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MS

Michael Schwebel

February 16, 2026 at 4:17PM

Correspondence to Sampson Creek CDD regarding Pickleball at Basketball Courts in St. Johns Golf and Country Club

To: yurocdd@gmail.com, lweitzelcdd@gmail.com, mikedaviscdd@gmail.com, Graham leary & 12 more

[Details](#)

Good afternoon,

Please see attached correspondence and attachments from homeowners in St. Johns Golf & Country Club regarding discussion of removing a basketball court and installing pickleball courts. There is one additional attachment that will be sent in a follow-up email momentarily.

Please feel free to contact me with any questions, or let me know if you have any difficulty opening the attachments.

Regards,

Michael L. Schwebel, Jr., Esq.
Partner/Shareholder/Founder



WILSON & SCHWEBEL, P.C.

ATTORNEYS AT LAW

MS

Michael Schwebel

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Re: Correspondence to Sampson Creek CDD regarding Pickleball at Basketball Courts in St. Johns Golf and Country Club

To: yurocdd@gmail.com, lweitzelcdd@gmail.com, mikedaviscdd@gmail.com, Graham leary & 12 more

[Details](#)

The final attachment.

Thank you again.

Regards,

Michael L. Schwebel, Jr., Esq.
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February 16, 2026

Board of Supervisors of The Sampson Creek CDD

Mike Yuro – Chairman

Lori Weitzel – Assistant Secretary

Michael Davis – Assistant Secretary

Graham Leary – Vice Chair

Kyle Geary – Assistant Secretary

Re: Proposed Pickleball Courts at the Basketball Courts or other Locations Near Homeowners in St. Johns Golf and Country Club

Dear Supervisors:

This letter is from concerned homeowners related to the Board's continued entertainment of removing a basketball court from our community and replacing with multiple pickleball courts. We are disturbed that due to the excessive noise and nuisance pickleball courts undoubtedly create, the quality of life for those most close to the courts will be significantly impacted as will their home values. We are further troubled with the precedent the Board will set by bending to the whims of a minority of homeowners to the severe detriment of others. To be clear, *even if* a majority or even 99% of the community wanted to take action that results in harm and nuisance to some homeowners, it is the duty of the Board to make sure such harmful actions are not taken.

Purpose of the CDD and Protection of Minority Homeowner Rights

Homeowners have an absolute right to a peaceful home. The purpose of a Community Development District (CDD) is to maintain the community facilities for the benefit of the property owners – all of the property owners. A CDD that takes action where the majority rules versus minority rights would not follow the spirit of the purpose of CDDs. It is even more critical for a CDD to protect individual homeowners where a minority of the community wishes to take action to the detriment of such individual homeowners.

The instant case involves such drastic misuse. If a CDD was run in such a way to allow minority rule to hurt others, it is not hard to see the ultimate result. Any minority with access to the board could push unfounded agenda, or others could use elections to engage in retaliatory measures. Pitting neighbor vs. neighbor is not the purpose of a CDD.

Only a Minority Favor Pickleball

Since pickleball courts result in harm and nuisance to nearby homeowners, the Board should never consider installing pickleball courts where any homeowners will be adversely affected. This is true even if a majority of the community supports the pickleball courts. However,

in this instance, there is no debate the pickleball agenda is pushed by only a minority of the community. The most recent Petition submitted in favor of pickleball was signed by **only 17% of the households** of this community. (Petition attached for your reference). In 2019, only **20%** of homes favored a pickleball court. In 2024, just **18%** of homes in the neighborhood wanted pickleball. There is no evidence that anything other than a minority of homeowners in this community want pickleball here. In fact, if the homeowners surveyed were fully informed, the real number would be even lower.

Recent Petition is Flawed, Provided Under False Pretenses and Mis-States Facts

The **17%** of homes that favor pickleball include some who were induced to sign a petition under false pretenses based on mis-representation and omission of key facts. We are aware of several persons who would “un-sign” the petition if they could. The petition is critically flawed, based on broad generalizations unsupported by evidence and omits any concerns adding pickleball (and removing basketball) result in.

First, the petition boldly and falsely states that “the majority of homebuyers are asking for neighborhoods with pickleball,” without citing to a single reference. Common sense alone dictates this is not a true statement. The best evidence of the exaggerative nature of this statement is that **only a 17% minority of this community** wants pickleball here. So even if true (which it is not) that a majority of homeowners want pickleball, the majority of homeowners in this community do not. The reason there is no evidence cited by the petition is because there is none. This exaggerated statement was made for the sole purpose of inducing people to sign something under the false pretense that the majority want pickleball. Untrue and sensationalist remarks that lead to petition signatures should not result in the petition being taken seriously.

Even more jarring is the petition’s ignorance of the nuisance-level nature of pickleball sounds. Without pointing to any scientific study or research of any kind, the petition states “noise concerns are negligible if comparing decibel levels between basketball (estimated 80 decibels) and pickleball (estimated 70 decibels).” The petitioner falsely claims that the current level of basketball noise will be greater than any potential pickleball sound. There is no evidence the outdoor basketball courts *in this community* produce 80-decibel level sounds. However, it is known the high-pitched and repetitive sound of pickleball, exacerbated with the presence of multiple courts, will result in adjusted decibel levels **over 100**. (See Spendiarian & Willis report, attached, and discussed further below).

As you know, a Pickleball Noise Assessment was prepared by Spendiarian & Willis Acoustics & Noise Control to determine the impact of proposed pickleball courts on homes in this community. Attached is a courtesy copy of the study, performed by Lance Willis, Ph.D., who holds degrees in mechanical engineering and a multidisciplinary certificate in acoustics from Georgia Tech. Dr. Willis explains in his report the impact of the pickleball on the paddle causes a sharp popping sound that can be heard hundreds of feet from the courts. It is not only the high decibel level of sound that can make it annoying, but the pitch and frequency as well. Decibels measure sound intensity on a scale where every 10 decibel-increase represents a tenfold rise in sound power and roughly doubles perceived loudness. Therefore, a decibel level of 80 is roughly double the level of a 70. The typical sound made by a pickleball being hit by a paddle creates a sharp noise

in the range of about 1,000 – 2,000 cycles per second, or 1 -2 kilohertz per Dr. Willis. As explained by Dr. Willis, humans perceive higher-pitched noises as being louder than lower-pitched ones. For example, humans perceive a 60-decibel noise at a pitch of 1,000 Hertz to be just as loud as an 80-decibel noise at a pitch of just 100 Hertz.

There is also an adjustment that needs made for “impulsive” sounds. Dr. Willis explains the main concern in regards to noise from pickleball courts is the sound produced by the impact of the hard plastic ball on the paddles. The sound is characterized by a sudden onset and brief duration, thus classifying it as “impulsive” sound. The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz, which is near the most sensitive frequency range of human hearing. A study on the metrics of noise annoyance supports Dr. Willis, concluding that impulsive sound can be perceived more annoying than a steady-state sound having the same sound pressure level. Therefore, in comparing the true level of sound of two separate noises, it is appropriate to add decibel levels for “impulsive” sounds as compared to sounds that are not impulsive. (See “Annoyance penalty of impulsive noise – the effect of impulse onset,” published in the Building and Environment, Volume 168, attached). Dr. Willis find that due to the highly impulsive nature of pickleball sound that it is difficult to set appropriate abatement treatments. **Applying extra decibels for the impulsive nature of pickleball sounds, Dr. Willis states that the adjusted sound power of pickleball can be as high as 102.8 Decibels.**

Therefore, even if basketball at these courts were measured at a higher decibel level than pickleball (which there is no evidence of), humans will perceive the pickleball noise at a much higher level due to the higher-pitch of the pickleball sound. The petition completely ignores the nuanced nature of the sound of pickleball. A single pickleball hit produces a high-pitched and successive “pop” noise, that will register as high as 70 unadjusted decibels *from 100 feet away*. Adjusting the decibel level as described by Dr. Willis will result in significantly higher decibel levels. The high-pitched nature of the “pop” has been described as the same frequency as the beeping noise from a garbage truck backing up. The petition also asks for “at least three courts” – *thus; tripling the “pop”-“pop”-“pop”* noise, which serves to *increase* the overall decibel levels if all three courts are in use at the same time. So even if true that the sound of a singular pickleball game resulted in 70 unadjusted decibels, three games at the same time will be much louder, reaching levels above 100 decibels. The number of distinct audible “pops” is typically 15 hits per minute, per court. With three courts, that is 2,700 “pops” per hour. This type of “pop” sound travels further and penetrates walls more so than lower pitched noises. Noise from pickleball has been known to cause stress and disrupt sleep. (See Romito Study, discussed below). In extreme cases, the consistent “pop” has triggered post-traumatic stress disorder symptoms and resulted in chronic high blood pressure. Sound experts and engineers around the country have testified to these facts in pickleball litigation.

As further explained by Charles Leahy, a mechanical engineer and former HOA board member involved in pickleball litigation, it is not just the “loudness, it’s the impulsive sharpness and randomness of the ‘pops’” that make pickleball noise so noxious based on “the persistence and repetition of the random noises over many hours a day.” (See Leahy article, attached). Leahy believes the highly impulsive noise of pickleball is incompatible with residential living. Leahy’s

sentiments are supported by a recent study conducted by Kathleen Romito, perhaps the largest of its kind specific to pickleball in residential areas.

The Romito study was conducted on residents of over 250 communities nationwide who lived within 1,000 feet of a pickleball court. (See Romito Study, attached). The study revealed most residents described both loss of enjoyment of home and property from chronic noise exposure to pickleball and significant health concerns consistent with a physiological and psychological noise-induced stress response. Homeowner responses included comments describing the noise such as “CRIMINAL ASSAULT,” “Absolute torture,” “soul destroying,” and “abusive.” The study found that 88% of respondents found the noise repetitive, with 73% noting the noise could be heard inside their home or office. Over half (54%) felt the noise constantly affected their ability to be mindful, calm or to rest. 57% found the noise constantly affected their ability to enjoy the indoors of their home. Approximately 80% stated the noise impacted their sleep. **Over half – approximately 53% - either moved or had to consider moving due to the pickleball noise.** 82% used the word “frustration” to best describe their response to pickleball noise. The health affects described by homeowners were numerous – 70% experienced intense emotional reactions, 60% suffered elevated blood pressure, 58% began hearing phantom “pops,” 35% headaches, etc. The worries did not end over physical detriments. Nearly 87% were concerned over potential decline in property values. The study’s conclusion is dire, finding that for many respondents, the noise severely disrupted daily life and caused significant stress. Most residents reported being impacted constantly or very often. People reported being unable to enjoy their homes, gardens, or outdoor spaces, and many have altered routines or even relocated to avoid the noise.

The petition does not inform those surveyed regarding the science of sound. The petition fails to explain that most municipalities place limits on acceptable residential decibel levels in the 50-decibel range. Contrary to the petition, studies have shown outdoor pickleball is significantly louder than outdoor basketball, again, with sharp pickleball peaks in excess of 100 decibels. (See Spendiarian reports attached). Dr. Willis explains there is a common misconception that pickleball is acoustically equivalent to tennis, volleyball, or many other outdoor activities. Dr. Willis specifically opines that pickleball is significantly louder than tennis. Similarly, according to engineer Bob Unetich, who has been quoted in the L.A. Times and the Wall Street Journal for his studies on pickleball sounds, tennis hits are typically about 14 decibels lower than pickleball, and other researchers have shown that the sound of a solid pickleball strike can be more than 25 decibels louder than that of even the hardest-swing tennis racket. There is no evidence the sound level at this basketball court is at or even anywhere near the level of 80, which is a high-noise level comparable to the noise of a sidewalk next to a busy highway. (See Spendiarian report attached).

Spendiarian & Willis Sound Study Resulted in a “No” Recommendation for the Basketball Location

The original purpose of the Spendiarian & Willis study was to determine if the cemetery location for pickleball would result in nuisance-level noise for nearby homeowners. The two nearest homes to the proposed site were 540 and 570 feet away from the proposed site. Comparatively, there are many homes located nearer than 500 feet to the basketball court, with the closest being less than 200 feet. Dr. Willis concluded the decibel levels would approach the 50-range for these two homes that were over 500 feet away from the cemetery location. The

engineer's advice was that any sound levels above 55 decibels for any home would be inappropriate and would impact the quality of life for those homeowners and incur complaints. Dr. Willis was then asked to investigate the basketball location, which has homes much nearer than 540 or 570 feet. Dr. Willis concluded **there would be noise concerns for the homes located nearest to the courts and that it would only "be possible to get sufficient noise reduction provided the homes across the street are not two story."** However, all of these homes are two-story. Dr. Willis opined the setbacks for the basketball courts are smaller than he would recommend and will be a challenge, therefore; the basketball courts as a location would be a poor choice. Moreover, even if such extensive mitigation measures were attempted, they would restrict airflow to the pickleball courts. After the sound engineer's opinions were voiced to the Board, this basketball location was no longer considered appropriate and other locations were discussed. These sound concerns have not changed. As far as noise abatement is concerned, all of the homes located nearest the basketball courts are two-story homes, so noise abatement would be fruitless. If the Board approved pickleball and chose the basketball location, it would be doing so **against the advice of the sound engineer retained by the very Board to give a professional, science-based opinion.** This report was forwarded to the entire St. Johns Golf & Country Club community and remains posted on the Sampson Creek CDD website. Perhaps most revealing of the misleading nature of the petition, the petition fails to mention this sound study even though the petitioner unquestionably was provided the study.

The petition also misleads about the impact of home values with the addition of pickleball courts. The petition insinuates home values across the neighborhood will increase with the presence of pickleball courts, without any mention of the very real, significant and dramatic lowering of home values for houses located within earshot of the pickleball courts. It defies common sense and logic to argue that building a known nuisance near a home would increase its value. There is a reason why not a single home within ear-shot of either the basketball location or the cemetery location signed this petition.

The petition is silent as to lawsuits being litigated nationwide relating to the use of pickleball courts in neighborhoods and the financial detriments litigation can cause on communities. (See Romito report, quoting Josh Wostal of the Hillsborough County Commission, "I was stunned to find out there are over 200 lawsuits that I've been able to find throughout the nation, all pertaining to HOA's and local municipalities concerning pickleball reports.")

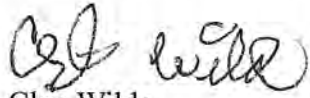
There is no doubt if the homeowners surveyed had been given the true facts and full breadth of the problems pickleball can cause, instead of sensationalized, biased generalizations, an even smaller minority would have signed the petition. In any event, **only 17% of the households** of this community support pickleball here. The survey and the petition did not mention whether the signor would be in favor of pickleball even if it meant that building the courts could result in years of litigation with high costs in attorney and expert fees, and that pickleball could have disastrous consequences for some neighbors. The petition did not ask those in favor of pickleball if they would offer commitment to fund and indemnify the Board for any litigation fees and costs that arises from installing pickleball courts in this community, including the inevitable cost of removing the pickleball courts upon successful litigation, as there is no reason the 83% of homes that do not want pickleball here should watch their CDD's funds drained due to the greedy nature of a few.

The petition fails to mention the impact of removing basketball. Many children of the neighborhood, especially the young ones, use the basketball court with the smaller goals. Removing an existing amenity used by many, especially small children, in order to install an unnecessary, noxiously loud amenity, likely to only be utilized by a select few is nonsensical. It also appears the Board has wholly failed to consider the impact of removing an existing basketball court on those who favor basketball.

Adding pickleball to this community already lush in amenities is not mandatory and should not be entertained **where it will cause damage to any homeowners**. Therefore, it is clear if the Board elects to move forward with pickleball at the basketball courts, or any other location near homes, it is doing so to cater to a minority and to the severe detriment of a select few homes. There is no question such an outrageous decision will result in litigation by homeowners seeking to enforce their common rights to enjoin this activity. The centerpiece of the trial will be asking the trier of fact to use their common sense to figure out why a Board would take such an adverse and needless action against a few for the benefit of a few. The facts and science laid out in this letter is not exaggeration nor puffery. Aggrieved homeowners will have no problem putting forth engineers to explain the science of sound to a trier of fact. The trier of fact will not be made up of people from this community, let alone people of this community who favor pickleball. The trier of fact will need to be convinced by the Board as to why such harmful action was taken when only a small minority of the community wanted that action. Again, it is irrelevant whether a majority of the homeowners want pickleball – if it negatively impacts even a few, the idea should not be entertained. It is for that reason the cemetery location was abandoned as a prospective site. The trier of fact will wonder why the Board did not follow the recommendations of the very engineer and expert they hired and relied upon to give an opinion. The Board will not be able to justify such inexcusable and harmful conduct. Not only will pickleball impact the homes as described in this letter, but the portions of this community and their children that frequent the basketball courts. CDDs must not operate this way and no trier of fact will conclude otherwise. The Board is already on notice of the potential nuisance the pickleball courts propose and have already shied away from one location – near the cemetery – due to the complaints of homeowners in that area. To then knowingly and willingly injure other homeowners is inappropriate and a dereliction of duties. The Board must act consistently as to all homeowners. In addition, there is potential conflict installing pickleball courts could have with the HOA, which owes a duty to enforce noise-related standards when noise impacts homes or common enjoyment, or is recurring, predicable or ongoing.

A petition based not on facts or science, backed by a small minority of the community should go nowhere. The Board has no way to effectively mitigate the sound of pickleball and its prospective limited efforts at doing so will be ineffective at protecting the undersigned homeowners from the harmful effect of the nuisance. The choice here is clear. The only reasonable action the Board has is to shut down any possibility of placing pickleball courts near any homeowners that will be adversely affected.

Sincerely, the undersigned Concerned Homeowners,

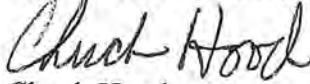


Clay Wilde
200 St. Johns Golf Drive

Andy Frisch
204 St. Johns Golf Drive



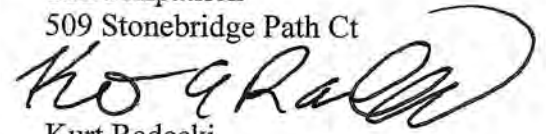
Michael Schwebel
208 St. Johns Golf Drive



Chuck Hood
216 St. Johns Golf Drive

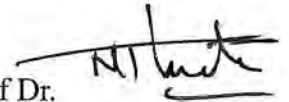


Tim Fitzpatrick
509 Stonebridge Path Ct



Kurt Radecki
504 Stonebridge Path Ct

Nabil Mitri
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cc: Daniel Laughlin, District Manager
Wes Haber, Esquire
Lisa Jones, HOA



Pickleball Noise Assessment

Sampson Creek

Prepared for

Saint Johns Golf and Country Club

205 St Johns Golf Drive

St Augustine, FL 32092

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R. 0, November 15, 2023

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1. Summary

The noise impact of three proposed pickleball courts at the Saint Johns Golf and Country Club has been analyzed in regard to neighboring residential land uses. Acoustical modeling has been constructed accounting for pickleball court directivity, the topology of the area, and adjusting for the impulsive nature of the paddle impacts according to ANSI S12.9 Part 4. A set of sound pressure level contours has been shown indicating the spread of the sound from the pickleball courts into the adjacent neighborhood. Results have been compared to the Saint Johns County Noise Ordinances.

The ANSI S12.9 Part 4 assessment of the adjusted sound pressure levels at the nearest residential land uses found that the levels were below 55 dBA at the property lines for the homes. This is considered to comply with the annoyance criterion of Saint Johns County Ordinance 2015-19. No prescribed noise abatement treatments are needed for the proposed pickleball courts.

2. Characteristics of Pickleball Sound

Spendiarian & Willis has prepared many noise abatement plans for pickleball courts. This chapter summarizes some of the knowledge gained over the years of working with this sound source.

The main concern in regard to noise from the pickleball courts is the sound produced by the impact of the hard plastic ball on the paddles. This sound is characterized by a sudden onset and brief duration, thus classifying it as impulsive sound. The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz. This is near the most sensitive frequency range of human hearing.

2.1 Acoustical Characteristics

The sound produced by the impact between a pickleball and paddle is characterized by a rapid onset and brief duration, typically on the order of two milliseconds (0.002 seconds) for the direct path sound. This classifies it as impulsive sound. Figure 2.1 shows a time trace of a pickleball paddle impact measured near Phoenix, Arizona. The main part of the direct sound impulse can be seen to be less than two milliseconds followed by a rapid decay and some later reverberant arrivals.

The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz (see Figure 2.2). Although it does not meet most guidelines for tonal prominence such as Annex C of ANSI S12.9 Part 4 or ANSI S1.13, it does impart a vague sensation of pitch similar to a wood block percussion musical instrument. The radiation pattern of the paddle is more or less a dipole, i.e. the sound from the front and back of the paddle is of opposite polarity and cancels itself in the plane of the paddle. Therefore, orienting the courts so that the direction of play faces away from noise sensitive areas can provide some attenuation.

The sound power spectrum of the pickleball and paddle impact has two basic shapes depending on how the ball is hit. Figure 2.2 and Figure 2.3 show the power spectra of a 'sharp' hit and a 'dull' hit. The curves are not calibrated for absolute level, but can be compared relatively.

The sharp hit spectrum shows a narrowband signature. The frequency of the peak typically varies between 1,000 and 2,000 Hz. The energy in the dull hit is more spread out, but still peaks between 1,000 and 2,000 Hz.

