Annex D of these versions rectifies the EPA method's shortcoming by providing an adjustment method for "strong low-frequency content". The low-frequency sound level L_{LF} is computed as the decibel sum of the 16, 31.5, and 63 Hz octave-band sound pressure levels (Eqn. 1). An adjusted sound exposure level L_{NE} is computed as in Equation 2. The factor of 2 "accounts for the rapid increase in annoyance at low frequencies" near threshold as well as "additional annoyance from (vibration-induced) rattles" for $L_{LF} > 70\ dB$. L_{NE} is combined with the A-weighted sound level by decibel addition prior to applying other adjustments.

$$\mathrm{L}_{LF} = 10\log_{10}(10^{0.1L_{p,16}} + 10^{0.1L_{p,31.5}} + 10^{0.1L_{p,63}}) \tag{1}$$

$$\mathrm{L}_{NE} = 2\mathrm{L}_{LF} - 75 \tag{2}$$

The chief advantages of this approach are:

- it is based on outdoor sound pressure levels,
- the calculation is compact and straightforward,
- it addresses the rapid growth of annoyance near threshold,
- it addresses potentially feelable building vibration (especially in the 16 Hz band),
- it addresses rapid growth of annoyance due to rattles,

- the LFN descriptor can be combined with A-weighted levels to create a single descriptor incorporating LFN into a forecast of community reaction.

The foregoing method was not retained in the 2021 revision [7]. One of the concerns stated at the time was that the Committee could not determine the origin of the method or locate documentation supporting it. As one of its few users (apparently), the author has taken up the challenge of validating, modifying, and/or proposing a replacement for the method.

3. BASIS OF THE PROPOSED METHOD

The purpose of the present work is to design and document a metric that achieves what the previous method intended, compare the results, and make a recommendation to ANSI's S12 Working Group 15. The desired metric would generate a continuous equivalent dBA value (analogous to L_{NE}) from outdoor sound pressure levels. It should address both audible sound and feelable vibration and their respective thresholds of perception and annoyance. The proposed method combines a simplified version of DIN 45680 [8] with an adaptation of Shephard and Hubbard [3].

3.1. Adaptation of DIN 45680

DIN 45680 describes an annoyance score H based on the perceived loudness of indoor one-third octave band sound pressure levels from 8 to 125 Hz. The threshold of hearing is extended to low frequencies and encompasses the hearing sensitivity of 90% of the population. The annoyance parameter has value 0 at threshold, and the values 20, 25, and 30 are presented as annoyance limits for Night, "Rest times" (evening and weekend days), and Day, respectively.

The DIN 45680 method has been simplified and adapted to use outdoor sound pressure levels as follows:

- Estimate indoor sound pressure levels by subtracting the noise reduction of a "typical" residence from outdoor levels (see Table 1, drawn in part from ANSI S12.9 Part 4-2005 Annex H).
- Tabulate the locus of outdoor sound pressure levels in individual one-third octave bands that yield indoor H values of 0, 20 and 30 per DIN 45680.
- Make a least-squares line fit for each band, tabulating the threshold, intercept and slope (see Table 2).

Then, to implement the proposed method:

- In each band, if the outdoor sound pressure level exceeds the threshold, compute the audible contribution H_A in band i from the slope $m_{A,i}$ and intercept $b_{A,i}$ (Equation 3).
- Add the $H_{A,i}$ contributions from all bands using decibel addition (Equation 4).

Table 1: Noise Reduction of residential structure with windows closed

Band	**8**	**10**	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**
Noise Reduction (dB)	4	6	7	8	9	10	11	12	14	15	17	18	19

Table 2: Outdoor Sound Level Parameters – Audible Sound

Band	**8**	**10**	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**
Threshold (dB)	104	98	91	84	78	69	61	53	48	43	38	35	31
Slope	3.1	2.9	2.6	2.4	2.2	2.0	1.8	1.7	1.5	1.4	1.3	1.2	1.0
Intercept	-318	-280	-232	-197	-167	-134	-105	-87	-68	-57	-48	-41	-31

$$H_{A,i} = \mathrm{m}_{A,i} \cdot [10\ \log_{10}(10^{0.1L_{pi,op}} - 10^{0.1L_{pi,amb}}) - NR_i] - \mathrm{b}_{A,i} \tag{3}$$

$$H_A = 10\ \log_{10}\left(\sum_i 10^{0.1H_{A,i}}\right) \tag{4}$$

3.2. Potential Feelable Vibration

Shephard and Hubbard's research [3] determined outdoor sound pressure levels necessary to achieve feelable vibration [9] on residential windows, walls, and floors. In contrast to audible threshold sound pressure levels, which increase strongly towards low frequency, the sound pressure levels causing just-noticeable vibration perception *decrease* strongly. Surprisingly small LFN levels are sufficient to set a residential structure into feelable motion. Their approach has been adapted as follows:

