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To: Prince William County, VA, Board of Supervisors

Memorandum Report 1618-01: Prince William County Noise Ordinance Update - Basis and Background

EXECUTIVE SUMMARY

Nelson Acoustics was engaged in September 2024 to assist Prince William County (PWC) in updating its Noise Ordinance by providing insight from extensive experience and references to the noise control engineering literature. The goal of the update is to set limits for steady noises that persist with little change for extended periods of time, a common feature of electro-mechanical and industrial equipment. The purpose of this Memorandum is to educate the PWC Board regarding the technical basis for the Ordinance update under consideration.

The current noise Ordinance effectively addresses intermittent noise sources commonly experienced in suburban communities. However, new industrial installations are increasingly being located near residential areas in PWC. The current Noise Ordinance limits may not be able to address this "steady tonal sound" because of round-the-clock operation with near-constant sound levels and the potential for excessive low-frequency noise.

The proposed Ordinance update characterizes this noise type as "steady tonal sound" and defines it as:

> *Steady tonal sound means a sound characterized by a droning nature and which may be referred to as a whine, hum, rumble or buzz, which may either be broadband or include a single frequency or a narrow cluster of frequencies, Such sound sources include, but are not limited to, heating, ventilating or air-conditioning units, refrigeration units, transformers and backup generators. The sound level from the source must remain essentially constant for the duration of any given measurement.*

The experience of noise annoyance depends on both objective (measurable) and subjective (perceptual) factors including sound level, sound spectrum, sound characteristics, accustomed background noise levels and degree of

change from those levels, time of day, neighborhood type, the history of how the noise came to be, it's perceived significance for the future, and interactions with the person or organization creating the noise.

"Compatible", "Marginally Compatible", and "Incompatible" noise levels are well established in engineering standards and the noise control engineering literature for transportation noise and "typical" community noise sources. The relationship between sound levels and community response in various neighborhood types has also been studied in detail. These concepts are adapted for constant-level noise.

Because the new limits are part of an enforceable regulation for criminal conduct, they are set at the edge of Incompatibility with suburban residential living. As such it should be clear that compliance does not equate to silence, nor will it necessarily eliminate annoyance or complaints, and should not be confused with a "good neighbor" prescription.

The new limits consist of not-to-exceed octave band sound pressure levels applied to steady noise. They are based on currently observed sound levels in unaffected PWC residential areas combined with compatibility-based guideline spectra. The levels are low enough that residents who have not been previously overexposed should find the situation manageable, and high enough to avoid classifying currently unaffected suburban neighborhoods as "out of compliance".

(External references are denoted by square brackets [Ref. x] and are listed at the end of the document. Internal footnotes are denoted by superscript[x] which appear in most cases at the bottom of the page where they are indicated.)

1. SOUND LEVELS COMPATIBILE WITH RESIDENTIAL LIVING

Environmental noise has historically been evaluated in terms of the "equivalent average A-weighted sound level", $L_{pA,eq}$. The A-weighting filter approximates the perceived sensitivity of human hearing to low- and moderate-level pure tones[1]. The equivalent average sound level has the same energy as the average energy observed during the measurement period. This approach is used for both brief and longer-term noise measurements.

[1] Speaking broadly in musical terms, A-weighting emphasizes "treble clef" sounds (above middle-C) and de-emphasizes "bass clef" sounds (below middle-C). A-weighted measurements regularly underestimate the impact of low-frequency noise which can be problematic because it is more easily transmitted into residences.

Long-term community response to noise has historically been evaluated using the weighted[2] "equivalent average day-night sound level", L_{dn} [Ref. 1]. The L_{dn} approach successfully tracks community response to transportation noise in urban areas. Additional modifiers ("adjustments") account for heightened community response in other contexts and when objectionable noise characteristics are present.

The American National Standard ANSI S12.9 Part 5 defines an adjusted sound level above 60 L_{dn} as incompatible with urban residential living [Ref. 2]. Suburban and rural communities are more sensitive by 5 and 10 dB respectively [Ref. 1,2,3], so the unadjusted compatibility limits for those neighborhood types are 55 and 50 L_{dn}, respectively[3].

Table 1: Day-Night Sound Levels compatible with residential living

	Compatible	Marginally Compatible	Incompatible
Urban	≤ 55	55 – 60	> 60
Suburban	≤ 50	50 – 55	> 55
Rural	≤ 45	45 – 50	> 50

Prince William County comprises all three neighborhood types. With an approximate overall population density of 1,400/square mile, PWC can be categorized between "quiet urban/normal suburban residential" and "quiet suburban residential". The expected pre-existing L_{dn} for that population density is 50 L_{dn} [Ref. 4]. Incompatibility, for the purposes of this project, is therefore based on the limit for suburban residential living: 55 L_{dn}.