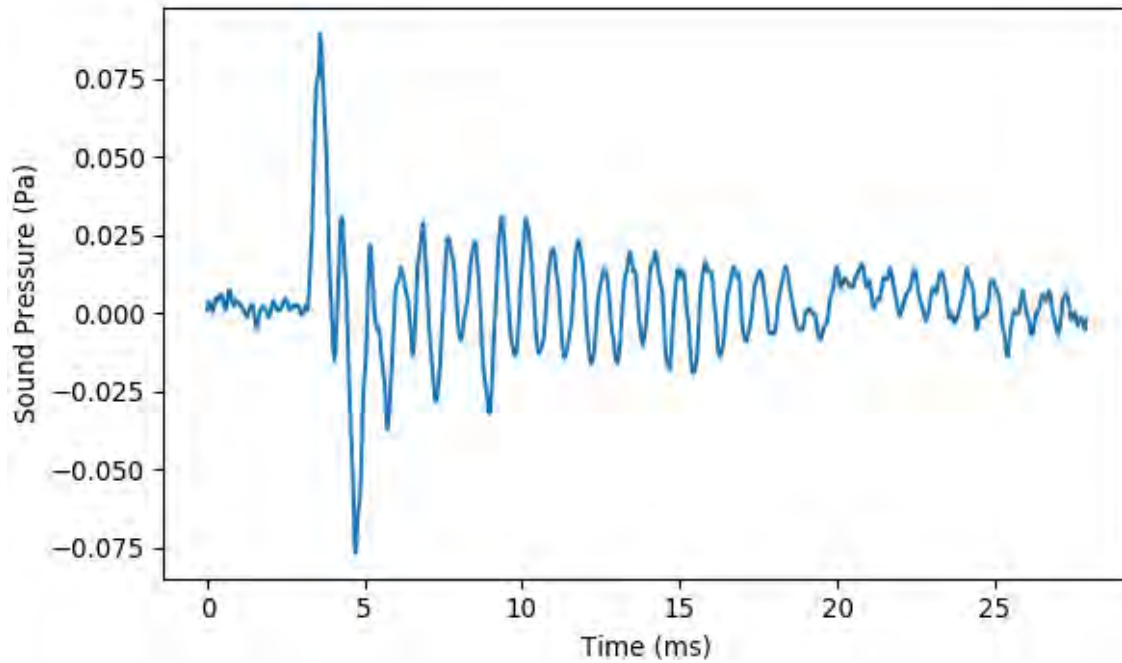


Figure 2.1. Pickleball Paddle and Ball Impact Sound Pressure Trace
1 millisecond (ms) = 0.001 seconds.

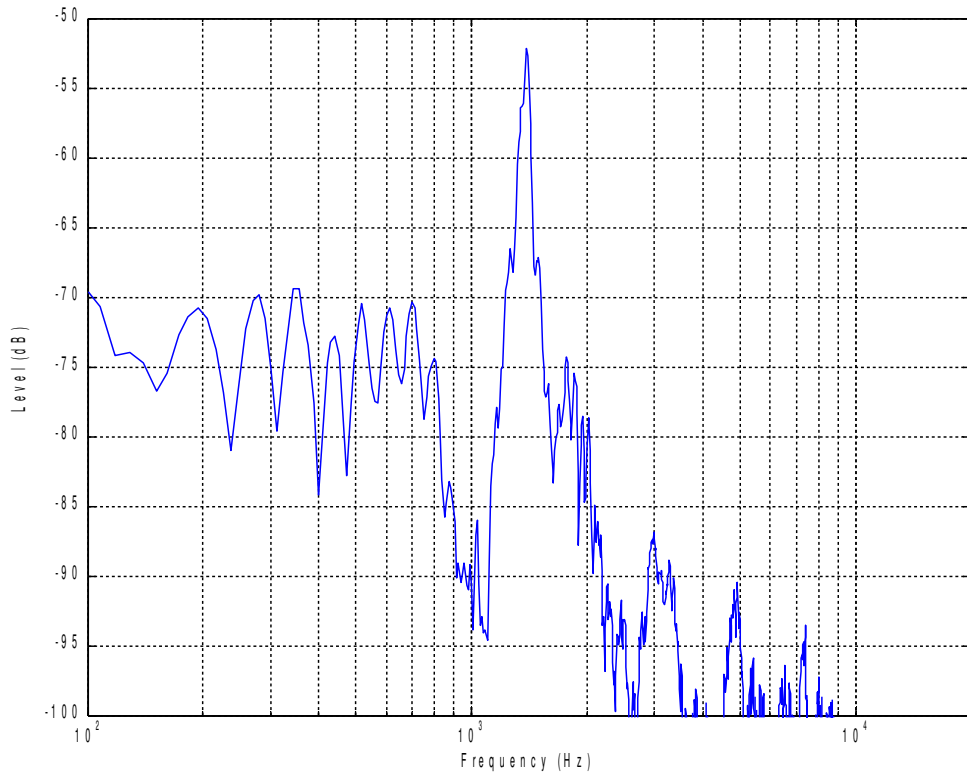


Figure 2.2. Spectral Response of a Sharp Hit

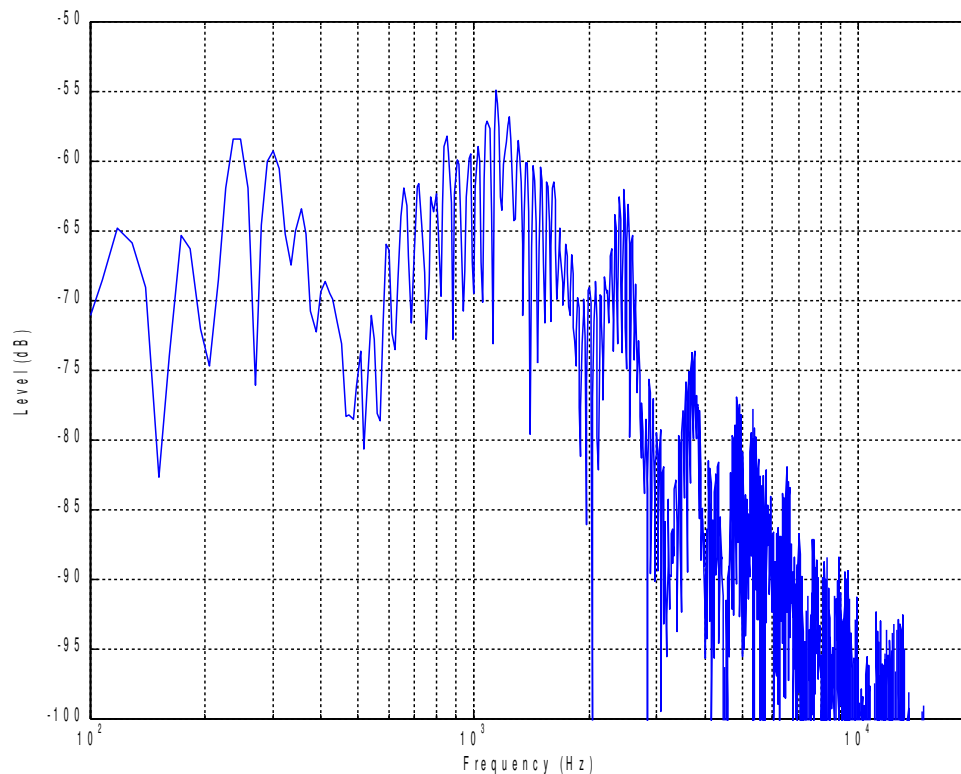


Figure 2.3. Spectral Response of a Dull Hit

A sound wall design will require effective attenuation in the 1,000 Hz octave band and above. In most applications, any material having a sound transmission class meeting STC 20 can be used to construct a sound wall or fence for pickleball provided best practices for sound barrier construction are followed.

2.2 Measuring Pickleball Sound

Due to the short duration of the impact, averaging sound pressure level metrics such as equivalent-continuous level (L_{eq}), maximum fast exponential time weighted level (L_{max}), and impulse time weighting (LAI) fail to accurately represent the perceived loudness and annoyance of the paddle impact and impact processes in general. The fast exponential time weighting filter is a first order lowpass filter with a 125 millisecond time constant applied to the square of the acoustic pressure waveform. If a tone burst is applied to the squaring circuit and filter, after two milliseconds the filter output will only rise to a level that is 18 dB lower than the equivalent-continuous sound pressure level of the input signal. Because the short impulse is being significantly attenuated by the averaging in the sound level meter, in practice it is generally not possible to distinguish pickleball paddle impacts from the background noise when measuring L_{eq} or L_{max} even though the paddle impacts may be identified by a listener as the primary

sound source. To get a better correlation with the actual response of the surrounding community to this type of sound, metrics with a shorter time scale are needed.

The paddle impact sound pressure level is better represented by a combination of peak sound pressure level and sound exposure level (SEL). Using the sound exposure level involves windowing the measured sound pressure in time to include only the paddle impact and reflections from nearby surfaces as seen in Figure 2.1. The equivalent-continuous sound pressure level of the windowed impact is then normalized to the length of the window giving a representation of the energy in the impact alone. Appropriate adjustments for impulsive sounds can then be applied to the impacts as described next.

Most acoustical standards for sound pressure levels with regard to compatible land use provide adjustment factors for different types of sound, e.g. impulsive, tonal, time of day, etc. Each of these categories of sound produces different levels of community impact and annoyance due to their temporal or spectral characteristics in comparison to a broadband sound that does not vary in level or frequency content with time. The purpose of the adjustment factors is to normalize these types of sound to a neutral broadband sound pressure level so that they can be reasonably compared to a defined sound pressure level limit or the background noise level.

ANSI S12.9 Part 4 and ISO 1996 Part 1 give criteria for assigning adjustment factors to a variety of impulsive sounds. Sounds produced by impact processes are typically classified as ‘highly impulsive’ due to their high onset rates and assigned a 12 dB adjustment. Experience has shown that pickleball paddle impacts should be adjusted as highly impulsive sounds in order to set appropriate performance goals for abatement treatments. Inadequate abatement treatment may lead to ongoing complaints, strained relations with neighbors, legal action, the need for continued involvement on the part of authorities, retrofitting, and possibly demolition costs to improve the abatement later.

2.3 Problems with Exponential Time Weighting

Fast exponential time weighting is often recommended for assessing impulsive sound. For highly impulsive sounds having short durations this metric does not work well. When the averaging time of the time weighting is longer than the duration of the impulse, the impulse is in the stopband of the filter. In other words, the time weighting is filtering out the impulsive sound source being measured.

Figure 2.4 demonstrates the filter response to a burst of sound just long enough to achieve a reasonably accurate reading within 0.5 dB of the true sound pressure level. The red curve represents the envelop of a burst of sound 0.277 seconds in duration. This is the time required for the output of the fast exponential time averaging filter (blue curve) to rise to within 0.5 dB of the actual sound pressure level of the sound burst. When the sound burst ends, the output of the exponential time averaging filter begins to decay. The peak value in the output of the fast exponential time averaging filter, after being converted to sound pressure level, is known as the L_{max} level.

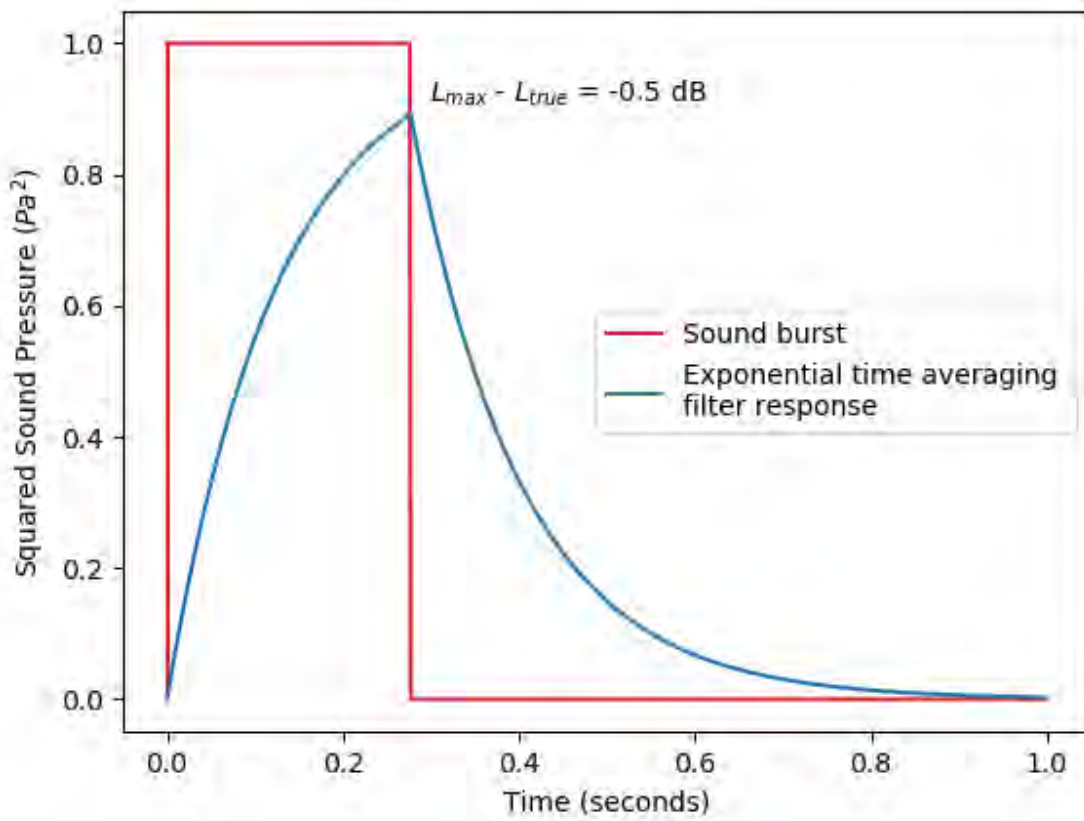


Figure 2.4. Fast Time Averaging Filter Response to a 0.277 Second Sound Burst

Figure 2.4 shows the behavior of the fast exponential time averaging filter and L_{max} when used properly. Figure 2.5 illustrates how the fast exponential time averaging filter responds to a typical pickleball paddle impact. Note that the time scale has been reduced for clarity. At the end of the 0.002 second impulse, the fast exponential time averaging filter has only had time to rise to a level that is 18 dB below the true sound pressure level of the impulse. The pickleball paddle impulse is so much shorter than the time constant of the averaging filter that the exponential curvature of the filter response is not even visible. It is clear that fast exponential time weighting, much less slow exponential time weighting, cannot be used to assess the noise impact of pickleball paddle impacts.

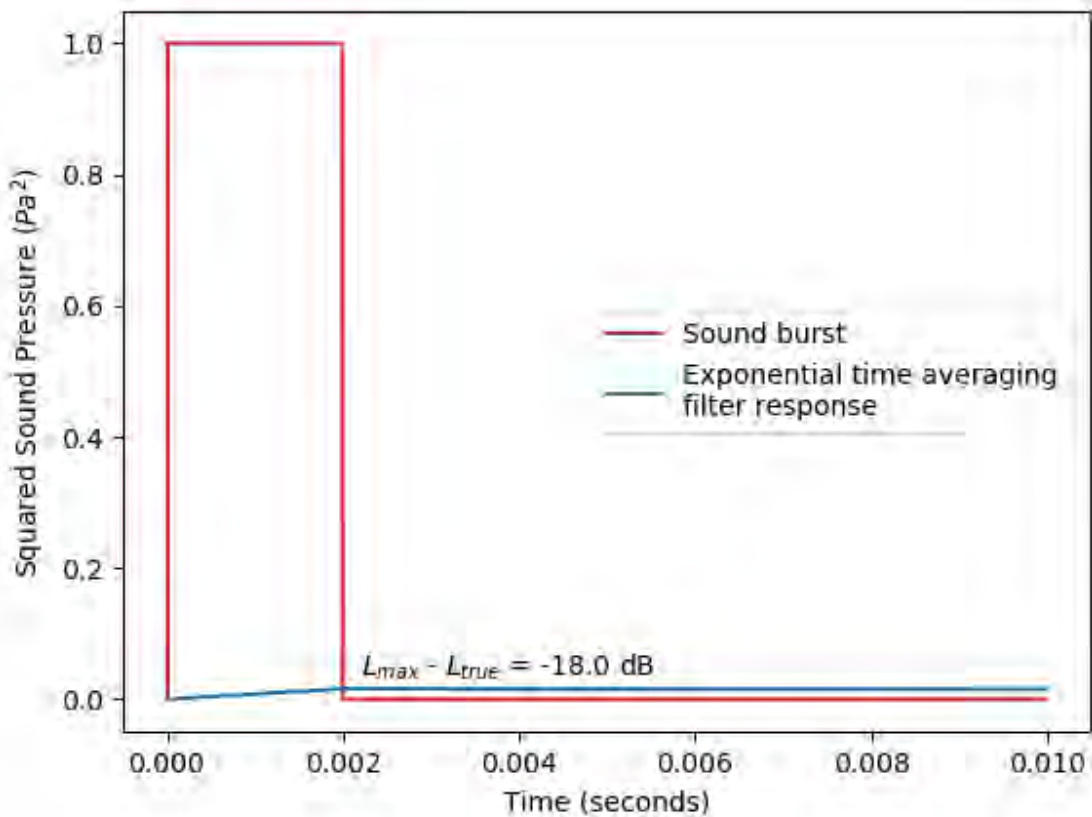


Figure 2.5. Fast Time Averaging Filter Response to a Typical Pickleball Paddle Impact

2.4 Directivity of Pickleball Courts

The impulsive sound of the paddle impacts is radiated mainly by the large, flat paddle surface. Since both faces of the paddle are connected internally by a honeycomb structure and move together in vibration, one side of the paddle will produce a positive sound pressure while the other produces a negative sound pressure similar to a loudspeaker diaphragm that is not mounted in a cabinet. The result is that these two pressure waves having opposite polarity will cancel in the plane of the paddle where the path length from each face is the same to all receiver locations. This is known as a dipole or figure eight radiation pattern.

The positions of the paddles relative to the court change with each hit; however, the object of the game is to hit the ball to the opposite half of the court. Therefore, the dipole axis of each paddle impact will be in the general direction of play and not completely random. Measurements of several pickleball facilities have shown that this results in a null depth of four to five dB. Figure 2.6 compares a typical pickleball court directivity pattern to a mathematical dipole where 0° and 180° are in the direction of play and the null is on the 90° and 270° bearings. Several decibels of attenuation can often be obtained simply by optimizing the orientation of the courts with respect to noise sensitive areas.

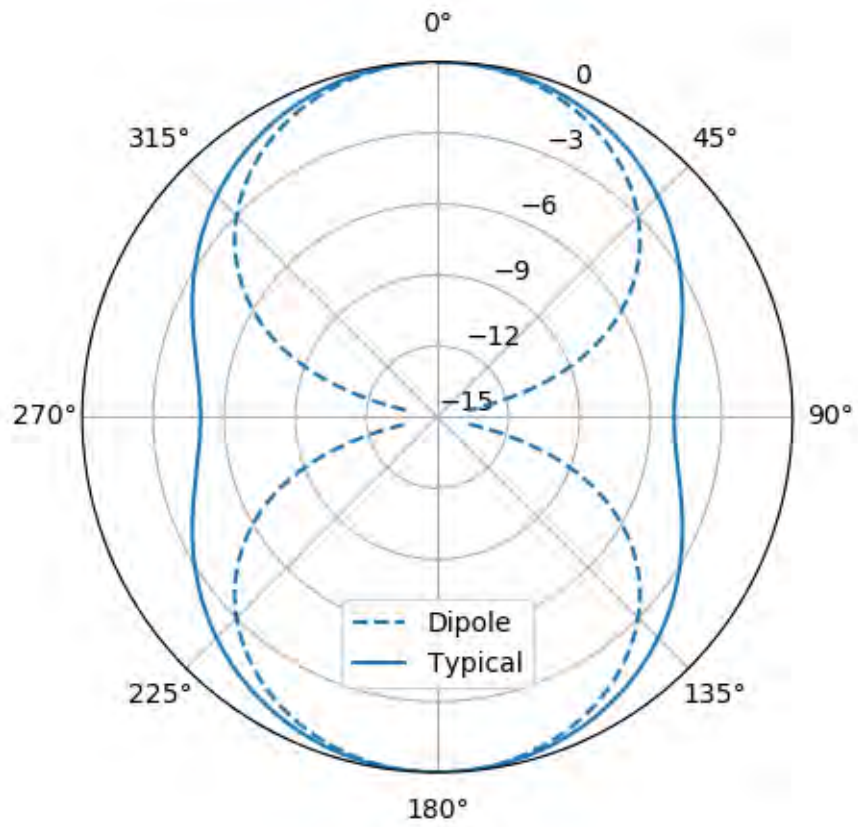


Figure 2.6. Typical Pickleball Court Directivity in Decibels

3. Site Plan Analysis

3.1 Noise Assessment Criteria

Saint Johns County Ordinance 2015-19 gives subjective criteria for assessing noise. In Section 4 noise is defined as,

a sound or vibration that annoys or disturbs a human or which causes or tends to cause an adverse psychological or physiological effect on humans; loud or offensive disturbing sounds or vibrations. This term shall be used synonymously with "sound."

Section 3 states the measurement method.

The measurement of sound or noise under this Ordinance shall be "plainly audible" by a human ear without the benefit of a hearing aid by a reasonable person of ordinary sensibilities, or "plainly discernible" by the human senses of a reasonable person of ordinary sensibilities.

These two parts of the Ordinance are in conflict with each other. While plainly audible or plainly discernible can serve as minimum thresholds for finding a noise violation, not all plainly audible or plainly discernible sounds cause annoyance. In fact, one will always be able to hear one's neighbors at certain times or under certain atmospheric conditions when the background noise level is low and conditions are favorable for propagation. The plainly discernible criterion is therefore a moving target and cannot be used as a basis for determination of the amount of noise mitigation required by a project site or what sound pressure level would be considered reasonable.

Annoyance, however, has specific meaning in the context of noise. There are national and international standards for quantifying and assessing this criterion. ANSI S12.9 is a national standard for quantifying annoyance caused by sound and is an appropriate method for assessing the noise impact of highly impulsive sound produced by impact processes such as pickleball paddle impacts. Part 5 of the standard recommends a maximum day-night level of 55 dBA for residential areas. This translates into a 55 dBA adjusted equivalent-continuous sound pressure level limit for daytime activities. While using this sound level as a design goal for abatement does not guarantee that a sound will not be plainly audible, it does reduce the noise impact of a site to a level that would be considered normally acceptable.