- Determine the outdoor sound pressure levels necessary to excite a lightweight building surface into just-noticeable vibration[2] in one-third octave bands from 8 to 80 Hz[3]. Assume that all frequencies of interest are below the partition's mass-air-mass resonance so that it vibrates as a single unified structure.
- Assume that the threshold of perception defines $H_V = 20$. Assume that just-perceptible wall vibration, which requires 12 dB greater outdoor sound level (per Shephard and Hubbard) defines $H_V = 30$.

Then, to implement the proposed method:

- In each band, if the outdoor sound pressure level exceeds the threshold, compute the H_V contribution in band i from the slope $m_{V,i}$ and intercept $b_{V,i}$ (Equation 5).
- Add the $H_{V,i}$ contributions from all bands using decibel addition (Equation 6).

Finally, combine H_V and H_A by decibel addition and add 33.2 dB (Equation 7).

The "calibration factor" equates a continuous outdoor sound producing $H = 20$ indoors to $60\ L_{dn}$, the limit of "marginal compatibility". This value is analogous to the previous L_{NE} in ANSI S12.9 Part 4.

---

[2] Assume insulated glass with one light each of single- and double-strength glass (2.845 psf) and allow 10 dB for possible resonance in all bands (after Shephard and Hubbard).

[3] This feelable vibration method could be readily extended down to 1 Hz.

Table 3: Outdoor Sound Level Parameters – Feelable Vibration

Band	**8**	**10**	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**
Threshold (dB)	59	60	61	62	64	65	67	69	71	73	75		
Slope	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8		
Intercept	-27	-28	-29	-30	-31	-32	-34	-35	-37	-38	-40		

$$H_{V,i} = \mathrm{m}_{V,i} \cdot [10\ \log_{10}(10^{0.1L_{pi,op}} - 10^{0.1L_{pi,amb}})] - \mathrm{b}_{V,i} \tag{5}$$

$$H_V = 10\ \log_{10}\left(\sum_i 10^{0.1H_{V,i}}\right) \tag{6}$$

$$\mathrm{L}_{NE} = 10\log_{10}(10^{0.1H_A} + 10^{0.1H_V}) + 33.2 \tag{7}$$

4. RESULTS COMPARISON

4.1. “Minimal Annoyance” case

A note in S12.9/4 Annex D states that “Generally, annoyance is minimal when Z-weighted octave-band sound pressure levels are less than 65 dB at 16 and 31.5 Hz, and less than 70 dB at 63 Hz”. It is not explicit whether outdoor or indoor levels are meant. These values are familiar as indoor sound levels from ANSI S12.2 [10] associated with “Moderately perceptible vibration and rattle *likely*” (italics are the author’s). It doesn’t seem plausible that “likely rattles” correlates to “minimal annoyance”. For this analysis we assume the cited levels are *outdoor* levels.

Table 4 compares results for sounds occurring separately in individual octave bands using the familiar A-, C-, and Z- sound level metrics, the DIN 45680 annoyance value *H* and the corresponding audible sound L_{NE} that would be computed from it (by adding 33.2 dB), the older Annex D L_{NE} metric, and the proposed L_{NE} metric. See a combined chart in Figure 1.

Table 4: “Minimal Annoyance” case

Octave Band [Hz]	**Outdoor L_p (dB)**	**Indoor L_p (dB)**	**DIN 45680 H (L_{NE})**	**S12.9/4D-05 L_{NE}**	**Proposed L_{NE}**
16	65	57	< 0 (< 33)	55	55
31.5	65	54	14 (47)	55	45
63	70	55	37 (70)	65	74

The forecast annoyance is not quite minimal: 65 dB at 16 Hz is just feelable (L_{NE} =55), 65 dB at 31.5 Hz is just audible (L_{NE} = 45), and 70 dB at 63 Hz exceeds the audible threshold by some 30 dB and produces an L_{NE} of 74 dB. Even the lesser L_{NE} values could represent problem cases after adding the day-night adjustment and if other large positive Adjustment Factors are warranted.