2. CURRENT LIMITS APPLIED TO STEADY NOISE

The day-night sound level associated with a round-the-clock steady sound meeting the current nighttime limit (55 dBA) would be 62 L_{dn}, clearly incompatible with all three neighborhood types. The strongest contribution to annoyance for a constant-level noise occurs during nighttime hours. Table 2 gives some insight into how this weighted average is calculated[4].

[2] where 10 dB is added to LpA,eq measured at night (10 pm to 7 am), 5 dB is added to LpA,eq levels measured on weekend days (7 am Saturday to 10 pm Sunday); and LpA,eq levels measured during weekdays remain unchanged.

[3] Further references in this document will be to unadjusted L_{dn}.

[4] The time-of-day weightings reflect heightened sensitivity to noise, and the hours-per-week weightings are related to the fraction of a week each sensitivity factor is in effect. The contribution for each period is the arithmetic sum of $L_{pA,eq}$ and the corresponding weighting factors. The contributions are then combined by decibel addition [1]. The L_{dn} for a constant-level sound can be estimated by adding 7 dB to the A-weighted sound level. Values in Table 2 are rounded to the nearest whole decibel.

Table 2: Median Percent Highly Annoyed at 65 L_{dn}

Period	$L_{pA,eq}$	Weighting Time of Day (dB)	Weighting Hours/Week (dB)	Contribution
Weekday	55	+ 0	-4	51
Weekend		+ 5	-7	53
Night		+ 10	-4	61
L_{dn}				**62**

Large mechanical equipment tends to include a significant amount of low-frequency noise (LFN). Even a moderate amount of LFN would raise the effective L_{dn} from 62 to an adjusted 65 L_{dn}[5] [Ref. 1]. Thus, the current nighttime regulation could allow a constant mechanical equipment noise with impact equivalent to 65 L_{dn} or greater.

The long-term response of communities to 65 L_{dn} can be forecast [Ref. 1] as the percentage of persons "highly annoyed"[6]. The initial response to a new intrusive noise, especially if public relations are poor, is equivalent to increasing the L_{dn} by an additional 5 dB [Ref. 1,3].

Table 3: Median Percent Highly Annoyed at 65 L_{dn}

	Long-term	New
Urban	15 %	25 %
Suburban	25 %	40 %
Rural	40 %	55 %

Some communities may be more sensitive than the median values tabulated above.

From the foregoing it should be clear that a constant 55 dBA industrial noise introduced into a suburban environment would elicit numerous, strong complaints despite being acceptable under the current Ordinance.

[5] Using methods described in Annex D of the 2005 version of [1], a moderate low-frequency sound level L_{LF} of 65, which might often occur in conjunction with L_{pA} 55, is equivalent to adding 62 L_{dn} to the previous total: in decibel math, 62 + 62 = 65 L_{dn}.
[6] Broadly speaking, "highly annoyed" suggests persons willing to go beyond making sporadic individual complaints. This may take the form of sustained opposition to current or future similar noise sources through group social, political or legal action.

3. DEVELOPING THE OCTAVE-BAND CRITERIA

The increasing size and power of modern mechanical equipment brings with it increasing low-frequency noise (LFN) emission. Complaints about LFN typically arise indoors where the building structure filters out the higher frequencies. What remains is a disproportionately bass-heavy sound spectrum sometimes characterized as "rumble". If in addition the noise does not abate at nighttime the experience of intrusive noise is heightened. Listeners may associate it with something large, powerful, unrelenting, and unwelcome just outside while trying to sleep.

The recommended criteria are expressed in terms of a octave-band outdoor limit spectrum for daytime and for nighttime. Octave band analysis is necessary to account for the frequency-dependent sensitivity of human hearing.

The limit spectra represent the convergence of two complementary approaches to defining Incompatibility:

- Identify octave-band levels likely to cause significant complaints in unaffected residential areas, based on a 5 dB departure from measurements made around PWC.
- Identify octave-band spectra at the edge of Incompatibility based on guidance from the engineering literature.

In the first approach, community reaction to intrusive noise is due in part to the increase from accustomed background sound levels. A 5 dB increase is associated with "widespread complaints" [Ref. 3]. Thus, a spectrum 5 dB greater than the observed median sound levels[7] provides a reference point for Incompatibility over a representative portion of the County.