The 55 dBA day-night level recommended in ANSI S12.9 Part 5 is based on attitudinal survey studies funded by various federal agencies. Day-night level is a 24 hour equivalent-continuous sound pressure level with a 10 dBA adjustment for nighttime hours. It works well for most transportation noise sources (community response to aircraft flyovers has been found to correlate better with maximum fast exponential time weighted level). It does not work for impulsive or tonal sound sources. Additional research was therefore funded in the 1980s and 1990s to

determine adjustments for sounds with special characteristics so that they could be compared to established day-night level limits for more neutral sound sources. In 1996, this noise assessment methodology was standardized in ANSI S12.9.

3.2 Modeling Parameters

3.2.1 Methodology

The acoustical site model has been constructed using the iNoise package version 2023.01 developed by DGMR. The sound propagation model is ISO 9613. This software conforms with the ISO/TR 17534-3 quality standard for implementing the ISO 9613 Part 2 outdoor sound propagation model.

3.2.2 Pickleball Paddle Sources

Spendiarian & Willis has not conducted measurements of pickleball on this site; however, we have test data from numerous other sites that has been used to construct the pickleball paddle sources for this site model.

For the reasons described in the previous chapter, neither the equivalent-continuous nor the fast exponential time weighted sound pressure level is sufficient to provide an assessment of the short duration paddle and ball impact sounds that correlates well with the community response to this type of sound. Therefore, the methodology of ANSI S12.9 Part 4 has been selected to assess the annoyance of the sound of the pickleball paddle impacts.

Pickleball paddle impacts in the model are based on measurements at a location in California using Dura 40 regulation balls with various paddles. The data was measured at 60 to 65 feet from the pickleball courts over a hard surface. The various ground types on and around the existing site have been included in the site models according to ISO 9613. The sound pressure levels of the paddle impacts are calculated from the mean sound exposure levels using 12 paddle impacts per minute for each court. Paddle impacts have been adjusted according to ANSI S12.9 Part 4 for highly impulsive characteristic (12 dB) and time of day (weekend, 5 dB). The resulting sound power is 102.8 dBA per court for an omni-directional sound source. The sound source for each court has been split into two vertical area sources placed at the serve lines with dipole directivity profiles applied having a null depth of 5.5 dB. The vertical area sources extend to the sidelines of the pickleball court (20 feet) and from the playing surface to a height of 8 feet to include overhead paddle impacts.

3.2.3 Sound Pressure Level Contour Maps

Sound pressure level contours in the figures below are displayed in 5 dBA increments. The grid height for the contours is 5 feet above grade. The legend identifying the map symbols is in Figure 3.1 and all sound pressure levels are A-weighted ANSI S12.9 adjusted levels as described above. Sound walls are labeled as barriers in the iNoise software.

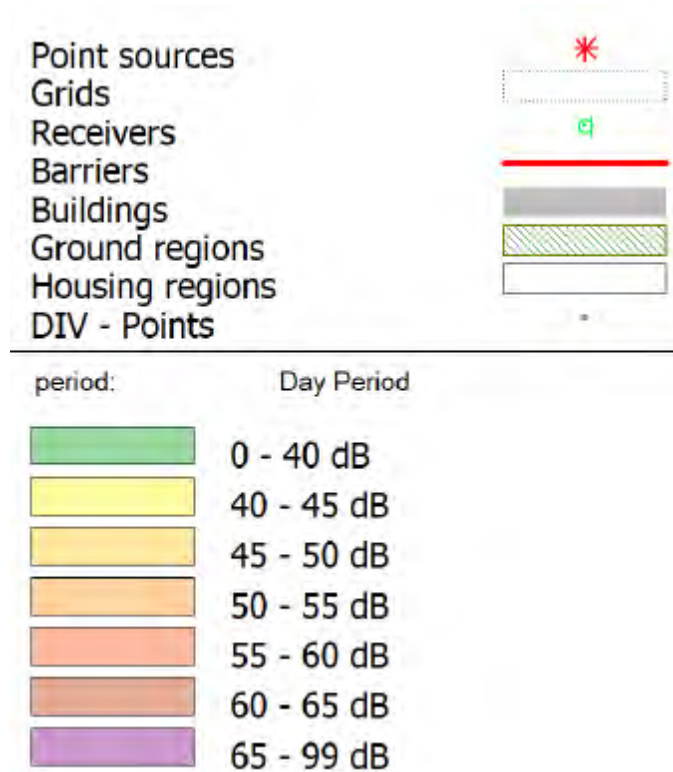


Figure 3.1 Legend for Sound Pressure Level Contour Maps

3.3 Pickleball Courts and Surrounding Area

Three pickleball courts are proposed at Sampson Creek on Cemetery Road. These are outlined in blue in Figure 3.2. The two closest residences have been selected as noise assessment locations. The residences are:

- 509 Stonebridge Path (540 feet east of proposed pickleball courts)
- 933 Brookhaven (570 feet south of proposed pickleball courts)

The noise assessment locations are shown as small green dots in Figure 3.2 and are called out by house number. The house at 933 Brookhaven is to the right of the figure.

Ground types in the ISO 9613 model are friable soil (ground factor = 1.0) everywhere except the pickleball and tennis court surfaces (ground factor, 0.0), water (ground factor, 0.0), and streets (ground factor, 0.1).



Figure 3.2. Proposed Pickleball Courts at Sampson

3.4 Proposed Pickleball Courts without Noise Abatement

Adjusted sound pressure level contours for the proposed pickleball courts are shown in Figure 3.3. The north-south projection of the sound in the direction of play can be seen in the oblong shape of the contours near the courts. The 55 dBA contour extends north to the clubhouses across the lake. Propagation in this direction is aided by the hard surface of the water and reflections from the facades of the clubhouse buildings.

Adjusted sound pressure levels are listed in Table 3.1 with ANSI S12.9 Part 5 recommended limits for single family residential land uses. Due to the distance of these homes, the adjusted levels are well below the target sound pressure level.

Location	Height Above Grade (ft)	Adjusted Sound Pressure Level (dBA)	Recommended Limit (dBA)	Exceeds Limit
509 Stonebridge Path	5	48.0	55	no
933 Brookhaven	5	50.2	55	no

Table 3.1. Adjusted Sound Pressure Levels for Proposed Courts



Figure 3.3. Adjusted Sound Pressure Level Contours for Proposed Pickleball Courts

4. Conclusions and Recommendations

4.1 Summary of Results

The noise impact of three proposed pickleball courts at the Saint Johns Golf and Country Club has been analyzed in regard to neighboring residential land uses. Acoustical modeling has been constructed accounting for pickleball court directivity, the topology of the area, and adjusting for the impulsive nature of the paddle impacts according to ANSI S12.9 Part 4. A set of sound pressure level contours has been shown indicating the spread of the sound from the pickleball courts into the adjacent neighborhood. Results have been compared to the Saint Johns County Noise Ordinances.

4.2 Noise Assessment

In order to avoid impacting the quality of life of neighbors and incurring complaints, Spendiarian & Willis has found that it is necessary to limit adjusted sound pressure levels at residential land uses to 55 dBA as recommended in ANSI S12.9 Part 5. This is not only to reduce impacts inside the home, but to preserve the ability to utilize outdoor spaces as well. Pickleball paddle impacts greater than this level are commonly audible inside homes.

The ANSI S12.9 Part 4 assessment of the adjusted sound pressure levels at the nearest residential land uses found that the levels were below 55 dBA at the property lines for the homes.

4.3 Saint Johns County Code Compliance

The Saint Johns County Ordinance 2015-19 does not provide an objective standard for compliance. Instead, two subjective criteria are given. As discussed in Section 3.1 above, the plainly discernible criterion cannot be used for quantitatively determining the amount of noise abatement needed due to unpredictable variations in background noise levels and meteorological conditions. The annoyance criterion is well researched and can be quantitatively assessed using ANSI S12.9 Part 4. This is the noise assessment methodology used in this report.

The ANSI S12.9 Part 4 analysis of sound produced by pickleball paddle impacts at the proposed site resulted in adjusted sound pressure levels that are within the range of sound pressure levels considered normally acceptable in ANSI S12.9 Part 5. This is considered to comply with the annoyance criterion of Saint Johns County Ordinance 2015-19.

4.4 Recommendations

Due to the long setbacks to the nearest homes, no prescribed noise abatement treatments are needed for the proposed pickleball courts.

References

ANSI S12.9-2021, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long Term Community Response*, American National Standards Institute, 2021.

ISO 1996-1, *Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures*, International Organization for Standardization (ISO), 2016.

ISO 9613-2, *Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation*, International Organization for Standardization (ISO), 1996.

Schultz, T. J., “Synthesis of Social Surveys on Noise Annoyance,” *Journal of the Acoustical Society of America* v. 64, pp. 377-405, 1978.

World Health Organization, *Night Noise Guidelines for Europe*, <http://www.euro.who.int>, 2009.

Appendix

A1. Glossary of Acoustical Terms and Abbreviations

A1.1 Abbreviations

AI: articulation index

ASEL: A-weighted sound exposure level

ASTC: apparent sound transmission class

dB: decibel

DNL: day - night level

FSTC: field sound transmission class

Hz: Hertz

IIC: impact insulation class

kHz: kilohertz

L_{eq}, LA_{eq}, LC_{eq}: equivalent sound pressure level

L_{max}, LA_{max}: maximum fast sound pressure level

NC: noise criteria

NIC: noise isolation class

NIPTS: noise induced permanent threshold shift

NR: noise reduction

Pa: Pascal

POE: probable occupant evaluation (see room criteria)

PTS: permanent threshold shift

PWL: sound power level

QAI: quality assessment index (see room criteria)

RC: room criteria

RT₆₀: reverberation time

SEL: sound exposure level

SII: speech interference index

SIL: speech interference level

SLM: sound level meter

SPI: speech privacy index

SPL: sound pressure level

STI: speech transmission index

TTS: temporary threshold shift

A1.2 Terms

A-weighting: see frequency weighting

absorption coefficient: see sound absorption coefficient

acoustical coupler: a cavity of predetermined shape and volume used for the calibration of earphones or microphones in conjunction with a calibrated microphone adapted to measure the sound pressure developed within the cavity

anechoic room: a room whose boundaries absorb practically all of the sound incident thereon, thereby providing essentially freefield conditions

articulation index (AI): a number (ranging from 0 to 1) which is a measure of the intelligibility of speech- the higher the number the greater the intelligibility. This metric has been replaced by the Speech Intelligibility Index (SII) defined in ANSI S3.5.

average sound level: see equivalent-continuous sound level

background noise: the total noise from all sound sources excluding a particular sound source that is of interest

band: a subsection of the frequency spectrum

C-weighting: see frequency weighting

coupler: see acoustical coupler

day-night level (DNL): the 24 hour equivalent (average) A-weighted sound pressure level. A 10 dBA penalty is incurred between the hours of 10:00 PM and 7:00 AM. The DNL system has been adopted by the U.S. Department of Housing and Urban Development, the Department of Defense, and the Federal Aviation Administration.

decibel (dB): a unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the common logarithm (base 10) of this ratio.

diffuse field: a sound field which has statistically uniform energy density and in which the

directions of propagation of the sound waves are randomly distributed. In a practical sense, the sound pressure levels at all points in the room are nearly the same except near the room boundaries and a sound wave reaching a given point in the room is equally likely to arrive from all directions.

direct sound: sound which reaches a given location in a direct line from the source without any reflections.

equivalent-continuous sound level (L_{eq}): the level of steady sound which, in a stated time period and at a stated location, has the same sound energy as the time varying sound. If frequency weighting is applied, the equivalent continuous sound level may be designated LA_{eq} to indicate A-weighting or LC_{eq} to indicate C-weighting, etc. See also frequency weighting.

fast exponential time weighting: a lowpass filter for the purpose of averaging a signal having a time constant of 0.125 seconds applied to the square of the sound pressure as specified in ANSI S1.4.

field sound transmission class (FSTC): a single number rating similar to sound transmission class (STC), except that the transmission loss values used to derive this class are measured in the field. FSTC ratings are typically lower than STC ratings which are measured under laboratory conditions.

flanking path: A wall or floor/ceiling construction that permits sound to be transmitted along its surface; or any opening, which permits the direct transmission of sound through the air.

freefield: a sound field in which the boundaries have negligible effect over the frequency range of interest.

frequency: the number of times that a waveform repeats itself in a given period of time, usually one second, i.e. the number of cycles per second). Unit: Hz.

frequency weighting: a prescribed frequency dependent attenuation or amplification applied to measured sound data usually intended to better approximate the sensation of loudness in a human listener. For example, A, B, and C weighting approximate the frequency dependent shape of the equal loudness contours for soft, moderate, and loud sounds.

Hertz (Hz): unit of frequency, cycles per second.

impact insulation class (IIC): a single number metric used to compare the effectiveness of floor-ceiling assemblies in providing reduction of impact-generated sounds such as footsteps. This rating is derived from values of normalized impact sound pressure levels in accordance with ASTM E492.

impulsive sound: sound that is characterized by brief excursions of sound pressure, typically less than one second, whose peak pressure significantly exceeds the background sound pressure.

insertion loss: the reduction in sound level at the location of the receiver when a noise reduction measure such as a barrier, attenuator, muffler, etc. is inserted into the transmission path between the source and receiver. Unit: dB.

level: the logarithm of the ratio of a given quantity to the reference quantity of the same kind. Levels represent physical quantities such as sound pressure on a logarithmic scale and are

therefore expressed in decibels. Unit: dB.

loudness: that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. Unit: sone.

masking: the process by which the threshold of hearing for one sound is raised by the presence of another sound.

maximum fast sound pressure level: the maximum sound pressure level recorded using fast exponential time weighting.

noise criteria (NC): a single number criteria for the HVAC or mechanical noise level in a room derived from measured octave band data. The octave bands are weighted to de-emphasize low frequencies because the human ear is least sensitive to these frequencies. This metric is not valid for outdoor measurements.

noise induced permanent threshold shift (NIPTS): the permanent hearing loss resulting from noise exposure.

noise isolation class (NIC): a single number rating derived from measured values of noise reduction between two enclosed spaces that are connected by one or more paths. This rating is not adjusted or normalized to a standard reverberation time.

noise reduction (NR): the difference in sound pressure level between any two points along the path of sound propagation, e.g. the difference in level between the interior and exterior of a building where the sound level inside is due only to exterior noise.

octave: the frequency interval between two tones whose frequency ratio is 2.

omnidirectional microphone: a microphone whose response is independent of the direction of the incident sound wave.

Pascal (Pa): a unit of pressure. 1 Pascal = 1 Newton per square meter (1 N / m²).

permanent threshold shift (PTS): a permanent increase in the threshold of hearing at a given frequency.

point source: a source that radiates sound as if from a single point.

receiver: a person (or persons) or equipment which is affected by sound.

refraction: (1) the phenomenon by which the direction of propagation of a sound wave is changed as a result of a spatial variation in the speed of sound. (2) The angular change in direction of a sound wave as it passes obliquely from one medium to another having different sound speed.

reverberation time (RT₆₀): of an enclosure, for a sound of a given frequency or frequency band, the time that is required for the sound pressure level in the enclosure to decrease by 60 dB after the source has stopped. Unit: second.

room criteria (RC, RC Mark II): an octave band metric for evaluating HVAC noise inside a room. RC is a two dimensional metric consisting of a curve number that is the arithmetic average

of the 500, 1000, and 2000 Hz octave band sound pressure levels and a qualitative descriptor identifying the character of the sound spectrum. The descriptor can be (N) for neutral, (LF) for low frequency dominance (rumble), (MF) for midfrequency dominance (roar), and (HF) for high frequency dominance (hiss). In addition, acoustically induced vibration can be designated by (LFV_B) for moderate, but perceptible vibration and (LFV_A) for clearly perceptible vibration. As an example, the maximum RC prerequisite for LEED is designated as RC 37(N) indicating curve number 37 with a neutral spectrum.

Further, two intermediary metrics are used in calculating the room criteria. The quality assessment index (QAI) is a measure of the deviation from the given RC curve. The probable occupant evaluation (POE) is based on the magnitude of the QAI and can be 'Acceptable,' 'Marginal,' or 'Objectionable.'

Sabin: a unit of measure of sound absorption; a measure of sound absorption of a surface. It is the equivalent of 1 square foot of a perfectly absorbing surface; a metric Sabin is the equivalent of 1 square meter of a perfectly absorbing surface.

sones: the unit of loudness. One sone is the loudness of a pure tone presented frontally at a frequency of 1000 Hz and a sound pressure level of 40 dB referenced to 20 micropascals.

sound absorption coefficient (α): ideally, the fraction of diffusely incident sound power that is absorbed (or otherwise not reflected) by a material or surface.

sound exposure level (SEL): over a stated time period or event, 10 times the logarithm base 10 of the ratio of the time integral of the sound pressure squared to the product of the reference sound pressure, 20 μ Pa, squared and the reference time, one second.

sound level meter (SLM): an instrument that is used to measure sound level, with a standard frequency weighting and standard exponentially weighted time averaging.

sound power level (PWL): the total acoustical power emitted from a sound source expressed in decibels relative to 10^{-12} Watts.

sound pressure level (SPL): the acoustical pressure amplitude expressed in decibels relative to 20 micropascals.

sound transmission class (STC): a single number rating used to compare sound insulation properties of walls, floors, ceilings, windows, or doors. See also field sound transmission class.

speech intelligibility index (SII): metric defined under ANSI S3.5 to quantify the intelligibility of speech under adverse listening conditions such as noise masking, spectral filtering, and reverberation. The SII is defined for a scale of 0 to 1 where values greater than 0.75 indicate good communication and values below 0.45 indicate generally poor communication conditions.

speech intelligibility test: a procedure that measures the portion of test items (such as syllables, monosyllabic words, or sentences) that are heard correctly.

speech interference level (SIL): an index for assessing the interference effects of noise on the intelligibility of speech, derived from measurements of the background noise level of contiguous octave bands; i.e. the arithmetic average of the octave band sound levels for the bands centered at 500, 1000, 2000, and 4000 Hz (four band method) or the corresponding average for the octave

bands centered at 500, 1000, and 2000 Hz (three band method). If other octave bands are used they must be specified. Unit: dB.

speech privacy index (SPI): The SPI is essentially the opposite of the speech intelligibility index and is defined as $1 - SII$ and usually represented as a percentage. An SPI above 80% is considered normal privacy while an SPI above 95% would meet the requirements of confidential privacy.

speech transmission index (STI): an index for rating the intelligibility of speech that takes both noise and reverberation into account.

temporary threshold shift (TTS): a temporary increase in the threshold of hearing at a given frequency.

threshold of hearing: for a given listener, the minimum sound pressure level of a specified sound that is capable of evoking an auditory sensation. The sound reaching the ears from other sources is assumed negligible.

transducer: a device designed to receive an input signal of a given kind and to furnish an output signal of a different kind in such a manner that the desired characteristics of the input signal appear in the output signal. For example, a microphone takes an acoustic pressure as an input and produces an electrical voltage as an output that is direct proportion to the instantaneous acoustic pressure amplitude. Other common examples in noise measurement would be a loudspeaker, accelerometer, or laser Doppler vibrometer (LDV).

transmission loss: the reduction in sound level from one side of a partition to the other.

wavelength: the distance a sound wave travels in the time it takes to complete one cycle.

weighting: see frequency weighting

A2. General Acoustics

Sound Pressure Level (SPL)

Sound is small, rapidly varying perturbations of atmospheric pressure with respect to the slowly changing ambient pressure. The ambient pressure is measured with a barometer while the small acoustic perturbations are measured with a microphone.

The unit of sound pressure is the Pascal (Pa). However, due to the wide range of acoustic amplitudes that can be heard by the human ear, sound pressure is normally expressed on a logarithmic scale having units of decibels (dB). Sound pressure expressed this way is known as the sound pressure level (SPL) and has the following relation to sound pressure.

$$SPL = 20 \log_{10} \left(\frac{p}{p_{ref}} \right) \quad (A2.1)$$

Here p is the sound pressure in Pascals. p_{ref} is a reference pressure, the threshold of hearing at 1000 Hertz (Hz), 20×10^{-6} Pa.

A-Weighting

The above formulation of SPL is a purely physical quantity. Due to the nonlinear and frequency dependent characteristics of the human ear it does not always correlate well with the perception of loudness. To improve the correlation for noise assessment purposes, a frequency weighting is often applied called A-weighting. The A-weighting function is based on listening tests in which human subjects adjusted tones throughout a range of frequencies to have equal loudness compared to a tone having an SPL of 40 dB at 1000 Hz. Figure A2.1 shows equal loudness contours according to ISO 226.

Thus applying A-weighting to measured sound pressures more closely represents the frequency response of the human ear for low to moderate amplitude sound. Sound pressure levels that have been A-weighted are denoted by the symbol, dBA. Figure A2.2 shows the A frequency weighting and several other common weightings.