The proposed metric agrees well with DIN 45680 in the 31.5 and 63 Hz bands where audible sound is dominant. The previous Annex D method varies between too sensitive and not sensitive enough because it does not consider the shape of either threshold.

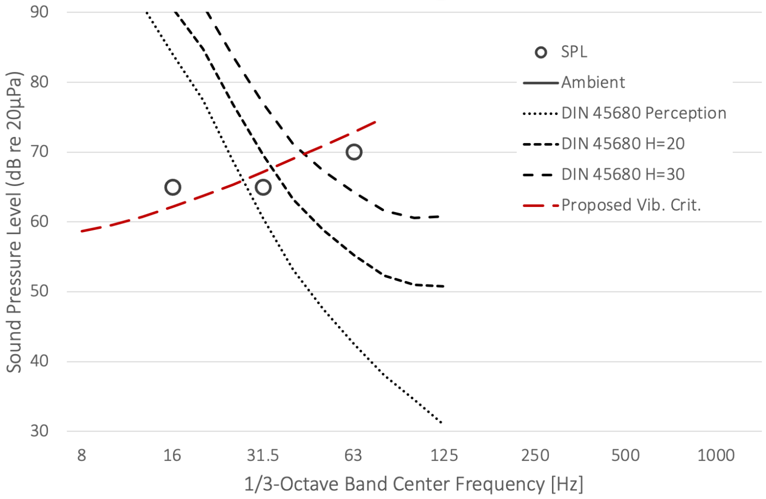

Figure 1: “Minimum Annoyance” Cases, Combined

4.1. Industrial Noise Examples

Examples are selected from the author’s measurements at four locations near three power plants:

- Site “F”, located ½ mile from a thermal power plant during continuous operation.
- Site “X”, located 1/3 mile from a thermal power plant during continuous operation.
- Site “L”, located ¼ mile from a thermal power plant during boiler startup. The residence at Site “L” is a manufactured home whose lightweight construction is probably more susceptible to vibration and rattles from the low-frequency tone.
- Site G, located ½ mile from a gas-turbine power plant, Operational Mode “C” (day only) was rated “Very annoying, definitely not acceptable” by the residents[4]. Data is from Hessler [4].
- Site “L” again, this time during steam venting. Although the 3 dB $L_{pC} - L_{pA}$ difference suggests this isn’t an LFN problem, very audible indoor sound and a strong likelihood of feelable vibration likely and rattles indicate otherwise.

Results are compared in Table 5 and the spectra are depicted in Figures 2 through 6.

Because of the opposite slopes of the feelable and audible thresholds it appears that noise in the 16 Hz band contributes primarily to feelable vibration while noise in the 63 Hz band contributes primarily to audibility. If strong enough, noise in the 31.5 Hz band can contribute to both.

---

[4] This site also experienced high sound levels in bands below 8 Hz which are not included or addressed here.

Table 5: Power Plant Noise Examples

Site	L_{pA} **(dB)**	L_{pC} **(dB)**	L_{pZ} **(dB)**	**DIN 45680** H **(**L_{NE}**)**	**S12.9/4D-05** L_{NE}	**Proposed** L_{NE}
F continuous	45	60	64	20 (53)	52	53
P continuous	50	62	65	25 (58)	52	58
L startup	41	72	82	26 (59)	88	70
G (Mode C)	46	73	78	35 (68)	80	71
L steam	91	94	94	43 (76)	95	80

All three methods are in good agreement in the first two cases where audible sound dominates. The proposed metric yields higher values than DIN 45680 as building vibration comes into play. The previous Annex D method yields even higher values where $L_{LF} > 70$ dB presumably in response to the possibility of building rattles, which are not addressed in the proposed metric.