The second approach makes use of two guideline documents:

- The Composite Noise Rating [Ref. 5] was introduced in the 1950s and was applied successfully to a wide variety of noise sources, including industrial sources. It was updated and promoted by Laymon Miller of BBN in the "Noise Course" notes [Ref. 6]. It defines a family of "balanced" environmental noise spectra and a method for forecasting community response.
- Research into the effects of LFN over the ensuing years have led to more stringent recommendations. A recent German (DIN) standard [Ref. 7] defines a method for evaluating LFN relative to recommended levels for residential living.

[7] 16 locations during daytime and 8 locations during nighttime, selected by County staff.

The DIN evaluation is used in the 31.5, 63 and 125 Hz bands[8]. The CNR evaluation is used in the bands centered at 250 Hz and above. Their values are spliced into a single row in Tables that follow.

The resulting recommended limits are such that higher levels would be incompatible with residential living, and lower levels would cause an increasing number of "false positives" and more difficult enforcement measurements.

3.1 Nighttime Limit Spectrum

The nighttime limit spectrum (Table 4) roughly equals the higher of the values arrived at using the two approaches. In other words, the limit spectrum is based on the DIN and CNR guidelines unless higher levels could be justified based on pre-existing levels.

Table 4: Nighttime Limit Spectrum

	Octave Band Center Frequency [Hz]								
	31.5	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Recommended	60	55	50	45	40	36	33	31	30
Median + 5 dB	53	55	50	42	39	37	33	31	25
DIN/CNR	61	53	47	45	41	36	33	30	28

The LFN limits (31.5, 63 and 125 Hz) based on the DIN standard are collectively 3 dB above the nighttime "reference level" below which significant residential LFN problems are avoided. The contribution to each of the octave bands to annoyance is roughly equal.

The CNR limits (250 Hz and above) are the arithmetic average of the "b" and "c" source curves. "Sporadic complaints" are forecast for a spectrum equal to these levels in any octave band, with "widespread" complaints possible if LFN is perceived as annoying.

The difference is split at 500 Hz and a more permissive value is included at 8000 Hz to better handle biogenic sounds (e.g., insects, etc.). The limit is

[8] Low frequency noise as evaluated in one-third octave bands according to the DIN standard covering the range 8 Hz to 100 Hz. Because significant mechanical equipment noise has not been observed below the 31.5 Hz band, the 8 Hz and 16 Hz octave bands have not been included in the recommended limits.

reduced slightly at 31.5 Hz to reduce below 50% the number of indoor listeners able to detect sound in that band[9] [Ref. 8].

3.2 Daytime Limit Spectrum

The daytime limit spectrum (Table 5) roughly equals the higher of the values arrived at using the two approaches. In other words, the limit spectrum is based on the guidelines unless higher levels could be justified based on pre-existing levels.

Table 5: Daytime Limit Spectrum

	Octave Band Center Frequency [Hz]								
	31.5	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Recommended	65	60	55	50	45	41	38	36	35
Median + 5 dB	61	60	54	48	43	41	38	33	23
DIN/CNR	66	59	52	50	46	41	38	35	33

The LFN limits (31.5, 63 and 125 Hz) are set 5 dB above the nighttime spectrum. The contribution to each of the octave bands to annoyance is roughly equal. This is 2 dB *below* the "reference level" for daytime, in consideration of the needs of day sleepers (e.g., firefighters, police, medical personnel).

The CNR limits (250 Hz and above) are the arithmetic average of the "c" and "d" source curves. "Sporadic complaints" are forecast for a spectrum equal to these levels in any octave band if LFN is perceived as annoying.

Modifications of 1 dB are made at 125 Hz, 500 Hz, and 4000 Hz to parallel the nighttime spectrum, exactly 5 dB higher. A more permissive value is included at 8000 Hz to better handle biogenic sounds (e.g., insects, etc.). The limit is reduced slightly at 31.5 Hz to avoid perceptible vibration [Ref. 9], particularly in windows[10].

3.3 Comparing Outdoor Sound Levels to $L_{pA,eq}$ and L_{dn}

A sound spectrum exactly equal to the recommended criterion in each octave band would result in the following overall sound levels:

[9] An outdoor sound level 60 dB in the 31.5 Hz octave band corresponds to approximately 49 dB indoors. If concentrated in the 40 Hz 1/3-octave band (the most sensitive within the 31.5 Hz octave band) approximately 40% of the population would be able to detect the sound.
[10] 66 dB is reported as the threshold for feelable window vibration in the 25 Hz 1/3-octave band (the most sensitive within the 31.5 Hz octave band) [9].