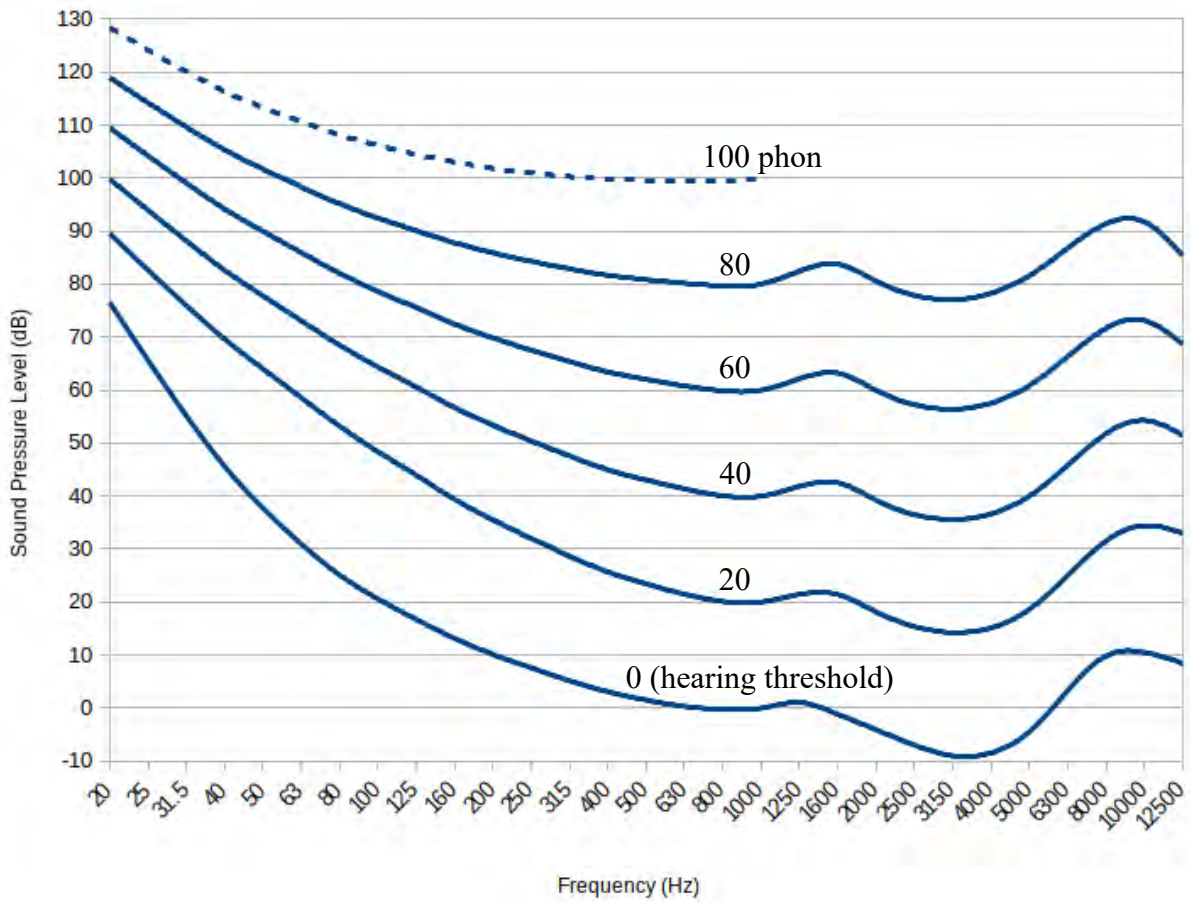


Figure A2.1. ISO 226 Equal Loudness Contours

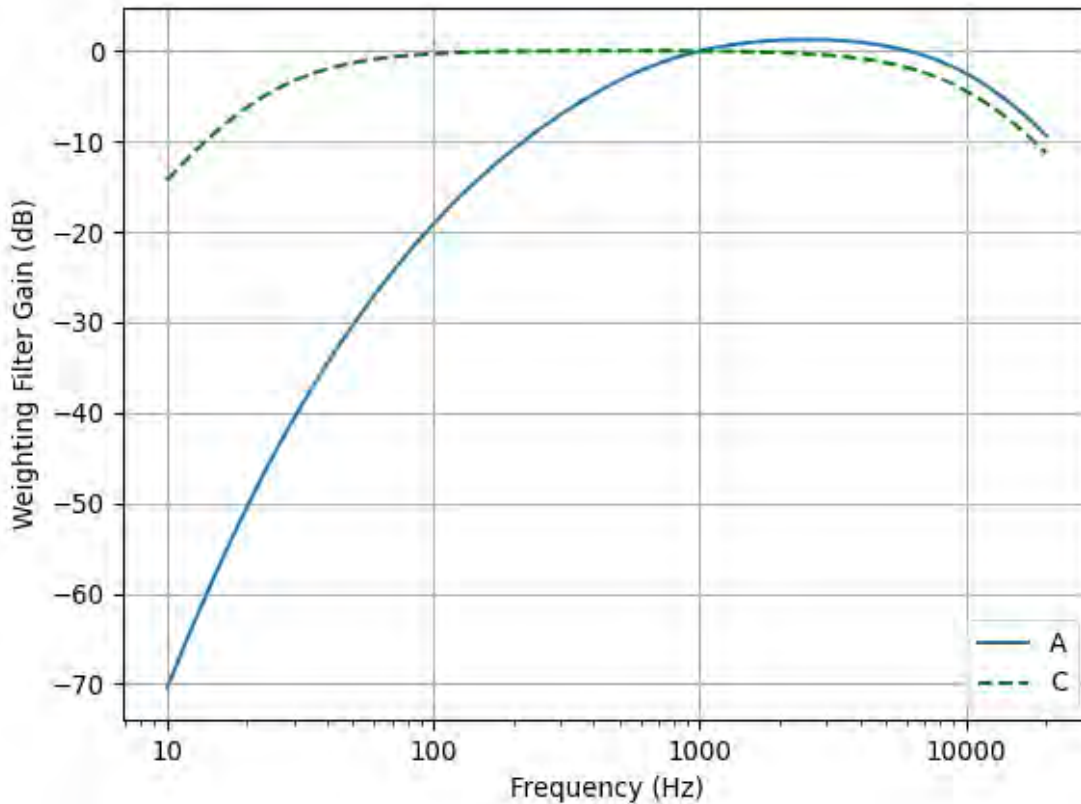


Figure A2.2. Frequency Weighting Filter Curves

The Perception of Sound

The most basic descriptions of sound are loudness (amplitude) and pitch (frequency). The frequency range of human hearing is roughly 20 to 20,000 Hz, although most people can not hear this full range because high frequencies are lost as a natural part of aging and other factors such as illness and exposure to high levels of noise that may cause permanent hearing loss.

Amplitude Attenuation with Distance

Sound originating from a small point source will spread spherically in all directions, absent any nearby surfaces. The conservation of energy requires the sound pressure spreading out from such a source to decrease by half with each doubling of distance. This is known as the inverse square law and is demonstrated in Table A2.1 and Figure A2.3.

Distance from Source (ft)	SPL (dBA)	SPL Loss Relative to 10 ft
10	90	
20	84	6
40	78	12
80	72	18
160	66	24
320	60	30

Table A2.1. Decrease of SPL with Distance Due to Spherical Spreading

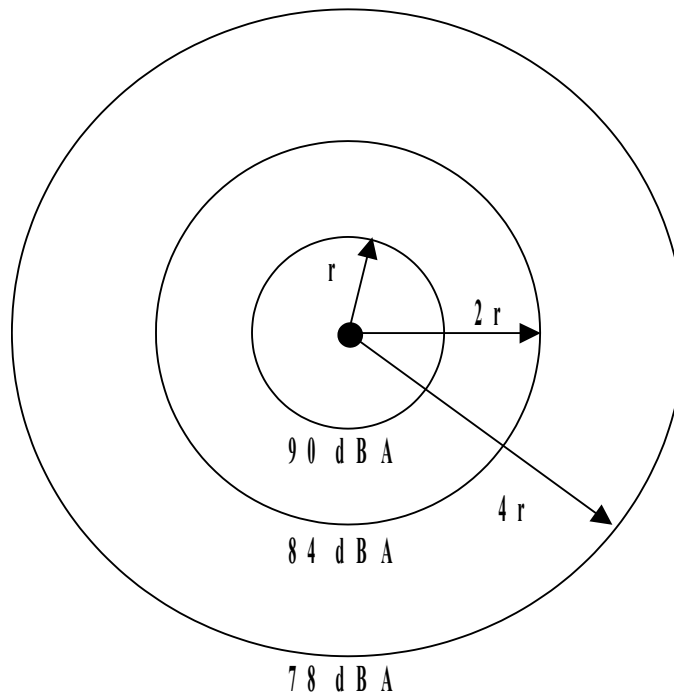


Figure A2.3. Decrease of SPL with Distance Due to Spherical Spreading

Adding Decibels

Summing the contributions from multiple sound sources to obtain the total SPL is *not* done simply by adding the decibel levels because SPL is a logarithmic quantity.

Imagine a fan produces a moderate SPL of 65 dBA at 6 feet. If a second identical fan were turned on the resulting SPL would not be 130 dBA. This would be equivalent to a commercial jetliner taking off at close range.

The correct method of adding the SPL from each source is to sum the acoustic power produced by each source. This implies that each time the number of sources having equal SPL is doubled, the SPL will increase by 3 dBA. Therefore, in the example with two fans, the correct total SPL would be 68 dBA. More examples with multiple sources producing equal SPL are shown in Figure A2.4.

$$65 \text{ dBA} + 65 \text{ dBA} \neq 130 \text{ dBA} \quad \text{WRONG} \quad (\text{A2.2})$$

$$65 \text{ dBA} + 65 \text{ dBA} = 68 \text{ dBA} \quad \text{RIGHT} \quad (\text{A2.3})$$

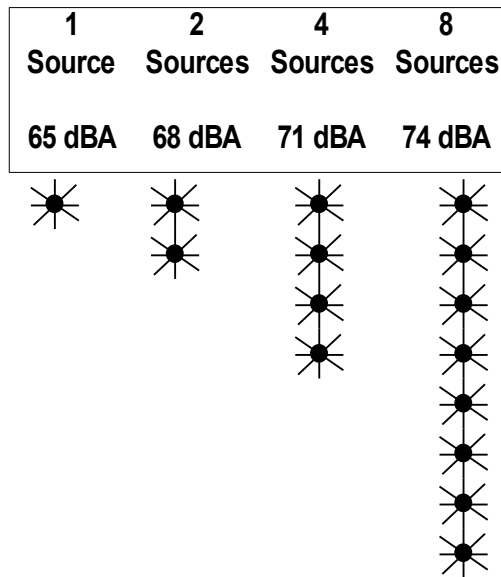


Figure A2.4. Total SPL from Multiple Sources with Equal SPL Output

Further Reading

Bruel and Kjaer, “Measuring Sound.” Covers topics in this appendix in more detail. Available on the Bruel and Kjaer website, www.bkhome.com. Find this and other primers under the library section of the site.

Cyril M. Harris, Ed. Handbook of Acoustical Measurements and Noise Control, 3rd Edition. Acoustical Society of America, Melville, NY, 1998.



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Pickleball Noise Impact Assessment and Abatement Planning

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R. 0, July 11, 2023

Executive Summary

As pickleball grows in popularity across North America it has become necessary to define more accurate methods of assessing the noise impact of the sport on the surrounding community and plan effective strategies for integrating it into various recreational venues. The purpose of this document is to provide descriptions of measurement protocols appropriate for assessing short duration impulsive sound such as pickleball and paddle impacts, definitions of terms and acoustical metrics, and guidance for acoustical planning of new pickleball courts. Basic methodologies and best practices for community noise assessment, environmental acoustics measurements, and noise regulation documents are described.

The main concern for neighbors living close to pickleball courts is the popping sound produced by the paddle when it strikes the ball. This sound is narrowband, imparting a sensation of pitch, and very short in duration. For the latter reason, measurement techniques that involve averaging the sound pressure over time tend to underestimate the noise impact of the impulsive sound produced by the paddles. For this type of sound, the noise assessment methodology described in ANSI S12.9 Part 4 for the highly impulsive classification of sound, based on adjusted sound exposure level, is recommended as the most accurate means of assessing the community response to pickleball paddle impacts.

Planning open air pickleball courts begins with selecting an appropriate site that has sufficient setbacks to ensure an effective noise abatement plan will be possible. Most of the work of reducing sound levels at the neighbors is done by noise barriers in the form of sound walls or mass-loaded vinyl (MLV) fence covers. These are, however, limited in the amount of noise reduction they can provide making setbacks a critical component for success of the overall noise abatement plan. In order for a noise barrier to provide acoustical shielding it must be able to block the line of sight from the players on the pickleball courts to the surrounding noise sensitive areas including upper level windows and raised decks. These geometrical considerations, which will include topography as well as the neighboring structures themselves, may affect the minimum setbacks needed in a particular application.

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1. Introduction

1.1 Pickleball and Pickleball Sound

Pickleball is popular and rapidly growing paddle sport in the United States and Canada. It is played with a hard plastic ball similar to a wiffle ball. A pickleball court is 44 feet long and 20 feet wide compared to a tennis court at 78 feet long and 36 feet wide. A tennis court can be converted into four pickleball courts.



Figure 1.1. Pickleball Game

As the sport has grown so have concerns from those living near pickleball courts over noise. The impact of the pickleball on the paddle causes a sharp popping sound that can be heard hundreds

of feet from the courts. Unfortunately, poor siting and inadequate noise impact assessment and abatement at many locations have made open air pickleball courts controversial additions in many neighborhood settings. This document will provide guidance on noise impact assessment in general, how to accurately measure the sound produced by pickleball courts, site selection, and effective mitigation treatments.

1.2 Properties of Sound

Sound, for the purposes of this document, is a small pressure disturbance in the atmosphere producing the sensation of hearing. It may be produced by the vibration of a surface or by the pulsation of an airstream such as a rotating fan blade or the human vocal cords. Sound propagates through the atmosphere as a compression wave with a speed that increases with the temperature of the air. The characteristics of a particular sound are described in terms of amplitude (loudness), frequency (pitch), and the change of amplitude and frequency with time (impulsiveness, modulation, onset rate, or rise time).

Noise is unwanted sound. This may be a subjective assessment or it may imply effects on health, well being, and speech communication. Community noise impact is assessed in terms of both annoyance and public safety.

1.3 Annoyance

The subjective aspect of noise is known as “annoyance.” Annoyance describes the quality of a sound that is perceived as objectionable. It differs from loudness, the perceived amplitude of a sound. Annoyance is often influenced by nonacoustic factors such as habituation or sensitization to the sound, involvement in activities that require concentration, attitudes towards sound sources and their operators, and the perceived necessity of the noise intrusions. For these reasons, reports of annoyance will have varying degrees of response bias.

Annoyance as a basis for determining acceptable noise levels can be traced to a paper by T. J. Schultz [Schultz, 1978] and the work of other researchers in the 1960's and 1970's. Schultz aggregated a group of social surveys regarding transportation noise in different cities and found that the results could be explained using a noise dosage relationship. This method has since been adopted by federal agencies tasked with regulating and evaluating road, rail, and air transportation noise.

Early research into the community impact of noise focused mainly on road traffic noise. As a result, other sound sources studied later were compared to traffic noise impact studies to determine their level noise impact. It was found that the sound pressure levels of sound sources having special characteristics such as impulsiveness and tonality did not correlate well with community questionnaires when directly compared to traffic sound pressure levels. The annoyance of these sources was often higher than the traffic noise for the same sound pressure level.

For this reason, the sound pressure levels of sound sources having these special characteristics are given an adjustment to compensate for the difference in noise impact. Part 4 of the ANSI S12.9 standard gives adjustments and measurement methodologies for a variety of sound

classifications and is used as the basis for the sound pressure level adjustments in this document.

1.4 Physiological Effects of Sound

While it is well known that high amplitude acoustical pressures can cause hearing impairment as well as other types injury to the body, lower amplitude sound can also have adverse long term physiological effects.

The World Health Organization recognizes that low level noise exposure has measurable health effects:

Sound/noise is a psychosocial stressor that activates the sympathetic and endocrine system. Acute noise effects do not only occur at high sound levels in occupational settings, but also at relatively low environmental sound levels when, more importantly, intended activities such as concentration, relaxation or sleep are disturbed. [WHO, *Night Noise Guidelines*, p. 61]

The sympathetic nervous system is part of the autonomic nervous system and is involved in the body's fight or flight arousal response. Chronic activation of the sympathetic system leads to stress, fatigue, and anxiety.

In addition to nervous system activation, sleep disturbance from noise can involve difficulty in falling asleep as well as awakenings that occur during sleep. Frequent awakenings lead to sleep fragmentation. This disrupts the normal stages of sleep and may lead to further neurocognitive manifestations not limited to daytime tiredness, loss of concentration, morning confusion, irritability, anxiety, and depression. [WHO, *Night Noise Guidelines*, p. 48, 26]

Environmental noise also has implications for the cardiovascular system, metabolism, and homeostasis, the ability of the body to regulate itself.

The auditory system is continuously analyzing acoustic information, which is filtered and interpreted by different cortical and subcortical brain structures. The limbic system, including the hippocampus and the amygdala, plays an important role in the emotional processing pathways. It has a close connection to the hypothalamus that controls the autonomic nervous system and the hormonal balance of the body. Laboratory studies found changes in blood flow, [blood pressure] and heart rate in reaction to noise stimuli as well as increases in the release of stress hormones... Acoustic stimulation may act as an unspecific stressor that arouses the autonomic nervous system and the endocrine system... The arousal of the sympathetic and endocrine system is associated with changes in the physiological functions and the metabolism of the organism, including [blood pressure], cardiac output, blood lipids (cholesterol, triglycerides, free fatty acids, phosphatides), carbohydrates (glucose), electrolytes (magnesium, calcium), blood clotting factors (thrombocyte, aggregation, blood viscosity, leukocyte count) and others. In the long term, functional changes and dysregulation may occur, thus increasing the risk of manifest diseases. [WHO, *Night Noise Guidelines*, p. 62-63]

The effects of stress can take many forms as seen above. Low level noise exposure that disturbs

sleep and concentration are known to produce a range of diagnosable illnesses and disorders.

1.5 Long Term and Short Term Community Impact

Community response to noise is different for short term and long term exposures. Short term impact refers to sounds that occur occasionally for a limited period of time, usually on an irregular basis, that are not part of the normal activities on a property. These types of sounds are generally addressed in the municipal code.

Zoning or land use regulations focus on long term community noise impact. These sounds occur regularly over a period of time measured in weeks, months, or years and are usually part of the normal activities on a property. In most cases, however, this would not include construction activities as these are temporary and not a normal part of the usage of the site.

Municipal code noise regulations and land use code noise regulations serve different purposes, but compliment each other to protect the community from excessive noise under differing circumstances. The land use code governs long term community noise exposure and is directed mainly to developers and commercial property owners. A municipal code applies to short term noise sources that generally do not operate on a regular basis. The table below shows a comparison of how these two codes work separately and together to provide a more complete community noise policy.

Table 1.1. Application of Short and Long Term Noise Regulation

	Municipal Code	Land Use Code
Assessment Type:	Short term noise impact	Long term noise impact
Directed Toward:	Residents, public gatherings, noise control officers, police officers	Developers, architects, acoustical engineers, planning & development dept., noise control officers
Purpose:	<ul style="list-style-type: none"> • Set threshold for offenses • Define penalties 	<ul style="list-style-type: none"> • Guidance for site planning • Standards for noise abatement • Long term noise assessment
Main Area of Law:	Criminal	Civil
Findings:	<ul style="list-style-type: none"> • Made by officer on scene • Immediate determination of required action 	<ul style="list-style-type: none"> • Assessment of all sound sources affecting surrounding properties by acoustical engineer • Analysis presented in detailed report
Expected Outcomes:	<ul style="list-style-type: none"> • Immediate action • Possible cease and desist order, citation, or arrest 	<ul style="list-style-type: none"> • Comprehensive plan to bring the site into compliance • Installation of noise abatement treatments

2. Definitions

A-weighted sound level

A measurement of a sound level obtained using “A” frequency weighting. This weighting curve approximates the frequency response of human hearing for low to moderate sound pressure levels. The frequency weighting characteristics of the A-weighting filter are defined in ANSI S1.42 and ANSI S1.4.

Background sound

Sound from all existing sources near and far that may interfere with a sound pressure level measurement, not to include the sound source being evaluated.

Decibel (dB)

Ten times the logarithm to the base ten of the ratio of two quantities that are proportional to power. Quantities denoted as a “level” are decibel quantities, e.g. sound pressure level.

Ensemble sound

Sound from all normal existing sources near and far at a given location, including the sound source being evaluated. The union of all sound sources observable at the point of assessment.

Equivalent-continuous sound pressure level

The sound pressure level of a steady, continuous sound having the same sound energy as the time varying sound measured. Ten times the logarithm to the base ten of the time average over the period of a measurement of the square of the ratio of the sound pressure to the reference sound pressure of 20 micropascals expressed in decibels (dB).

Fast exponential time weighting

A lowpass filter for the purpose of averaging or smoothing a signal having a time constant of 0.125 seconds applied to the square of the sound pressure as specified in ANSI S1.4-1983.

Highly impulsive sound

Impulsive sound having very rapid onset rate or rise time typically resulting from impact processes or small arms gunfire including, but not limited to: metal hammering, wood hammering, drop hammering, pile driving, drop forging, pneumatic hammering, pickleball paddle and ball impacts, pavement breaking, metal impacts during rail-yard shunting operation, and riveting. ISO 1996 differentiates highly impulsive sound from regular impulsive sound by its noted level of intrusiveness.

Impulsive sound

Sound that is characterized by brief excursions of sound pressure, typically less than one second, whose peak pressure noticeably exceeds the background sound pressure.

Insertion loss (IL)

For a sound attenuator, noise barrier, or other noise abatement treatment, the decrease in sound level at a point of observation when the noise abatement treatment is inserted between the sound source and point of observation.

Noise

Any sound which annoys or disturbs humans or which causes or tends to cause an adverse effect on humans, domesticated animals, or livestock.

Noise abatement plan

A detailed plan demonstrating the mitigation measures to be taken in order to meet the requirements of this noise regulation. The noise abatement plan should describe the construction and locations of abatement treatments with the expected sound pressure levels at the receiving properties.

Noise impact assessment

An analysis performed by a qualified acoustical engineer which determines the potential noise impacts of a proposed use.

Peak sound pressure

The largest absolute value of the instantaneous sound pressure in pascals (Pa) in a stated frequency band during a specified time interval.

Regular impulsive sound

Impulsive sound that is not highly impulsive sound. This includes speech and music.

Sound exposure level (SEL)

Sound exposure level is a descriptor for characterizing the sound from individual acoustical events. The sound exposure is the time integral of the square of the sound pressure over a time interval equal to or greater than an acoustical event having units of pascal squared seconds. The sound exposure level is ten times the logarithm to the base ten of the ratio of the sound exposure to the product of the square of the reference sound pressure of 20 micropascals and the reference time of one second expressed in decibels (dB).

Sound level meter (SLM)

An instrument used to measure sound pressure levels meeting the Type 1 standards for accuracy in ANSI S1.4-1983. Integrating sound level meters shall comply with ANSI S1.43-1997 Type 1. If octave band or fractional octave band filters are used, they shall comply with ANSI S1.11-2004 Class 1.

Sound pressure

A disturbance or perturbation of the atmospheric pressure with respect to the mean barometric pressure producing the sensation of hearing or vibration measured in units of pascal (Pa).