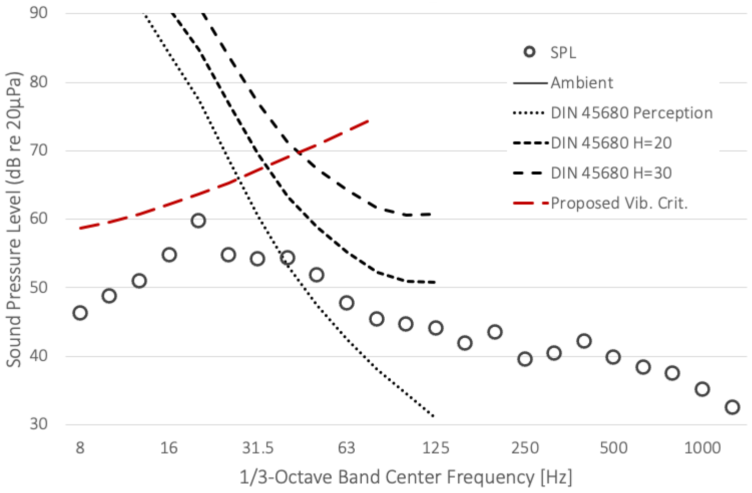

Figure 2: Site F, Thermal Plant, Continuous

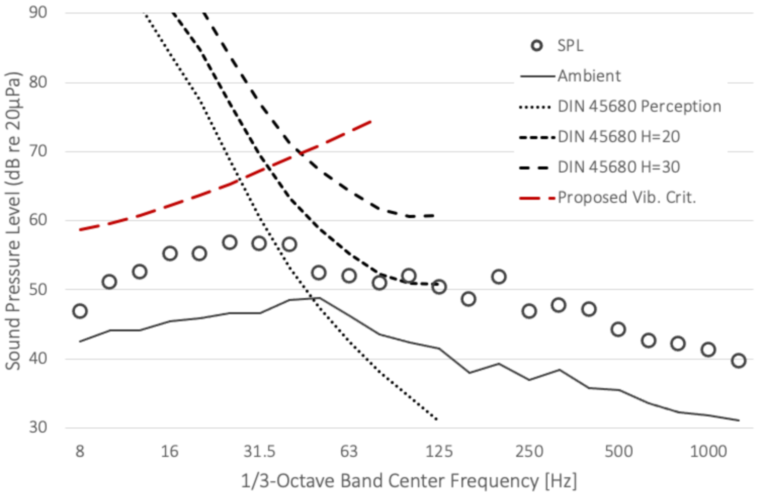

Figure 3: Site P, thermal plant, continuous

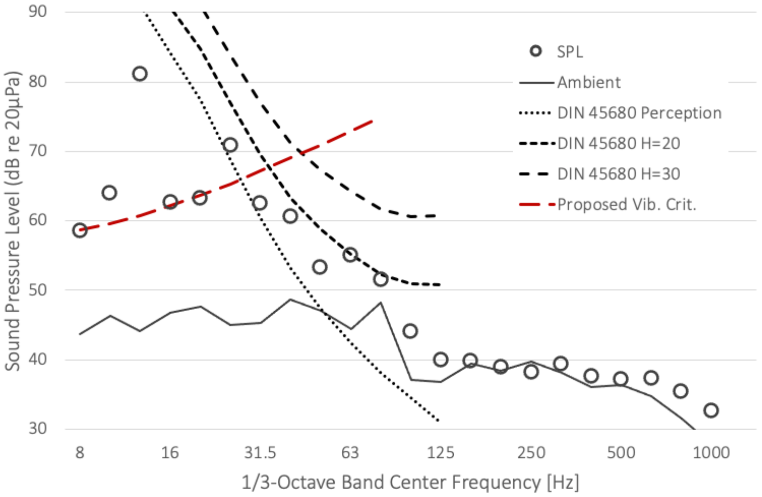

Figure 4: Site L, thermal plant, boiler startup

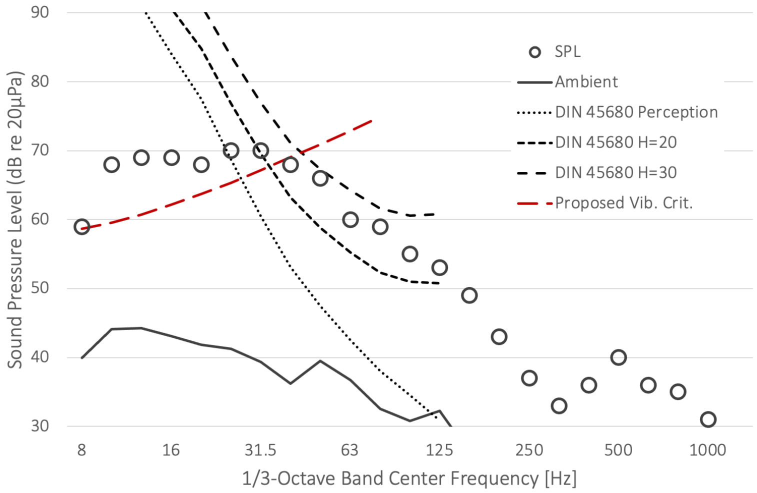

Figure 5: Site G, gas turbine plant, Mode "C" (Hessler)