- 43 dBA during nighttime, and
- 48 dBA during the daytime

This is 12 dBA more stringent than the current regulation of 55 dBA night, 60 dBA day.

A round-the-clock constant-level sound conforming to each of the nighttime octave band limits (43 dBA) would correspond to 50 L_{dn}. However, the A-weighted outdoor level formulation does not address LFN. The low-frequency portion of the same spectrum has an equivalent effect as 55 L_{dn}. Decibel addition of 50 L_{dn} and 55 L_{dn} gives a total of 56 L_{dn}.

The 56 L_{dn} overall result is compared to the 65 L_{dn} calculated above as possible for the current Ordinance, revealing that the new regulation is the equivalent of 9 L_{dn} points more restrictive. Significantly lower rates of annoyance are forecast.

Table 6: Median Percent Highly Annoyed at 56 L_{dn}

	Long-term	New
Urban	5 %	10 %
Suburban	10 %	15 %
Rural	15 %	25 %

As a practical matter, noise control designers typically observe an engineering safety factor of at least 3 dB. Furthermore, it's uncommon to exactly "fit the curve" – surplus noise control (i.e., lower sound levels) is usually unavoidable in some bands to achieve the desired result in one particularly difficult frequency range. Thus, a facility designed to comply with this Ordinance can be expected to have an overall sound level several decibels below those given above.

3.4 Comparison to indoor noise guidelines L_{pA} and NC

The Ordinance regulates outdoor noise levels. Indoor noise levels are inferred by subtracting the typical outdoor-indoor level difference (Noise Reduction or *NR*) for wood frame residential structures (with windows open roughly 2 inches) [Ref. 1]:

Table 7: Attenuation of Typical Residence

	Octave Band Center Frequency [Hz]								
	31.5	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
NR (dB)	11	15	19	21	23	25	25	25	30

Estimated overall indoor sound levels can then be calculated and compared to two indoor noise guidelines, L_{pA} and NC rating.

The World Health Organization (WHO) recommends indoor sound levels less than 30 dBA to facilitate sleep [Ref. 10].

Recommended indoor noise levels due to operation of HVAC and other building systems are given in ANSI Standard S12.2 [Ref. 11]. The guideline for residential bedrooms is NC-25. For comparison, NC-15 is the guideline for broadcast facilities such as TV studios.

The highest possible indoor L_{pA} and NC ratings are calculated by subtracting the attenuation of a typical residence from an outdoor sound spectrum exactly equal to the recommended outdoor criterion in all octave bands:

Table 8: Highest Possible Indoor Overall Sound Levels

Period	L_{pA}	NC
Day	27	16
Night	22	10

The quantity of noise is therefore expected to be typical for air-conditioned residences and compatible with sleep. If the character of the intruding noise is deemed objectionable, it's possible that masking noise could be employed and effective without becoming itself objectionable.

Noise just complying with the criterion spectrum has the potential to be audible in an otherwise quiet home and external environment. While audibility does not necessarily mean a noise is unacceptable, listeners form their individual opinions based on a variety of factors including the human brain's reflexive ability to focus attention on sounds.

3.6 Comparison to other regulations

The new limit spectra are compared to other octave-band regulations in Tables 9 and 10. A variety of measurement and averaging schemes are used in evaluating them, so the comparisons are not strictly "apples to apples".

Table 9: Comparison to other octave band limits, Nighttime

NIGHT	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Proposed	60	55	50	45	40	36	33	31	30
Warrenton	---	59	55	49	43	37	33	29	25
Illinois*	63	61	55	47	40	35	30	25	25
Oregon	65	62	56	50	46	43	40	37	34
New Jersey	86	71	61	53	48	45	42	40	38

* based on the most restrictive Illinois property designation

Table 10: Comparison to other octave band limits, Daytime

DAY	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Proposed	65	60	55	50	45	41	38	36	35
Warrenton	---	64	60	54	48	42	39	34	30
Illinois*	72	71	65	57	51	45	39	34	32
Oregon	68	65	61	55	52	49	46	43	40
New Jersey	96	82	74	67	63	60	57	55	53

* based on the most restrictive Illinois property designation

4. Related Topics

4.1 Extracting the Source Contribution from the Total Sound

The Ordinance governs the *contribution* of noise from a particular source. This prevents a facility from being penalized for noise generated by others or already present in the environment.