Sound pressure level (SPL)

20 times the logarithm to the base 10 of the ratio of the sound pressure to the reference sound pressure of 20 micropascals (μPa) expressed in decibels (dB).

Tonal sound

Sound having one or more single frequency oscillations (pure tones) or that is confined to a narrow band of frequencies meeting the criteria for tonal prominence. See ANSI S12.9 Part 4 Annex C or ANSI S1.13 Annex A.

3. Noise Regulation Best Practices

3.1 Purpose

A community is made up of individuals, families, businesses, government, land owners, tenants, and other groups conducting activities for their livelihoods and enjoyment. The purpose of noise regulation is to find a balance between the legitimate activities of one group and the need for peace and quiet of another and to provide a clear process for resolving disputes when they arise. Zoning noise regulations provide design goals for developers in planning a site for a specific activity and serve as criteria for assessing the community noise impact of existing sites. Clear guidance with regard to acceptable sound pressure levels is essential for ensuring new projects conform to community standards and for evaluating the compliance of existing land uses.

Noise regulations should set clear and enforceable limits on community noise exposure that accurately reflect the community response to a variety of common sound sources. Overly strict regulations lead to arbitrary and selective enforcement while overly simplistic sound pressure level limits lead to the impact of certain classifications of sound being underestimated or ignored completely.

A well provisioned noise regulation will therefore provide a comprehensive and accurate methodology for assessing the most common classifications of sound that impact a community. This ensures that community noise impact will be evaluated in a way that is representative of the experience of living and working in the community and also protects property owners from unreasonable demands for mitigation. Most importantly the noise regulations should provide a definitive means for bringing noise disputes to resolution.

Key goals of noise regulation include:

- Provide quantitative design targets for noise abatement
- Provide protections for neighbors for all classifications of sound
- Protect property owners from drawn out noise disputes

Benefits of good noise regulation:

- Defined design requirements for developers
- Easier to get financing for projects due to lower risk and uncertainty
- Enforceable standards for compliance
- No cutting corners for contractor at risk

3.2 Measurement Procedures

Noise regulation generally takes the form of specifying maximum allowable A-weighted sound pressure levels at a given location. It is important that the locations specified for assessment and compliance be accessible such as at a property boundary.

Property boundary regulations protect the receiving property in its entirety against noise intrusions from adjacent sites. They also do not require entering private property in order to conduct acoustical testing. Performing acoustical measurements on the offending site creates bias due to the closer proximity to the sound source. Creating a noise abatement plan for new developments using noise assessment locations on the receiving property or inside a structure makes ensuring compliance more complicated. This will be discussed further in Section 3.3.

3.3 Common Ordinance Noise Descriptors

Noise ordinances often do not have objective limits on sound pressure level, but instead use subjective criteria to evaluate noise impact. This leads to a great deal of difficulty in resolving noise disputes since neither side can agree on what the terms mean.

One common term is “audible” or “plainly audible.” The problem with this criterion is that neighbors will always be audible at certain times depending on meteorological conditions, time of day, etc. This places everyone in violation of the noise code leading to arbitrary and selective enforcement. The threshold of audibility depends on the background noise level at a specific location and time. It is therefore unpredictable for site planning purposes and unrepeatable. There is also no practical way to monitor without setting up a surveillance style recording system and reviewing the playback to identify the source in question.

Another common ordinance criterion is “excessive, unnecessary or offensive noise which disturbs the peace or quiet of any neighborhood or which causes discomfort or annoyance to any reasonable person of normal sensitivity residing in the area.” This regulation puts the arbiter in the position of deciding who is a reasonable person and what constitutes normal sensitivity. It turns an engineering problem of assessing noise impact based on decades on scientific field studies into a personal problem with no clear guidance on consistent application or how to reach resolution.

The Maricopa County, Arizona Code, section P-23, prohibits sounds that can be “heard from within closed residential structures.” This code is unenforceable because it is untestable. First, it requires access to a private home or place of business. The home or business must then be searched to verify that all doors and windows are closed. For a developer it is impossible to plan for or ensure compliance with such an ordinance because it is dependent on the construction of the receiving structures.

The subjective criteria described above may be difficult to enforce due to vagueness. Under the vagueness doctrine a statute may be void if it leads to arbitrary enforcement, does not provide fair notice of what is and is not punishable, or does not detail the procedures followed by officers or judges of the law.

3.4 Reducing Vagueness

The first step in reducing vagueness in noise regulation is to adopt a comprehensive, objective standard that addresses the most common sources of noise complaints, particularly impulsive and tonal sounds. There should be separate criteria for short and long term noise impacts. The zoning or land use code should focus on long term impacts while the municipal code addresses short term nuisance noise. The standards should not be overly restrictive such that common, everyday activities cause violations leading to arbitrary enforcement.

Sounds that are subjectively negative and disturbing for contextual reasons may require enumeration and specific restrictions in addition to sound pressure level limits. This may involve use limitation to certain times of day, complete prohibition, or other policies as deemed appropriate to the situation. A 5 to 10 dB adjustment for the enumerated sound sources may also be an effective means to address their greater noise impact.

3.5 Current Standards in Noise Regulation

3.5.1 European Union Directive 2002/49

The current, most up to date noise regulations with regard to scientific research have been enacted through European Union Directive 2002/49. This directive implements the noise assessment methodology in International Organization for Standardization standard ISO 1996. The American adaptation of ISO 1996 is ANSI S12.9 Part 4. These standards provide a comprehensive, objective method to assess the community noise impact of the most common sources of noise complaints including broadband continuous, impulsive, and tonal sounds.

In addition to the assessment methodology, ANSI S12.9 Part 5 provides guidance for acceptable day-night levels for a variety of land uses. In practice, setting sound pressure level limits for residential, commercial, and industrial zoning areas is usually sufficient.

4. Classification of Environmental Sound

The impact of noise on a community is not always simply determined by the amplitude of the sound. Sounds that vary rapidly with time or have certain frequency characteristics can have an additional impact. This chapter discusses the classification of sounds with special characteristics and how they relate to community noise response.

4.1 Amplitude Characteristics

4.1.1 Sound Pressure

The most fundamental characteristic of sound is its pressure amplitude measured in units of Pascals (Pa). Due to the extremely wide sensitivity range of human hearing, sound pressure is normally presented on a logarithmic scale known as the decibel scale and denoted by the symbol, dB.

It is important to note that the decibel is a scale or unit of level, not a unit of measure. A decibel quantity must therefore have a reference value to define it. Any acoustic quantity described as a “level” is by definition on a decibel scale. The sound pressure level (SPL) is the sound pressure in Pascals normalized to the standard acoustical reference pressure of $20 \cdot 10^{-6}$ Pascals as follows,

$$SPL = 20 \log_{10} \left(\frac{p}{20 \cdot 10^{-6}} \right)$$

where p is the sound pressure in Pascals and SPL is the sound pressure level in dB.

Figure 4.1 shows some typical sound pressure levels of common sound sources. Sound pressure levels in the blue range are very quiet and usually found only in special environments such as anechoic test chambers or remote forest areas. The green range is typical of quiet environments. For outdoor sound, most daytime noise regulations begin to apply in the yellow range at starting 55 dBA. The U.S Department of Housing and Urban Development will require a noise abatement before funding residential projects above 65 dBA. Above 75 dBA they will require a stringent approval process. At 90 dBA in the workplace, OSHA will require a hearing protection program for workers.

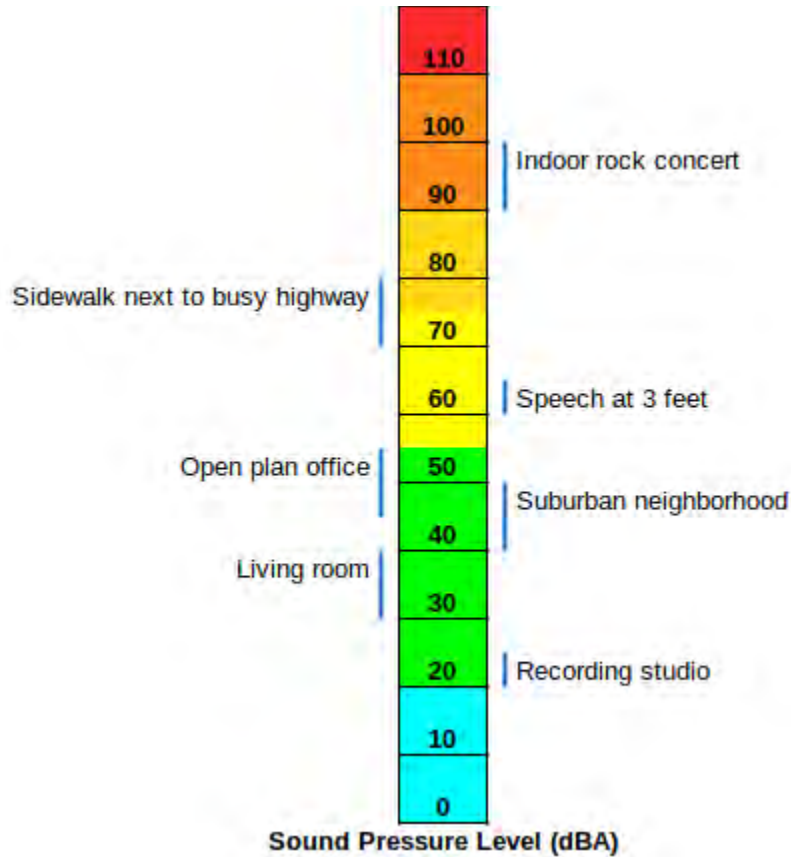


Figure 4.1. Sound Pressure Levels of Some Common Sources

4.1.2 Broadband Continuous Sound

A sound pressure level reading that does not change rapidly with time, does not contain tones, and covers a wide frequency range is said to be broadband with respect to frequency and continuous with respect to time. Broadband continuous sounds are characterized primarily by their sound pressure level. Common examples are fans, well pumps, and traffic noise.

Broadband continuous sounds are the simplest to quantify and are used as a point of comparison for other types of sound. That is, they provide a stable and relatively neutral basis for comparing tonal, impulsive, and other special sound classifications. The sound pressure level limits set in most noise regulations apply to this type of sound. Other sound classifications are adjusted so that their impact can be compared to a broadband continuous sound pressure level. This greatly simplifies noise regulations; however, it requires methodologies to be defined to accurately normalize sounds with special characteristics on the basis of community response to those characteristics.

4.2 Spectral Characteristics

The spectrum of an acoustic wave refers to its frequency content. The frequency range that a sound occupies may cover a wide band of frequencies, only a very narrow band, or even a single frequency in the case of a tone. Frequency is measured in units of Hertz (Hz) which are equivalent to one cycle per second.

4.2.1 Broadband

As described above, broadband means that the sound covers a broad spectrum of frequencies. This type of sound is in general the most neutral in terms of subjective sound quality. A broadband source with emphasis on the frequencies above 1,000 Hz may, however, be characterized as sharp or shrill.

4.2.2 Narrowband

Sounds occupying only a narrow portion of the auditory spectrum are said to be narrowband. Narrowband can be regarded as having a bandwidth less than 1/3 of an octave. This type of sound is sometimes encountered in impact processes where the impact excites a structural resonance, but the duration of the sound is very short due to damping in the structure. Narrowband sounds will require a sound pressure level adjustment due to their spectral characteristics in relation to broadband continuous sounds if they have tonal prominence (see Section 5.5.1 Assessing Tonal Sounds).

4.2.3 Tonal

Sounds containing pure tonal frequencies are usually produced by rotating machinery, but can also be electrically amplified signals such as those created by a backup alarm. Human hearing is sensitive to tones. Sounds having tonal prominence will require an adjustment in order to be compared to broadband continuous levels (see Section 5.5.1 Assessing Tonal Sounds).

4.2.4 Infrasound and Ultrasound

The nominal range of human hearing is 20 Hz to 20,000 Hz. Sounds outside this range are referred to as infrasound if below 20 Hz and ultrasound if above 20,000 Hz. Objectionable infrasound can sometimes be generated by wind turbines or industrial sound sources.

4.3 Temporal Characteristics

The way sound changes with time can have a significant influence on the noise impact. Accounting for these characteristics is important for accurately predicting community response.

4.3.1 Stationary or Continuous

Sound that changes slowly in amplitude with time is known as continuous or in statistical terms, stationary. In practice, sounds that do not meet the criteria for impulsive, rapid onset, or modulated are considered continuous and do not require any sound pressure level adjustment for

their temporal characteristics.

4.3.2 Impulsive

Impulsive sound is characterized by brief excursions of sound pressure whose peak pressure noticeably exceeds the continuous sound pressure. The duration of a single impulsive event is usually less than one second.

Impulsive sounds often create annoyance because they are similar to sounds that contain important information about our environment such as a sound outside the house or a door closing. We are sensitive to these types of sounds because they alert us to events occurring nearby that we may need to respond to. Continuous false alarms make it difficult to relax, concentrate, or sleep soundly without disturbance.

Many researchers have found that impulsive sound requires a level adjustment to properly account for the special characteristics and sensitivity to this class of sound [Buchta, Smoorenburg, Vos] and that listeners are able to differentiate between loudness and annoyance for sounds with temporal variance [Dittrich].

Impulsive sound is considered to have three subcategories: regular impulsive, highly impulsive, and high energy impulsive. Each of these categories has a different sound pressure level adjustment.

Highly Impulsive

Highly impulsive sound is characterized by a sudden onset and high degree of intrusiveness. This is common for impact processes and small arms fire. Highly impulsive sound in general has a duration too short to be accurately measured using maximum fast exponential time weighting. Impulses with a regular repetition rate greater than 20 Hertz may be perceived as tonal rather than impulsive and require a tonal level adjustment.

Research has indicated that highly impulsive sound should receive a 12 to 13 dB adjustment [Buchta, Smoorenburg]. ANSI S12.9 Part 4 and ISO 1996 Part 1 recommend a 12 dB adjustment.

High Energy Impulsive

High energy impulsive sound is usually produced by explosive sources where the equivalent mass of dynamite exceeds 25 grams. Common sources are blasting or artillery fire. Sonic booms not produced by small arms fire are also included in this subcategory. High energy impulsive sound differs from highly impulsive sound mainly in the amount of low frequency energy produced.

Regular Impulsive

Impulsive sound not categorized as high energy or highly impulsive is categorized as regular impulsive. ANSI S12.9 Part 4 and ISO 1996 Part 1 recommend a 5 dB adjustment for regular impulsive sound.

Modulated

Another type of transient sound is characterized by amplitude modulation. These sounds consist of a continuous series of impulsive events such as speech or music. Human hearing is most sensitive to amplitude modulation at a rate of about 4 Hz [Zwicker & Fastl, p. 177, 247-8]. This, not surprisingly, is the rate at which talkers typically produce syllables when speaking. Sounds having amplitude modulation near this rate may cause higher annoyance than continuous sounds at the same sound pressure level and should be treated as regular impulsive. When a large number of conversations is occurring at once such that the words of individual speakers cannot be understood, the noise impact may be more similar to a broadband continuous sound source.

4.3.3 Time of Occurrence

Sounds that occur at certain times may become more objectionable. The community noise impact of sounds that occur at night is higher than in the daytime. Community noise impact is also higher during times when people are normally at home than when they are normally away at work.

4.4 Ensemble and Background Sound Pressure Levels

Noise complaints usually involve a specific sound source. In any outdoor environment the source of interest will be among many background sources. Since it is in general not possible to remove the background sources, acoustical measurements must be performed in the presence of all active sound sources. “Ensemble sound pressure level” will refer to the sound produced by all sources at a given location including the source of interest. “Background sound pressure level” will refer to the sound present with the source of interest deactivated.

5. Measurement and Assessment of Environmental Sound

5.1 Quantification of Sound

5.1.1 Sound Pressure

The measurement of sound in regard to noise regulation focuses on the sound pressure level (SPL) as described in Section 4.1.1. The human ear is a pressure sensor; therefore, the SPL most directly relates to the community response to noise. The human sensation of hearing does not, however, work in the same way that a microphone does. Spectral and temporal characteristics of a sound source can have a significant effect on the community response to that source. Signal processing must be applied to the measured sound pressure in order to adjust the measurement to the actual sensitivities of human hearing.

5.1.2 Frequency Weighting

The first step in accurately representing the perceived loudness of sound is to simulate the frequency response of the human ear. Human hearing has lower sensitivity to sounds below 250 Hz and above 8,000 Hz as seen in Figure 5.1 [ISO 226]. Hearing sensitivity as a function of frequency is, however, also a function of amplitude. Different frequency weighting filters must therefore be used for different amplitude ranges. Figure 5.2 illustrates the A and C frequency weighting curves [ANSI S1.4] that simulate the equal loudness contours of human hearing with respect a 1,000 Hz tone at sound pressure levels of 40 and 100 dB respectively. Noise regulations generally specify the A-weighted sound pressure level since this curve most closely matches the target noise level goal for broadband sound sources.

A-weighted sound pressure levels are commonly expressed as dBA, dB(A), or L_A .

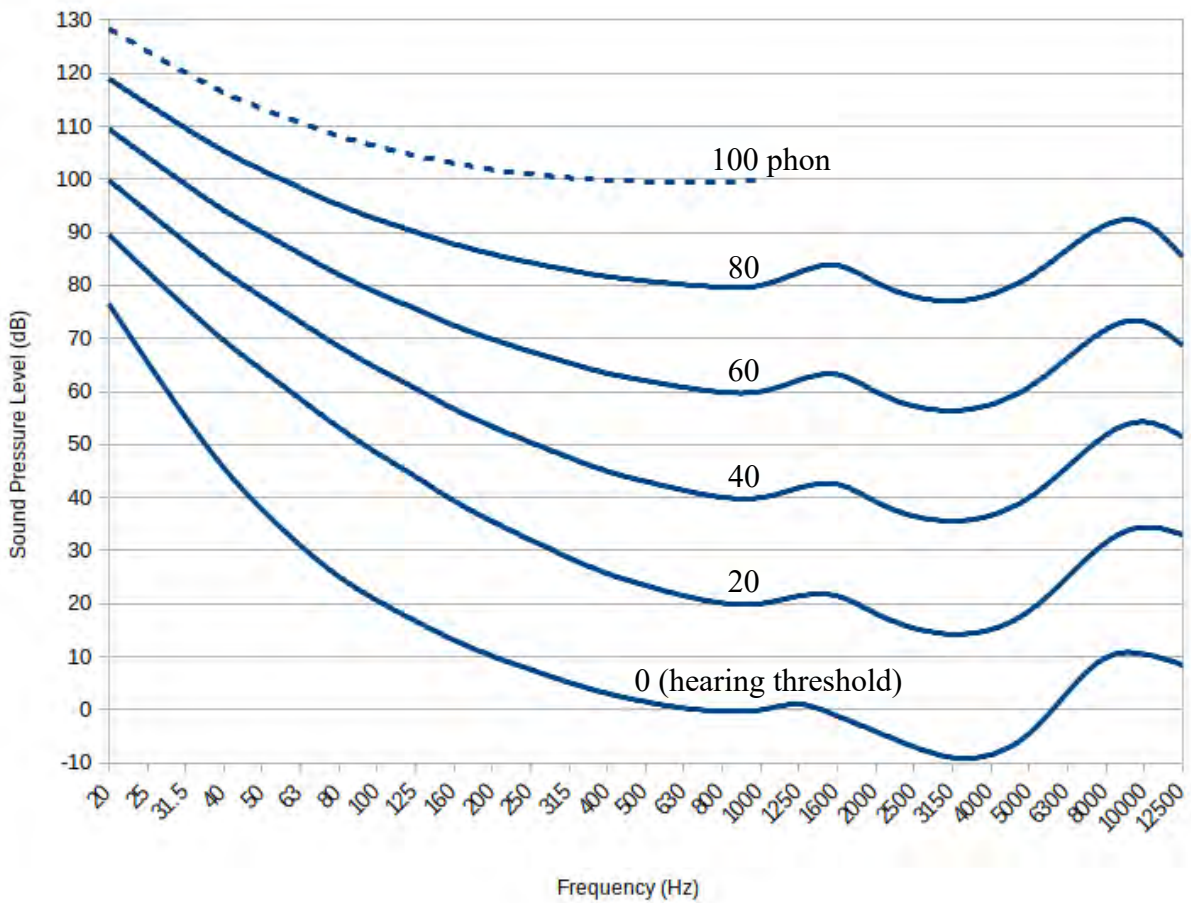


Figure 5.1. ISO 226 Equal Loudness Contours

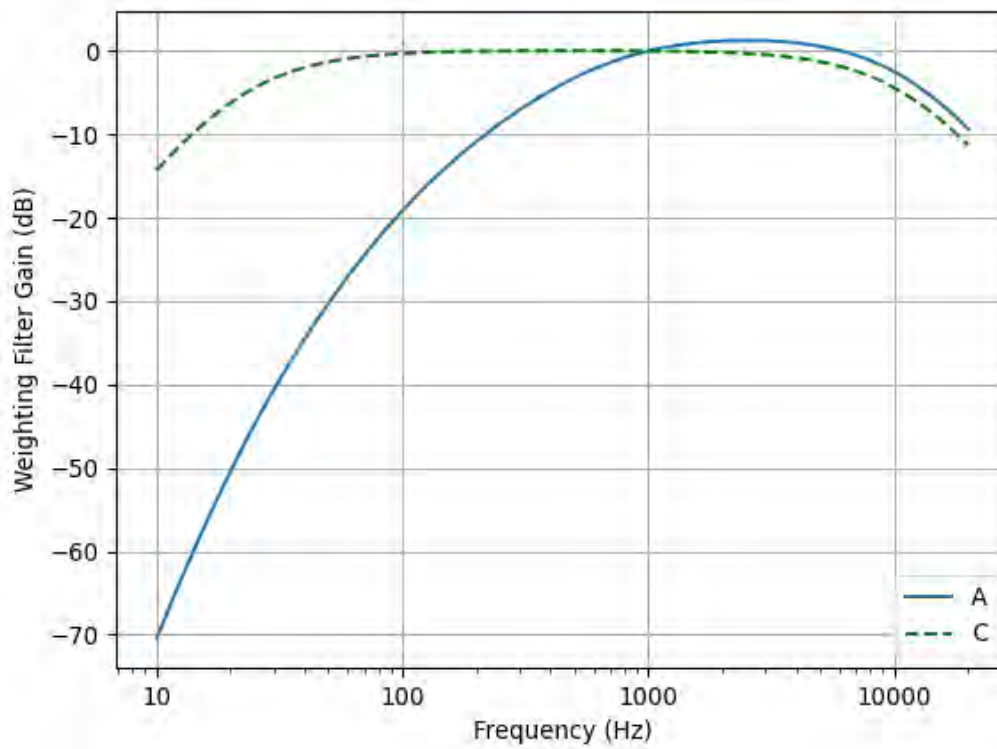


Figure 5.2. ANSI S1.4-2014 Frequency Weighting Curves

5.1.3 Equivalent-continuous Sound Pressure Level

The equivalent-continuous sound pressure level is the principal acoustical quantity measured for long term noise impact assessment. This is a root-mean-squared average of the sound pressure over a period of time expressed as a sound pressure level. Equivalent sound pressure levels may represent the average level over a period of minutes, an hour, or some other interval.