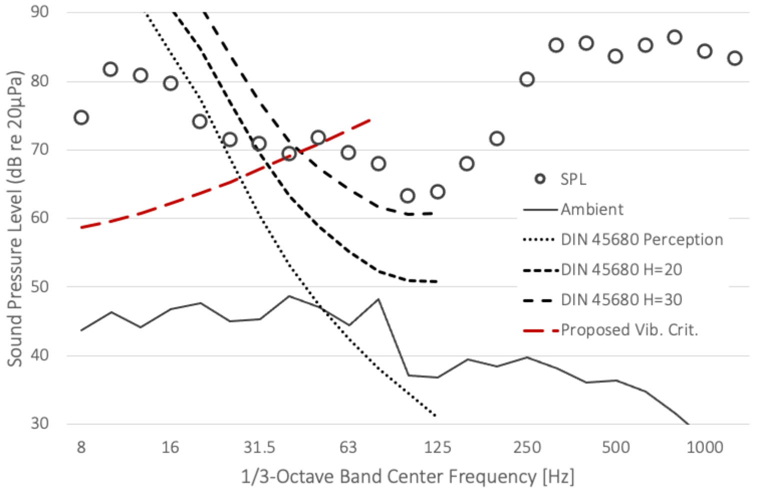

Figure 6: Site L, steam venting

5. CONCLUSIONS

An alternative method for assessing LFN has been proposed for comparison with and/or as a replacement for the previous method of ANSI S12.9 Part 4 Annex D [6]. It simplifies the DIN 45680 method and augments it by adapting the feelable vibration approach of Shephard and Hubbard. It yields a continuous adjustment factor analogous to L_{NE} which, when combined with A-weighted sound pressure level, is suitable for use in forecasting community response.

The proposed method agrees well with DIN 45680 when audible sound dominates. It yields elevated values when feelable vibration is present, as was intended. The previous Annex D method tends to agree with the proposed method at "moderate" LFN levels but forecasts even more annoyance when building rattles may be present. Given that building rattles are objectionable in any case, and because the corresponding highly-annoyed percentages are large, precision in this range may be less important than drawing attention to such a potentially serious problem.

Adjusted L_{DN} results are intended for comparison with land use compatibility criteria and to estimate the percentage highly annoyed. The Schultz Curve of the earlier S12.9/4 versions [6] was replaced [7] with Community Tolerance Levels (CTL). At present the standard provides CTL models for transportation noise sources only – the CTL approach has yet to be adapted for industrial noise sources.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the residents associated with these studies for their patience during long-term sound monitoring, and to ANSI S12 Working Group 15 on "Measurement and evaluation of outdoor community noise" for inviting the discussion.

REFERENCES

1. Hoover, R., Beware low-frequency gas-turbine noise. *Power,* **May 1973**, 87-88 (1973).
2. Stevens, K. N., Rosenblith, W. A., & Bolt, R. H., A Community's Reaction to Noise: Can it be Forecast? *Noise Control*, **January 1955**, 63-71 (1955).
3. Shephard, K. P. & Hubbard, H. H., Physical Characteristics and Perception of Low Frequency Noise from Wind Turbines. *Noise Control Eng. Journal* **36 (1)**, 5-15 (1991).
4. Hessler, Jr., G. F., Proposed criteria in residential communities for low-frequency noise emissions from industrial sources, *Noise Control Eng. Journal*, **52 (4)**, 179-185 (2004).
5. US EPA and Office of Noise Abatement and Control, *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*, aka "EPA Levels Document", Publication 550/9-74-004, 1974.
6. American National Standards Institute (ANSI), *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long-Term Community Response*, S12.9 Part 4 1996 and 2005 Editions.
7. American National Standards Institute (ANSI), *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long-Term Community Response*, S12.9 Part 4 2021 Edition.
8. Deutsche Institut für Normen, *Messung und Beurteilung tieffrequenter Geräuschemissionen,* DIN 45680 2013 Edition.
9. American National Standards Institute (ANSI), *Guide to the Evaluation of Human Exposure to Vibration in Buildings,* S2.71 2012 Edition.
10. American National Standards Institute (ANSI), *Criteria for Evaluating Room Noise,* S12.2 2019 Edition.