In most cases the source contribution will be established by subtracting the ambient sound levels[11] without the source operating (either by turning off the source or by measuring at a suitable proxy location) from the total sound level[12] with the source included. If the difference between the total sound (*TS*) level and ambient sound (*AS*) level is greater than 3 dB, the source contribution (*SC*) can be computed as [Ref. 4]:

$$SC = 10\log_{10}(10^{0.1TS} - 10^{0.1AS})$$

[11] Ambient sound refers to pre-existing sounds generally present in the area, excluding the sound source under investigation and intermittent extraneous sounds.
[12] Total sound comprises both the ambient sound and the sound source under investigation, excluding extraneous sounds.

If the 3 dB differential is not achieved in a particular band or for overall sound level, the source contribution cannot be accurately determined, and the situation is deemed unenforceable.

The minimum 3 dB differential occurs when the source and ambient levels are numerically equivalent[13]. In other words, the ambient level is the *de facto* criterion when it is higher than the Ordinance criterion. It's possible for residents to be able to perceive the noise source separately from the ambient even when the overall source sound level is less than the ambient. This is an unfortunate consequence of the fact that the human brain is far more sophisticated than a sound level meter.

4.2 Lower criterion levels

Some members of the community expressed a desire to mandate even lower sound levels. Criterion levels would have to be reduced by about 5 dB to produce a significant shift in community reaction. Rural residents would be the primary beneficiaries of this approach, but diminishing returns are apparent in other areas.

The lowered criterion would approximate the median measured spectra, which means (by definition) that in any given band the ambient would equal or exceed the lowered criterion at half of the evaluated locations. In these areas the ambient would be the *de facto* criterion (see discussion above); the lowered criterion values would not be fully enforceable. Residents might find it frustrating that enforcement is not possible against a noise that they may be able to perceive.

Measurements supporting enforcement would also become more complex. The number of potential ambient sources whose contributions need to be accounted for and avoided or subtracted out increases exponentially, and more exotic windscreens or lower maximum windspeeds would also be required to support low-frequency measurements.

Finally, existing facilities not currently generating complaints would be more likely to be categorized as non-compliant ("false positives"). Concern was expressed that such businesses would find themselves in an uncertain state and that businesses typical in suburban areas would have more difficulty complying with the Ordinance in quiet areas, inhibiting natural growth. In addition, a larger proportion of new and/or expanding facilities would require

[13] The addition of two equal sound levels yields 3 dB greater than the original level. This happens because decibels are logarithmic expressions of sound energy - doubling the energy corresponds to a 3 dB increase.

noise control plans, each of which would involve more complexity and higher cost that might be difficult to justify.

4.3 Higher criterion levels

Objections may arise that the criterion is too stringent and that criterion levels should be higher. This objection would suggest that a greater degree of Incompatibility should be accommodated before enforcement takes place. In such a scenario a rapidly increasing number of people would be highly annoyed for each decibel increase, especially in quiet areas. Indoor daytime sound levels could rise above 30 dBA, affecting day sleepers like firefighters, police, and medical personnel. In other words, $L_{dn} > 55$ serves as an inflection point for additional negative community reaction.

5. CONCLUSION

Recommended criteria for constant-level industrial and electro-mechanical equipment noise ("steady tonal sound") have been developed specifically for PWC during this project. They have been derived with extensive reference to well-known guidelines and engineering standards as well as samples of existing sound levels believed to be common within Prince William County. The criterion levels fall into a narrow range where higher levels would be incompatible with residential living and lower levels would cause an increasing number of "false positives" and more difficult enforcement measurements. Particularly in lower frequency bands the criterion values are notably more stringent than other regulations due to the inclusion of recent research on low-frequency noise annoyance.

Effective noise control planning should be required *in advance* to avoid situations in which a facility causes excessive noise as it initially comes online. Residents thus over-exposed may develop enhanced sensitivity to noise, requiring *even more* noise control to achieve a satisfactory result after the fact.

It is hoped that these recommendations will provide Prince William County with a robust, enforceable criterion that balances the needs of residents with future growth. In addition, it is hoped that these criteria will provide clarity for facility designers seeking to identify noise control needs well in advance of construction and operation.

The recommendations described in this memorandum have been specifically tailored to the needs and conditions of Prince William County, VA. While it is believed the methods described herein might be generally applicable, the limit spectra are not portable: detailed study would be needed to adapt them for other municipalities on a case-by-case basis.

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