The A-weighted equivalent sound pressure level is represented as LA_{eq} . The equivalent-continuous sound pressure level does not use exponential time weighting (see below).

5.1.4 Day Night Level

A variation of the A-weighted equivalent sound pressure level is the day night level (DNL or L_{dn}). This metric incorporates the increased sensitivity to noise at night by adding a 10 dBA adjustment to sound occurring between 10:00 pm and 7:00 am. DNL is the most common metric used for transportation noise and is often applied to other broadband continuous sound sources.

5.1.5 Percentiles

To gain more insight into the noise environment during a long term measurement, some statistical quantities may be employed. The quantities LA_{10} and LA_{90} represent the A-weighted sound pressure level exceeded during 10% and 90% of the time of the measurement. LA_{90} is often used as an indication of the minimum background noise level without the presence of single noise events. LA_{10} indicates the highest sustained levels.

5.1.6 Sound Exposure Level

The sound exposure level (SEL) is used to quantify single noise events. It is particularly useful when the duration of an impulsive sound is too short to be accurately measured with an equivalent-continuous or exponential time weighted sound pressure level measurement. The equivalent-continuous level represents the mean squared average sound pressure. It does not account for instantaneous peak pressures. Impulses with short durations tend to get averaged out although the peak pressure may be significant. This can sometimes lead to the mistaken conclusion that the impulse has no greater noise impact than the background noise.

The sound exposure level also allows single noise events to be extracted from the measurement so that adjustments for special characteristics can be applied to more accurately represent the community response.

5.1.7 Peak Sound Pressure Level

For impulsive sounds with rapid onset, the instantaneous peak sound pressure level may be important. This metric may be used to supplement the sound exposure level for highly impulsive noise events that do not occur frequently enough to accumulate a substantial amount of sound energy, but nevertheless do present a significant noise impact due to their high peak pressure levels.

It should be noted that peak sound pressure level alone does not necessarily differentiate between intrusive highly impulsive and regular impulsive sounds. Different impulsive sound sources with the same peak sound pressure may have different noise impacts. Noise impact assessment of impulsive sound is often multidimensional involving onset rate, frequency range, and impulse duration.

5.2 Acoustical Instrumentation

5.2.1 The Sound Level Meter

In the regulation of community noise, a sound level meter (SLM) meeting prescribed standards for accuracy and conformity is used. The meter consists of a microphone and a signal processing unit that performs frequency weighting (usually A and C) and time weighting functions. The sound pressure level is displayed on the meter. An SLM that can log sound pressure levels and compute an equivalent-continuous level is called an integrating SLM. Modern SLMs incorporate digital signal processing capable of logging many acoustical metrics at the same time and can save simultaneous calibrated audio recordings for source confirmation and further analysis.

Most professional acousticians use, and many noise regulations require, a meter meeting the ANSI S1.4 Type 1 standard. This is the highest accuracy used for field work. Type 2 meters meet a lower standard of accuracy and are allowed by OSHA and some municipal codes.

5.2.2 Exponential Time Weighting

When taking sound pressure level measurements in the field, the reading on the meter can fluctuate rapidly for some sound sources. Exponential time weighting is a method of stabilizing the reading by applying a smoothing filter to the sound pressure envelop. Professional sound level meters will typically have three exponential time weighting settings: fast, slow, and impulse. The slow setting has time constant of 1 second. The fast setting time constant is 0.125 seconds (1/8 of a second). For most measurements the fast setting is preferred with the exception of impulsive sounds with a rapid onset rate.

Impulse time weighting uses a 0.035 second time constant on the rise of the sound pressure envelop with a peak hold having a 1.5 second time constant on the decay. The purpose of this setting is to allow a faster response on the rise of the signal to reduce the attenuation of the maximum pressure of the impulse, but have a slow decay to hold the reading on the meter display so it can be read and recorded. This time weighting is, however, still much slower than the impulse produced by typical highly impulsive sound source such as a pickleball paddle impact.

5.2.3 Integrating Sound Level Meters

Integrating SLMs integrate the sound pressure over the time period of a measurement in order to calculate the equivalent-continuous sound pressure level (LAeq). An integrating meter is required for noise regulations that specify metrics based on equivalent-continuous sound pressure level such as the day night level (DNL) or hourly sound pressure level.

5.2.4 Frequency Band Analysis

Some sound level meters include filters for obtaining octave band and fractional octave band sound pressure levels. Frequency band data is needed for designing sound walls and other noise abatement treatments. Unweighted octave band sound pressure levels may also be used to assess low frequency sound in regard to acoustically induced vibration caused by air handling units or subwoofers.

5.2.5 Calibration

The calibration of the sound level meter should be recertified by a qualified, independent metrology laboratory at intervals recommended by the manufacturer of the meter, usually one year. The sound level meter shall be used as provided in the manufacturer's instructions.

It is standard practice when carrying out sound pressure level measurements to place a calibration device recommended by the meter manufacturer over the microphone before and after testing to verify that the sensitivity of the microphone has not changed and that the equipment has not been damaged prior to or during testing. The field calibrator should also be sent to a

qualified metrology laboratory to have the calibration certified at intervals specified by the equipment manufacturer. This period is usually one year.

5.3 Calculation Methods

5.3.1 Decibel Addition

When working with multiple sound sources, it may be necessary to understand how each individual source contributes to the total sound pressure level. Decibel levels do not add arithmetically, but must be combined logarithmically. Figure 5.3 shows a chart for adding two levels. First, calculate the difference in the levels. Next, find the level difference on the horizontal axis of Figure 5.3 and find the corresponding level addition of the vertical axis. Add this number to the highest of the two levels. For example, to add two levels, 50 and 56 dB, together, find the difference, 6 dB, on the chart. The addition is 1 dB. Therefore, the decibel sum of 50 and 56 dB is 57 dB. If the level difference is greater than 10 dB, the contribution of the lower level source is negligible.

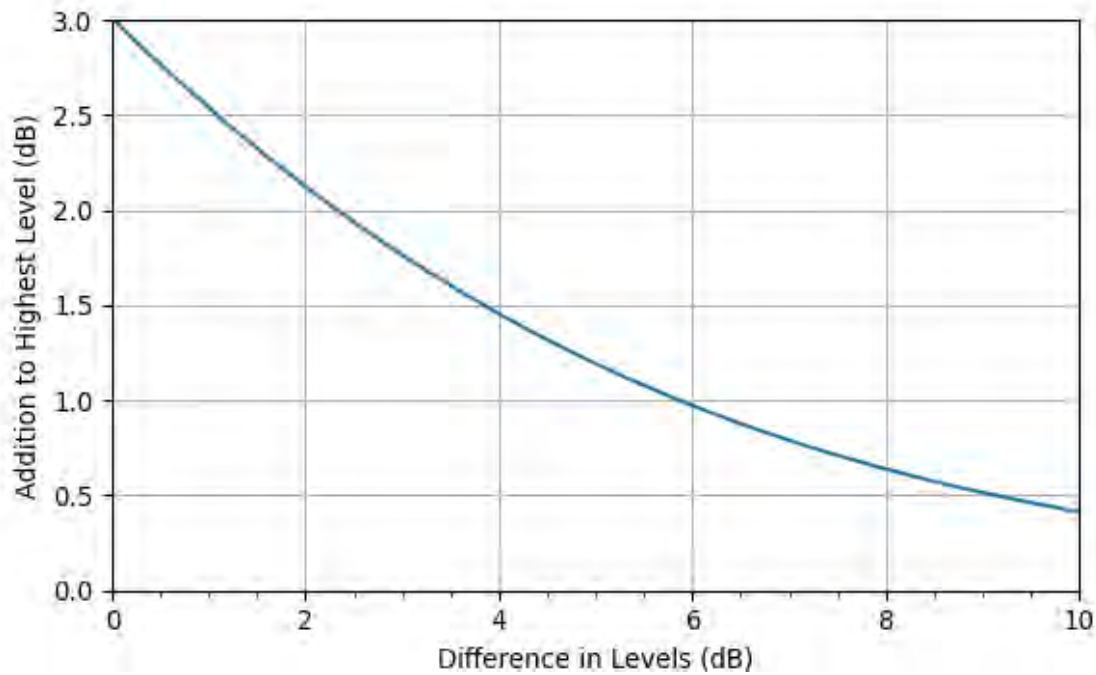


Figure 5.3. Decibel Addition

Equation 5.1 gives the direct calculation for the decibel sum, L_s , of levels, L_1 and L_2 .

$$L_S = 10 \log_{10} \left(10^{0.1L_1} + 10^{0.1L_2} \right) \quad (5.1.1)$$

5.3.2 Background Noise Correction

When assessing a noise issue it is common to measure the sound source of interest in the presence of other background sources. If the background noise level is within 10 dB of the ensemble noise level (see Section 4.4) a background noise correction should be applied to avoid overestimating the sound pressure level produced by the source of interest.

The corrected source level, L_{Source} , is found by the decibel subtraction of the background noise level, L_{bgn} , from the ensemble level, L_{ens} .

$$L_{Source} = 10 \log_{10} \left(10^{0.1L_{ens}} - 10^{0.1L_{bgn}} \right) \quad (5.2)$$

The background corrected sound pressure level of the source can also be found using Figure 5.4. Subtract the background sound pressure level from the ensemble level. Find this level difference on the horizontal axis of the figure and locate the corresponding decibel value on the vertical axis. Subtract this number from the ensemble sound pressure level to get the background corrected level of the source.

If the ensemble sound pressure level is within 3 dB of the background noise level, the source of interest is producing less sound pressure than the background sources and cannot be accurately assessed. When the conditions on the site prevent the background sound pressure level from being measured it should be noted in the measurement report.

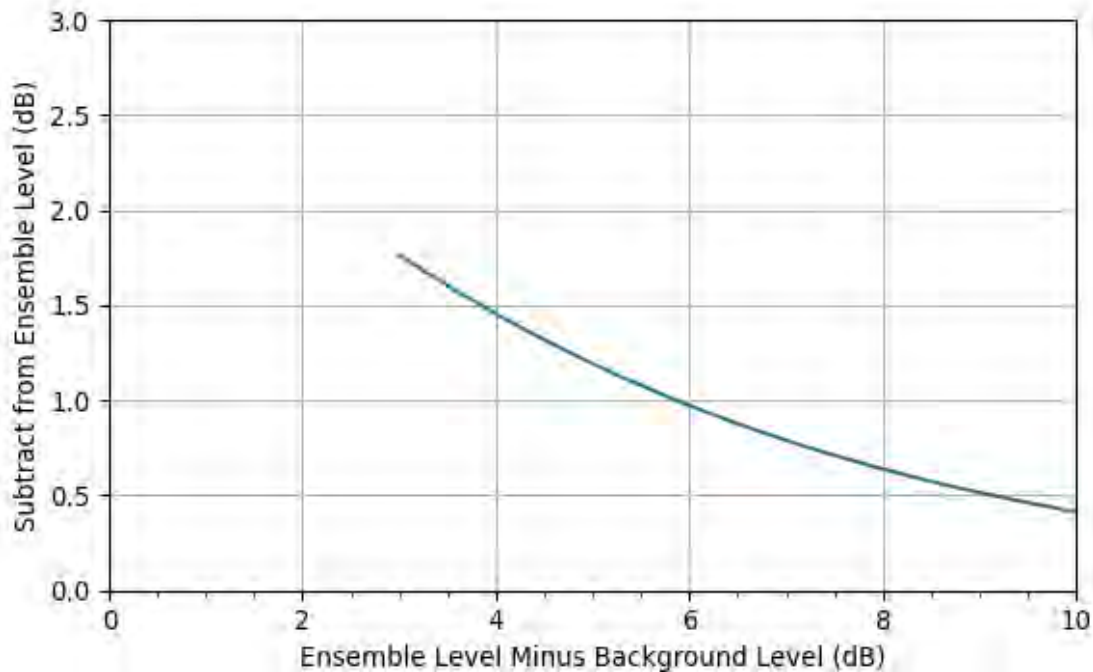


Figure 5.4. Background Noise Correction

Example:

An exhaust fan located on the exterior wall of a warehouse building runs continuously. A sound pressure level measurement taken at the nearest residential property line with the fan running reads 64 dBA. The fan is then shut off and the measurement repeated. The sound pressure level now reads 58 dBA due to a nearby roadway.

Subtracting the background noise level (58 dBA) from the ensemble level (64 dBA), which includes the fan and all other sound sources in the area, gives a difference of 6 dBA. From Figure 5.4, a 6 dB level difference on the horizontal axis corresponds to 1.0 dB on the vertical axis. Subtracting this number from the ensemble sound pressure level gives a result of 63 dBA for the sound pressure level of the exhaust fan by itself.

5.4 Measurement Procedures

5.4.1 Field Calibration

The calibration of the sound level meter shall be recorded before and after each series of measurements using a field calibrator or method recommended by the manufacturer of the meter.

5.4.2 Measurement Conditions

To the extent practical, all sound sources contributing to the ensemble sound pressure level at the point of measurement should be identified.

Measurements should not be performed when wind speeds exceed 10 knots (11 miles per hour, 5 meters per second), the SLM may become wet, or temperatures are outside the tolerance range of the SLM as specified by the manufacturer. A properly fitted windscreen shall be attached to the microphone.

Unless necessary, hourly or shorter duration measurements at distances greater than 100 feet (30 meters) should be performed on sunny days in order to avoid acoustic shadow zones formed by thermal inversions caused by ground heating. When the sun heats the ground, the relatively warm layer of air near the ground can cause sound to refract upward creating a complete or partial shadow. Measurements taken in the shadow zone can underestimate the sound pressure levels present at other times of the day.

5.4.3 Measurement Locations

The preferred noise assessment location is at the property line of the receiving property at the point most impacted by the sound source in question. More than one measurement location may be necessary for multiple sound sources or some noise sensitive areas.

In some situations the area most affected by the sound source of interest may be inside the boundaries of the receiving property. This is sometimes the case, for example, if there is a wall blocking sound at the property line. Measuring the sound directly behind the wall may not be representative of the sound levels farther from the wall inside the receiving property or at the upper floors of a building located on the property.

5.4.4 Sound Level Meter Placement

The microphone of the sound level meter should be placed at a minimum height of 45 inches (1.1 meters) above ground level and a minimum distance of 12 feet (3.6 meters) from any other reflecting surface. The microphone should not be placed closer than 12 feet (3.6 meters) from any sound source.

Other microphone placements may be used as necessary to assess a specific noise sensitive area, but their acoustical characteristics must be specified.

5.4.5 One Hour Equivalent-continuous Sound Pressure Level Measurements

One hour equivalent-continuous sound pressure level measurements shall be conducted using an integrating sound level meter. For sound sources that do not change in level over time, a shorter measurement period may be used provided the sound pressure level measured is typical of the source in question, but not less than 2 minutes. If a sound source has a regular operating cycle, the time period of the operating cycle, including both time on and time off, may be used for the measurement.

5.5 Adjusted Sound Pressure Levels

Sound sources that have special characteristics including impulsiveness and tonality have been found to have a noise impact greater than that indicated by the equivalent-continuous level. To account for this a set of adjustments to the equivalent-continuous sound pressure level have been defined based on the recommendations of ANSI S12.9 Part 4. These adjustments apply to equivalent-continuous sound pressure level measurement such as one hour A-weighted sound pressure levels (LAeq) and octave band equivalent-continuous sound pressure levels.

5.5.1 Assessing Tonal Sounds

Sounds having tonal prominence receive a 5 dB adjustment. Tonal prominence is determined according to ANSI S12.9 Part 4 Annex C by comparing adjacent unweighted one-third octave band equivalent-continuous sound pressure levels to the one-third octave band containing the tonal frequency. If the adjacent band level differences are greater than 15 dB for the 25 to 125 Hz bands, 8 dB for the 160 to 400 Hz bands, or 5 dB for the 500 to 10,000 Hz bands, the tone has prominence and a tonal adjustment shall be applied to the one-third octave band containing the tonal component.

Tonal prominence may also be determined using the narrowband methods in ANSI S1.13-2005 Annex A. This method may be necessary for tones that are close to the separation between two one-third octave bands resulting in bleed over into both bands.

5.5.2 Assessing Impulsive Sounds

Two categories of impulsive sound are addressed in this document: regular impulsive and highly impulsive.

Regular impulsive sound includes speech and music. It receives a 5 dB adjustment.

Highly impulsive sounds receive a 12 dB adjustment. Highly impulsive sounds occurring at a rate greater than 20 per second are usually not perceived as distinct impulses and no impulse adjustment shall apply; however, if the repetitions are regular in time a tonal sound adjustment may be necessary.

Equivalent-continuous sound pressure level alone is not sufficient to assess sounds characterized by impulsiveness. Highly impulsive and sporadic single events may produce a relatively small amount of energy compared to the background noise level. This does not necessarily mean they will not have a significant impact. Equivalent-continuous levels are often insensitive to short duration events even though the impulses may be clearly noticeable. In these instances the sound exposure method may be necessary to assess these events (see Section 5.5.3).

5.5.3 Applying Adjustments Using Sound Exposure Level

Impulsive sounds are usually spread out in time whereas background noise is continuous. The background noise will therefore often contribute more to an energy averaging metric like the equivalent-continuous sound pressure level than the impulses even though an observer on the site may report the impulses as the primary sound source due to their high peak sound pressures. In

cases like this a windowing method such the sound exposure must be used to separate the impulses from the background noise so that adjustments can be appropriately applied to the part of the ensemble sound containing the impulses.

One common use for the sound exposure level (SEL) is the comparison of two discrete sound events; however, in the context of applying adjustments to impulsive sound the SEL will be used to overcome the influence of the background noise by separating out the individual impulse events from the rest of the measurement data. The SEL of a single event, SEL_{event} , can be found from the background noise corrected equivalent-continuous sound pressure level over just the time of the event, $L_{eq,event}$,

$$SEL_{event} = L_{eq,event} + 10 \log_{10}(T_{event}/T_0) \quad (5.3)$$

where T_{event} is the duration of the event in seconds and T_0 is the reference time of 1 second. T_{event} should be inclusive of the entire event. In situations where the background noise level fluctuates it may be necessary to find the background noise level in the immediate vicinity of each impulse event in order to do the corrections.

The appropriate regular or highly impulsive adjustment can now be added directly to the SEL of the event. This process can be repeated for each impulse to obtain a set of SELs.

In order to compare the resulting sound exposures to the level limits in the regulations, the SELs must be converted to an equivalent-continuous level over the time period of the original measurement. The adjusted equivalent-continuous level of the impulses during the time of the measurement, $L_{eq,adj}$, is therefore the decibel sum of each event's background corrected sound exposure level, $SEL_{event,i}$, and its adjustment, K_i , minus the measurement time, T , in decibels.

$$L_{eq,adj} = \sum_i 10^{(0.1(SEL_{event,i} + K_i))} - 10 \log_{10}(T/T_0) \quad (5.4)$$

An alternative form of Eq. 5.4 is useful in when the mean SEL and the number of events over a period of time are known for an impulsive sound source.

$$L_{eq,adj} = SEL_{src} + K_{impulse} + 10 \log_{10}(N) - 10 \log_{10}(T/T_0) \quad (5.5)$$

Here $L_{eq,adj}$ is equal to the sum of the sound exposure level for one event occurrence, SEL_{src} , the adjustment for the type of impulse, $K_{impulse}$, the number of occurrences, N , in decibels, and total time period over which the impulses occur, T , in decibels.

$L_{eq,adj}$ can now be combined with the other adjusted sound source levels in the project using Eq.

5.1 to obtain the total adjusted equivalent-continuous sound pressure level. This level can then be compared to the level limits in the noise regulations.

For more information on sound exposure level see ANSI S12.9 Part 4 and Harris, Chapter 12.

5.5.4 Time of Day Adjustments

For noise impact assessment, the day is typically divided into three segments: day, evening, and night. For residential land uses, each of these time periods will have different noise sensitivities. During the daytime, usually defined as 7:00 am to 7:00 pm, many people are at work or busy with other activities away from home. In the evening, 7:00 pm to 10:00 pm, people tend to be at home and are more aware of noise in the area. Nighttime is the most noise sensitive time as people are sleeping. Weekends also have a higher noise sensitivity similar to evenings when people tend to be at home, but not sleeping.

For residential land uses, time of day adjustments include a 5 dB adjustment for the evening and a 10 dB adjustment for the nighttime hours. Weekend daytime hours also receive a 5 dB adjustment similar to evening hours.

5.6 Measurement Reports

After a set of field measurements have been completed, a report of the findings should be issued containing the following information:

1. Make, model, and serial number of each piece of measuring equipment
2. Date and location of the most recent laboratory calibrations
3. Site plan showing measurement locations
4. Statement of on-site calibration verification before and after each series of measurements
5. Name of the engineer conducting the tests

For each measurement location the following information should be noted:

1. Date and time of the measurement
2. Acoustical metrics measured
3. Time and frequency weighting used
4. Microphone location and height
5. Windscreen used
6. Description of the test location including the type of ground and any reflecting surfaces near the SLM or sound source being investigated
7. Primary and secondary sound sources contributing to the measurement

8. Background noise level if investigating a specific sound source
9. Weather conditions: temperature, humidity, wind speed and direction, cloud cover, and sun exposure
10. Photo image showing the sound level meter and intervening ground between the meter and the sound source of interest

5.7 Noise Impact Assessments

5.7.1 Purpose and Methods

A noise impact assessment provides a determination of the likely effects of introducing a new activity on the surrounding area. For new developments or modifications of existing developments involving on site activities that are likely to have a noise impact on the surrounding area, a noise impact assessment should be prepared by a qualified acoustical engineer. ISO 9613 and ANSI S12.62 provide a basic methodology for predictive acoustical site assessment; however, other methodologies may be used as appropriate for the area, conditions, and sound sources being evaluated. A noise impact assessment may be based on measurements of similar sound sources at a different location; however, differences in propagation paths that may affect the noise impact must be accounted for.

5.7.2 Present and Future Noise Exposure

With many sound sources, the noise impact may increase over time, e.g. roadways and other modes of transportation whose usage can be expected to increase in the future. In preparing noise impact assessments for proposed developments, future usage patterns should be included in the analysis.

5.8 Existing Noise Regulations

Best practices and current standards for noise assessment have been covered in Chapter 3. These criteria will be used here to evaluate noise regulations that apply within the City of Centennial.

5.8.1 City of Centennial Municipal Code, Chapter 10, Article 12

The City of Centennial does not currently have a land use noise regulation. Noise violations are defined in the Municipal Code. Two sections of the Code relate to noise assessment.

Sec. 10-12-10. - Legislative declaration.

It is hereby declared that protection and preservation of the home is of the highest importance; that unnecessary and excessive noise is a significant source of environmental pollution that threatens the public health, welfare, tranquility and good order of the community; and that the prohibitions and other protections set forth in this Article are enacted to secure and promote public peace, welfare, comfort and health.

Sec. 10-12-20. - General prohibition.

It shall be unlawful for any person to make, continue or cause to be made or continued any excessive or unusually loud noise which:

- (1) Disturbs, annoys or endangers the peace, repose, comfort, safety or health of others; or
- (2) Endangers or injures personal or real property.

These Code sections do not prescribe an objective measure of excessive noise, but state that “protection and preservation of the home is of the highest importance.” Section 10-12-20(1) prohibits sound that “disturbs, annoys or endangers the peace, repose, comfort, safety or health of others.” No guidance is given for compliance with the Code; however, ANSI S12.9 Part 4 is a standard for assessing annoyance in a community setting caused by noise and would be in alignment, as an objective assessment methodology, with the criteria in Section 10-12-20(1).

5.8.2 Colorado Revised Statutes 25-12-101

The Colorado Revised Statutes seeks to provide statewide minimum standards for noise levels.

25-12-101. Legislative declaration

The general assembly finds and declares that noise is a major source of environmental pollution which represents a threat to the serenity and quality of life in the state of Colorado. Excess noise often has an adverse physiological and psychological effect on human beings, thus contributing to an economic loss to the community. Accordingly, it is the policy of the general assembly to establish statewide standards for noise level limits for various time periods and areas. Noise in excess of the limits provided in this article constitutes a public nuisance.

C.R.S. 25-12-103(1) provides some objective maximum limits on permissible sound pressure levels. For residential land uses, the daytime limit is 55 dBA. Evening hours are not defined; however, nighttime hours are from 7:00 pm to 7:00 am. This includes hours that would normally be considered evening. The nighttime sound pressure level limit is 50 dBA which is more typical of a 5 dBA evening penalty than the more customary 10 dBA nighttime level limit reduction.

Acoustical measurements are to be made 25 feet inside the receiving property boundary. This is problematic for a number of reasons. First, it requires entering private property in order to assess the sound level. This makes assessment, monitoring, and enforcement more difficult. It also does not protect the entire receiving property. This can be especially impactful for residents on small lots or rental properties where the back patio may be within this distance.

While C.R.S. 25-12-103(3) does include provisions for impulsive sound,

Periodic, impulsive, or shrill noises shall be considered a public nuisance when such noises are at a sound level of five db(A) less than those listed in subsection (1) of this section.

with a 5 dBA reduction in the allowable sound pressure level, this approach is overly simplistic

and will underestimate the noise impact of highly impulsive sounds.

Overall, the noise assessment procedure in C.R.S. 25-12 appears to be a compromise between simplicity of noise assessment and completeness. While adequate for many sound sources, it will underestimate the noise impact some classifications of sound that include highly impulsive sound and sounds that occur during regular nighttime hours of 10:pm to 7:00 am when most residents are sleeping. The choice of noise assessment location 25 feet inside the receiving property increases the difficulty of monitoring and decreases the level of protection afforded to home owners for the use of their outdoor spaces.

6. Characteristics of Pickleball Sound

Spendiarian & Willis has prepared many noise assessments and abatement plans for pickleball courts. This chapter summarizes some of the knowledge gained over the years of working with this sound source.

The main concern in regard to noise from the pickleball courts is the sound produced by the impact of the hard plastic ball on the paddles. This sound is characterized by a sudden onset and brief duration, thus classifying it as impulsive sound. The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz. This is near the most sensitive frequency range of human hearing.

6.1 Comparison of Pickleball to Other Activities

There is a common misconception that pickleball is acoustically equivalent to tennis, volleyball, or many of the other activities typically found at outdoor recreation centers and parks. Numerous news articles covering disputes over pickleball noise, many of which originate when existing tennis courts are converted to pickleball, demonstrate that this is not the case:

- Cutler, Amy, “Rise of pickleball pitting neighbor against neighbor, leading to lawsuits,” Arizona's Family, Phoenix, Arizona. February 13, 2023. <https://www.azfamily.com/2023/02/13/rise-pickleball-pitting-neighbor-against-neighbor-leading-lawsuits/>
- Arden, Amanda, “Lake Oswego shuts down city pickleball courts indefinitely due to noise complaints.” KION 6 News, Portland, Oregon. January 23, 2023. <https://www.koin.com/local/lake-oswego-shuts-down-city-pickleball-courts-indefinitely-due-to-noise-complaints/>
- Columbo, Mike, “Pickleball plan pits Kirkwood residents against neighboring country club.” Fox 2 Now, Saint Louis, Missouri. January 26, 2023. <https://fox2now.com/news/contact-2/pickleball-plan-pits-kirkwood-residents-against-neighboring-country-club/>
- Sheets, Connor, “Pickleball noise is fueling neighborhood drama from coast to coast.” *Los Angeles Times*, Los Angeles, California. March 3, 2022. <https://www.latimes.com/california/story/2022-03-03/pickleball-noise-fueling-neighborhood-drama>
- Adler, Erin, “Apple Valley neighbors in a pickle over pickleball noise.” *Star Tribune*, Minneapolis, Minnesota. March 27, 2019. <http://www.startribune.com/apple-valley-neighbors-in-a-pickle-over-pickleball-noise/507726242/>
- Bartel, Mario, “Pickleball banished from Port Moody court after neighbours complain of

rising stress, anxiety.” The Tri-City News, Coquitlam, British Columbia, Canada. April 24, 2021. <<https://www.tricitynews.com/local-sports/these-games-are-loud-port-moody-pickleball-neighbours-revolt-against-rising-stress-anxiety-3662369>>

- City of Lakewood, “Green Mountain Courts Closure.” <https://www.lakewoodtogether.org/pickleball/news_feed/green-mountain-courts-update>
- Higgins, Sean, “No vote on residential pickleball until city adopts new land management code.” KPCW News, Park City, Utah. January 27, 2022. <<https://www.kpcw.org/park-city/2022-01-27/no-vote-on-residential-pickleball-until-city-adopts-new-land-management-code>>
- Maryniak, Paul, “Pickleball lights plan puts two HOAs at loggerheads.” Ahwatukee Foothills News, Tempe, Arizona. November 29, 2017. <https://www.ahwatukee.com/news/article_9056a946-d48e-11e7-9838-8b69fb2d50b2.html>
- Bottemiller, Kitty, “Too loud! Pickleball noise upsets neighbors.” Green Valley News, Green Valley, Arizona. August 28, 2013. <https://www.gvnews.com/news/local/too-loud-pickleball-noise-upsets-neighbors/article_542c2aac-0f91-11e3-acdc-0019bb2963f4.html>
- Clay, Joanna, “Woman sues Newport Beach over pickleball noise at park near her home.” Orange County Register, California. April 7, 2016. <<https://www.ocregister.com/2016/04/07/woman-sues-newport-beach-over-pickleball-noise-at-park-near-her-home/>>
- Wheatley, Mike, “Noisy pickleball courts cause upset with homeowners.” Realty Biz News. March 15, 2022. <<https://realtybiznews.com/noisy-pickleball-courts-cause-upset-with-homeowners/98768719/#:~:text=In one lawsuit in Newport Beach%2C Calif.%2C a,are causing them less enjoyment of their home.>>
- Lazaruk, Susan, “Pickleballers face off with residents over noise in Metro Vancouver.” Vancouver Sun, Toronto, Ontario, Canada. February 2, 2022. <<https://vancouversun.com/news/local-news/pickleballers-face-off-with-residents-over-noise-in-metro-vancouver>>
- Shanes, Alexis, “Village in a pickle: How Ridgewood plans to tone down the pickleball court noise.” northjersey.com, California. January 16, 2020. <<https://www.northjersey.com/story/news/bergen/ridgewood/2020/01/16/ridgewood-nj-pickleball-noise-reduction-measures/4480463002/>>
- Monterey Herald Staff, “Pickleball noise controversy goes before city leaders Pacific Grove neighbors object to game at nearby tennis courts.” The Mercury News, California. September 19, 2019. <<https://www.mercurynews.com/2019/09/19/pickleball-noise-controversy-goes-before-city-leaders/>>
- Fraser, Patrick and Rodriguez, Ambar, “What to do about constant pickleball noise?” WSVN 7 News Miami, Miami, Florida. March 27, 2019. <<https://wsvn.com/news/help-me-howard/what-to-do-about-constant-pickleball-noise/>>

- Sutphin, Daniel, “Nixing the noise: Sound fence construction underway at Gilchrist pickleball courts.” Port Charlotte Sun, Charlotte Harbor, Florida. May 20, 2019. <https://www.yoursun.com/charlotte/news/nixing-the-noise-sound-fence-construction-underway-at-gilchrist-pickleball/article_79a764de-7b1c-11e9-b4d4-6bcaa919f3f3.html>
- Corrigan, James, “York residents complain noise from pickleball club is hurting quality of life.” WMTW News 8, Portland, Maine. November 16, 2021. <<https://www.wmtw.com/article/york-residents-complain-noise-from-pickleball-club-is-hurting-quality-of-life/38271921>>

It should be clear from the above list of references that pickleball constitutes a significant change in the acoustic environment of the area surrounding the courts in comparison to tennis and must be planned for accordingly. In particular, the impulsive sound produced by the impact of the hard plastic ball on the paddle can cause significant noise impact for those living near the courts.

6.2 Effects of Impulsive Sound

Persistent impulsive sounds create annoyance because they are similar to sounds that contain important information about our environment such as footsteps, a door opening, a tap at the window, or speech. We are sensitive to these types of sounds because they alert us to events occurring nearby that we may need to respond to. Continuous false alarms such as the popping sound created by pickleball paddle impacts make it difficult to relax, concentrate, or sleep soundly without disturbance as each time a pop is heard it draws the attention, creating distraction.

6.3 Acoustical Characteristics

The sound produced by the impact between a pickleball and paddle is characterized by a rapid onset and brief duration, typically on the order of 2 to 10 milliseconds (0.002 to 0.010 seconds) for the direct path sound. This classifies it as impulsive sound. Figure 6.1 shows a time trace of a pickleball paddle impact measured near Phoenix, Arizona. The main part of the direct sound impulse can be seen to be less than two milliseconds followed by a rapid decay and some later reverberant arrivals.

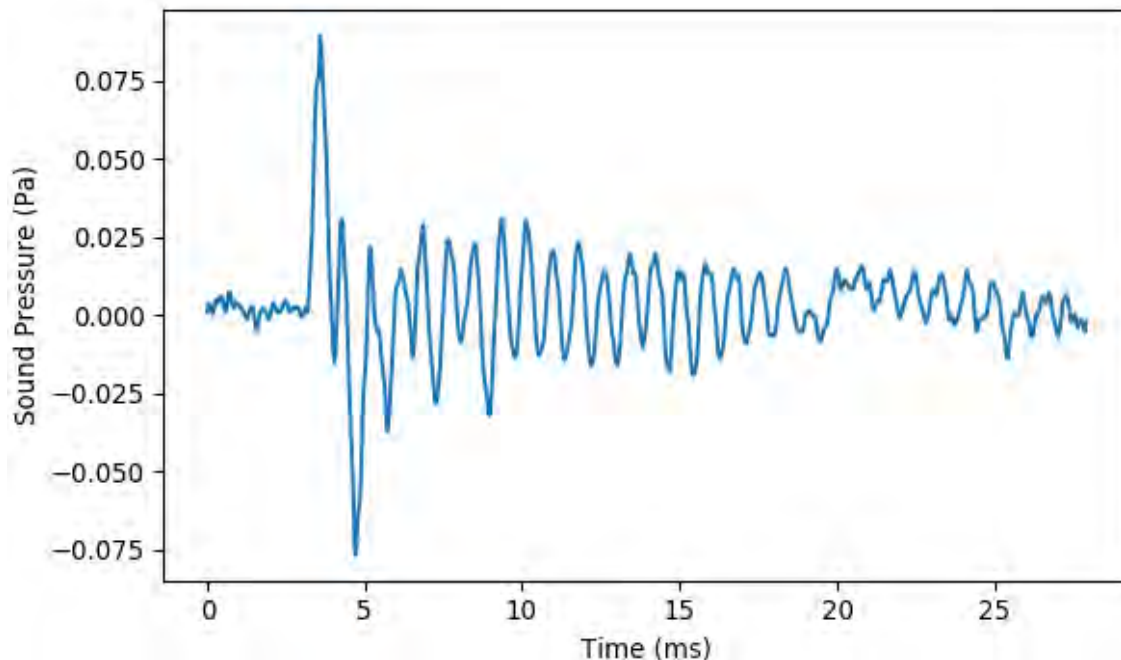


Figure 6.1. Pickleball Paddle and Ball Impact Sound Pressure Trace
 1 millisecond (ms) = 0.001 seconds.

The spectral content of the paddle impact is narrowband with a center frequency typically near 1,000 Hz (see Figure 6.2). Although it does not meet most guidelines for tonal prominence such as Annex C of ANSI S12.9 Part 4 or ANSI S1.13, it does impart a vague sensation of pitch similar to a wood block percussion musical instrument. The radiation pattern of the paddle is more or less a dipole, i.e. the sound from the front and back of the paddle is of opposite polarity and cancels itself in the plane of the paddle. Therefore, orienting the courts so that the direction of play faces away from noise sensitive areas can provide some attenuation.

The sound power spectrum of the pickleball and paddle impact has two basic shapes depending on how the ball is hit. Figure 6.2 and Figure 6.3 show the power spectra of a 'sharp' hit and a 'dull' hit. The curves are not calibrated for absolute level, but can be compared relatively.

The sharp hit spectrum shows a narrowband signature. The frequency of the peak typically varies between 1,000 and 2,000 Hz. The energy in the dull hit is more spread out, but still peaks between 1,000 and 2,000 Hz.

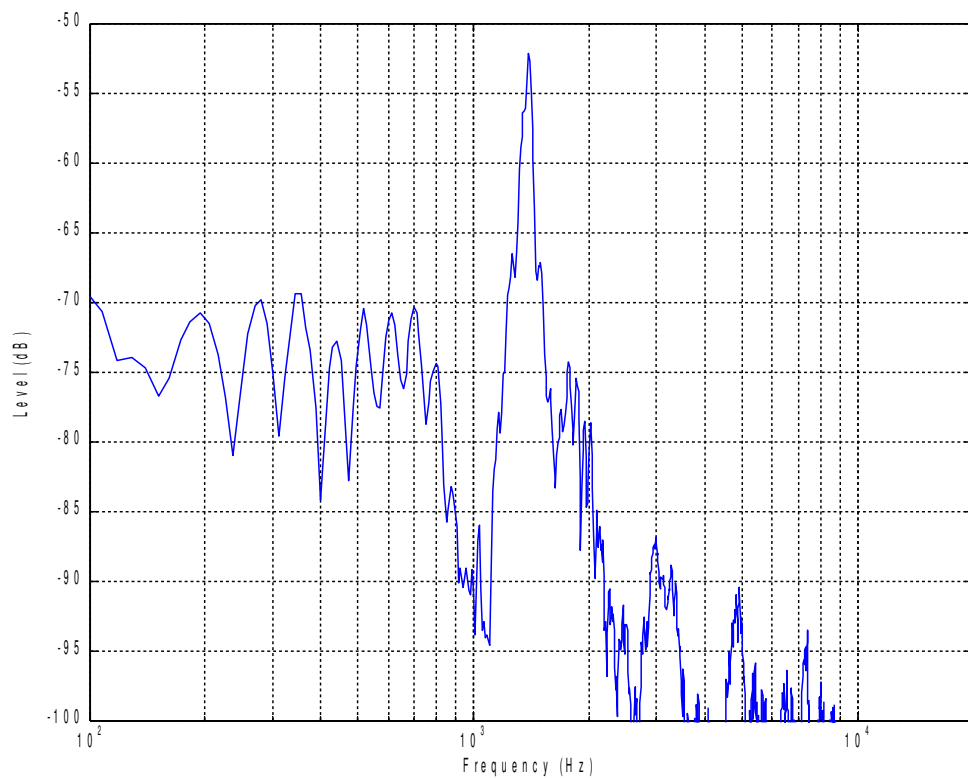


Figure 6.2. Spectral Response of a Sharp Hit

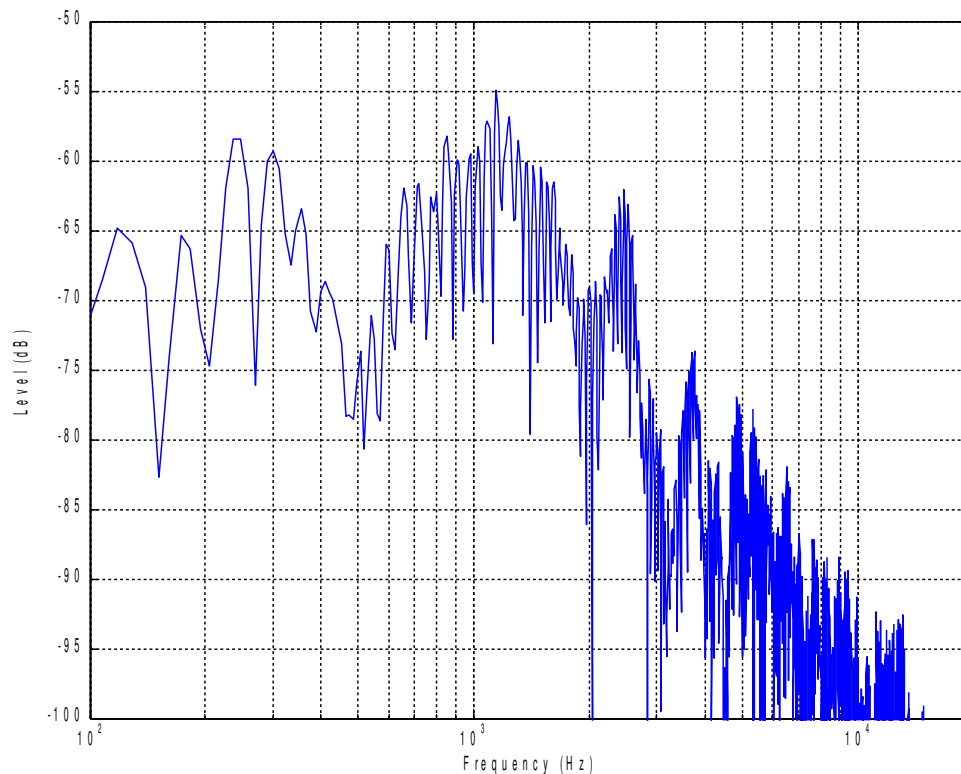


Figure 6.3. Spectral Response of a Dull Hit

A sound wall design will require effective attenuation in the 1,000 Hz octave band and above. In most applications, any material having a sound transmission class meeting STC 20 can be used to construct a sound wall or fence for pickleball provided best practices for sound barrier construction are followed.

6.4 Directivity of Pickleball Courts

The impulsive sound of the paddle impacts is radiated mainly by the large, flat paddle surface. Since both faces of the paddle are connected internally by a honeycomb structure and move together in vibration, one side of the paddle will produce a positive sound pressure while the other produces a negative sound pressure similar to a loudspeaker diaphragm that is not mounted in a cabinet. The result is that these two pressure waves having opposite polarity will cancel in the plane of the paddle where the path length from each face is the same to all receiver locations. This is known as a dipole or figure eight radiation pattern.

The positions of the paddles relative to the court change with each hit; however, the object of the game is to hit the ball to the opposite half of the court. Therefore, the dipole axis of each paddle impact will be in the general direction of play and not completely random. Measurements of

several pickleball facilities have shown that this results in a null depth of 4 to 5 dB. Figure 6.4 compares a typical pickleball court directivity pattern to a mathematical dipole where 0° and 180° are in the direction of play and the null is on the 90° and 270° bearings. Several decibels of attenuation can often be obtained simply by optimizing the orientation of the courts with respect to noise sensitive areas.

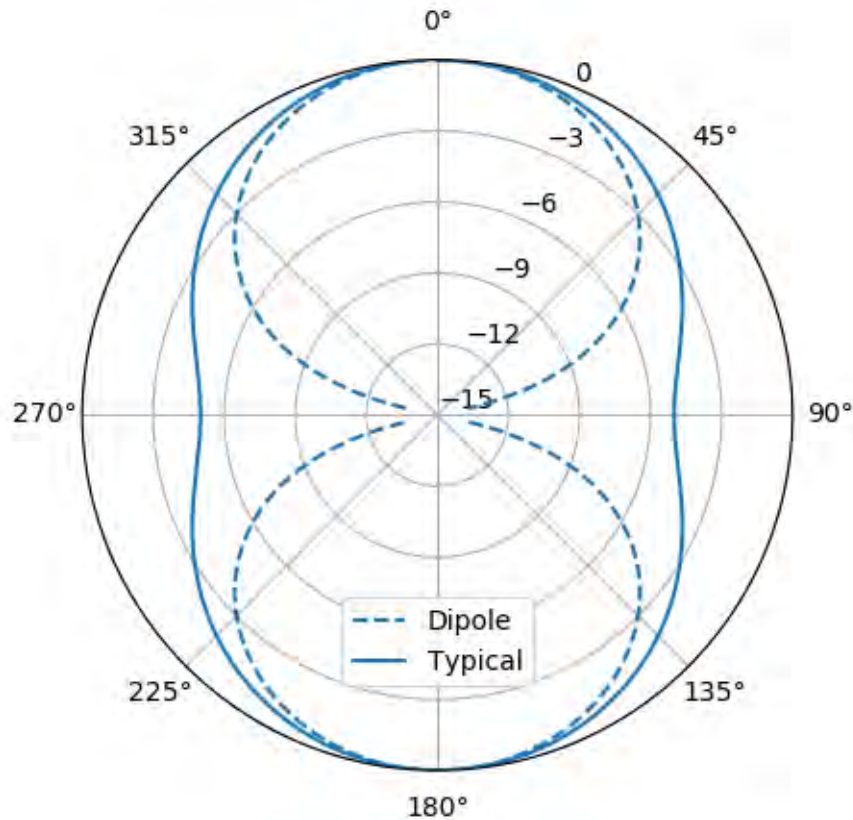


Figure 6.4. Typical Pickleball Court Directivity in Decibels

6.5 Noise Impact of Speech

In addition to the paddle impacts, speech is also a sound source on pickleball courts. While there are standards for speech sound power levels at various degrees of vocal effort such as ANSI S3.5, sound from speech emitted from pickleball courts can vary greatly with who is playing on the courts at a given time and be difficult to predict. In practice, noise abatement treatments sufficient to mitigate the paddle impacts should also be sufficient for speech from the courts as the paddle impacts typically have a greater noise impact.

Most noise objections regarding speech on pickleball courts are related to the content of the speech rather than the loudness. While the sound level of the speech can be reduced through abatement treatments, it cannot be made inaudible in most situations. A noise impact of this type must be addressed through court usage policy.

For tournament play, the overall speech pattern becomes more predictable. There are more sound sources that will approach a statistical average such as that described in ANSI S3.5. A total sound power level for the bleachers or spectator area can be calculated based on seating capacity or through direct measurement during a tournament.

7. Influence of Environmental Factors

7.1 Number and Arrangement of Pickleball Courts

Pickleball courts are usually placed on a rectangular concrete pad approximately 30 by 60 feet. This is one quarter the size of a typical tennis court pad such that a tennis court can be converted into four pickleball courts. An important factor influencing the amount of sound reaching neighboring properties will be the number of pickleball courts. A doubling of the number of courts will result in a doubling of the number of sound sources and therefore the sound power emitted. This corresponds to a 3 dB increase in sound power level. Pickleball courts are, however, not a single sound source, but a distribution of many sound sources spread over the area of the courts. For this reason, sound radiated from pickleball courts will not follow the inverse square law unless the distance from the center of the courts to the point of observation is large compared to the dimensions of the court or group of courts.

Figure 7.1 shows the ANSI S12.9 adjusted sound pressure level contours (see Section 8.3.3) at a height of 5 feet above grade for four courts, indicated by the red box, at the center of the main group of pickleball courts. For reference, the two groups of eight courts together have a width east to west of 136 feet and a length north to south of 268 feet. The oblong shape of the contours is not a result of the rectangular layout of the courts, but the directivity of the individual courts themselves (see Section 6.4).

The 55 dBA contour extends about 480 feet from the courts in the direction of play and 260 feet laterally. Figure 7.2 expands the number of pickleball courts to eight arranged in pairs end to end. The 55 dBA contour extends about 630 feet from the courts in the direction of play and 350 feet laterally. Figure 7.3 rearranges the eight courts into two rows side by side. The 55 dBA contour extends about 685 feet from the courts in the direction of play and 340 feet laterally. Doubling the number of courts causes the 55 dBA contour to move out 30% to 40% of the distance from the courts pad (red boxes) depending on how the courts are arranged.

The hypothetical examples above were created on level ground with a mixed ground type outside of the concrete pads for the courts (ISO 9613 ground factor, $G = 0.5$). In practice, noise complaints about pickleball courts at distances greater than 500 to 600 feet are rare. Real pickleball sites will usually have topographical features that hinder sound propagation at farther distances as well as structures that block or scatter sound. Pickleball courts across water may be an exception with the possibility of complaints occurring at distances approaching 800 to 1,000 feet.

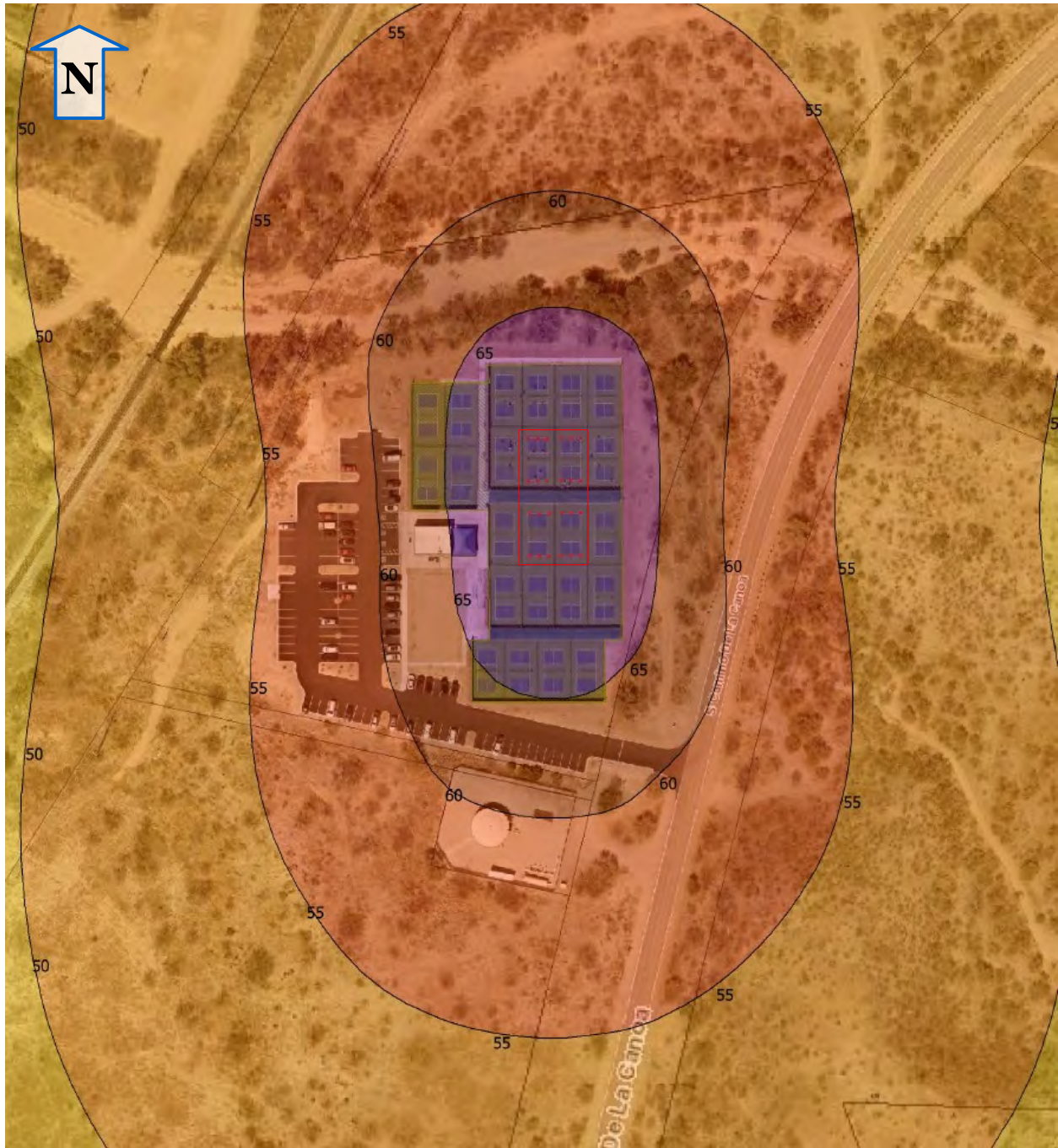


Figure 7.1. Adjusted Sound Pressure Level from Four Pickleball Courts

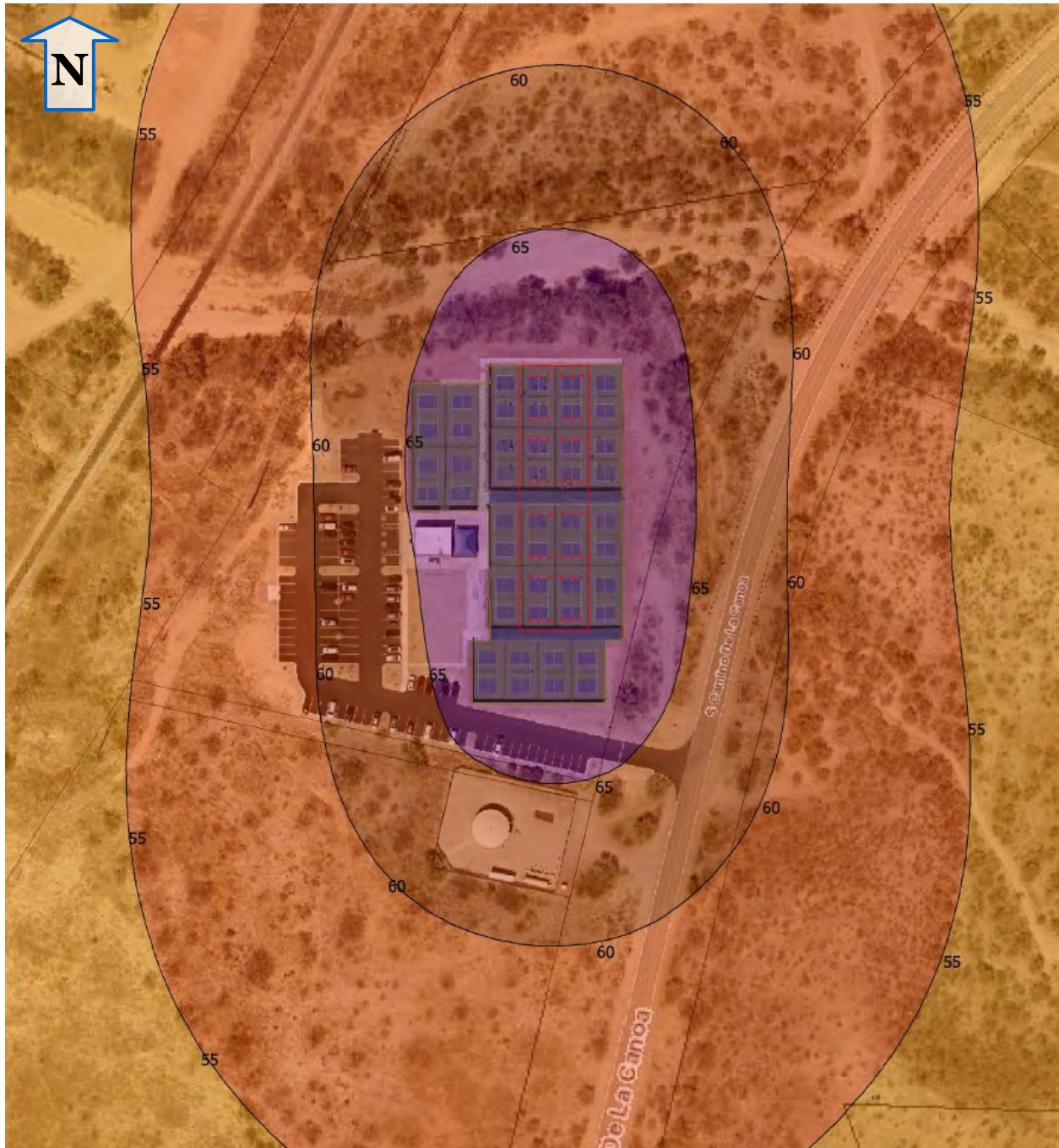


Figure 7.2. Adjusted Sound Pressure Level from Eight Pickleball Courts Aligned Longitudinally

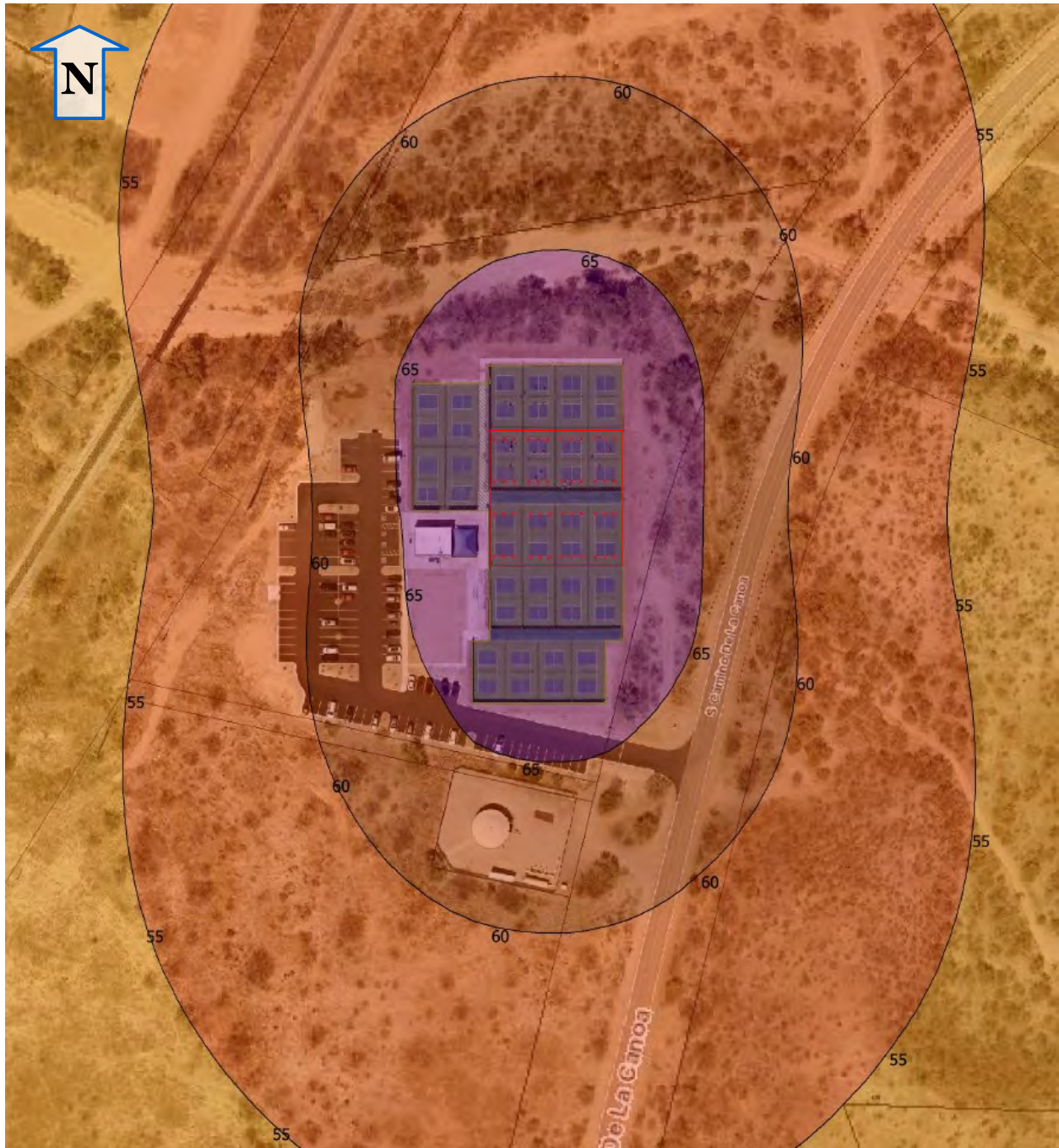


Figure 7.3. Adjusted Sound Pressure Level from Eight Pickleball Courts Aligned Laterally

7.2 Topography

7.2.1 Sight Lines

In order for a noise barrier to be effective, it must block the line of sight from the sound source to the point of observation. Homes sitting at an elevation higher than the proposed pickleball courts can be difficult to shield, particularly if they have more than one floor, balconies, or raised decks. Attention must be given to sight lines to determine whether a sound wall system can be a practical solution as a noise abatement treatment.

7.2.2 Noise Sensitive Locations Above Ground Level

In addition to elevation differences between the pickleball courts and surrounding properties, multistory housing can also result in sight line issues that lead to poor shielding. Figure 7.4 shows a mitigation example with four active pickleball courts in the southwest corner of the complex and a two story building to the south. A 10 foot sound wall (red line) has been placed along the south and west sides of the courts. The sound pressure level contours are at an elevation of 5 feet above grade. The 55 dBA contour does not reach the building.

In Figure 7.5, the elevation of the sound pressure level contours has been raised to 15 feet above grade, about the height of a second floor bedroom window or a person standing on a second floor balcony or raised deck. The 55 dBA contour can now be seen to contact the building. This shows the importance of checking all floors of nearby structures to ensure that acoustical design targets are being met.

It is important to note that, since the observation point on the second floor can overlook the sound wall, some paddle impacts will not be shielded. Although the partial shielding of the majority of the sound source locations is enough to lower the adjusted sound pressure level close to the target level of 55 dBA, peak sound pressures may not decrease as much as the adjusted level since some individual paddle impacts will not be shielded and may still have a significant noise impact.

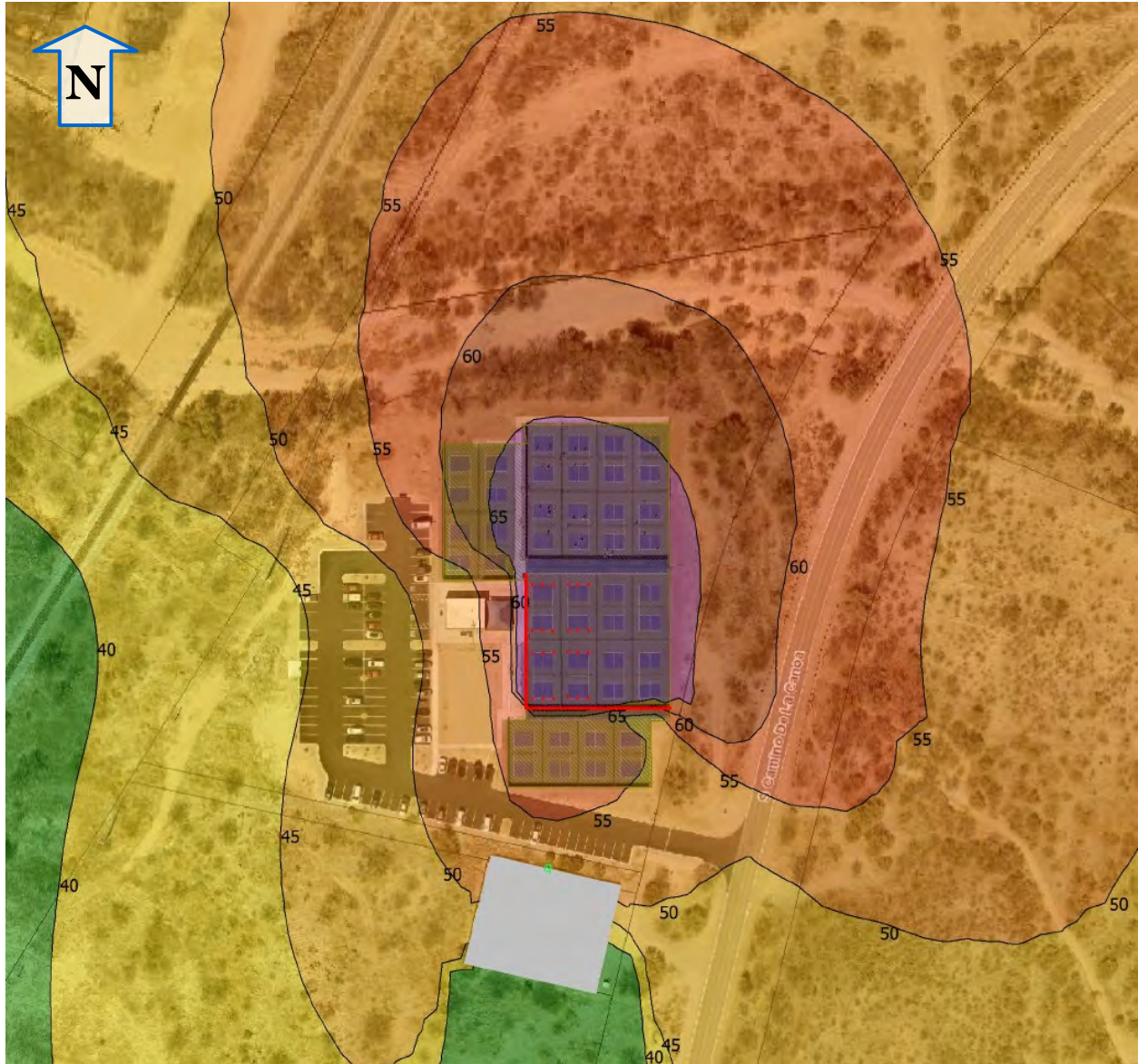


Figure 7.4. Adjusted Sound Pressure Level Contours, Four Courts, 10 Foot Wall, 5 Foot Elevation

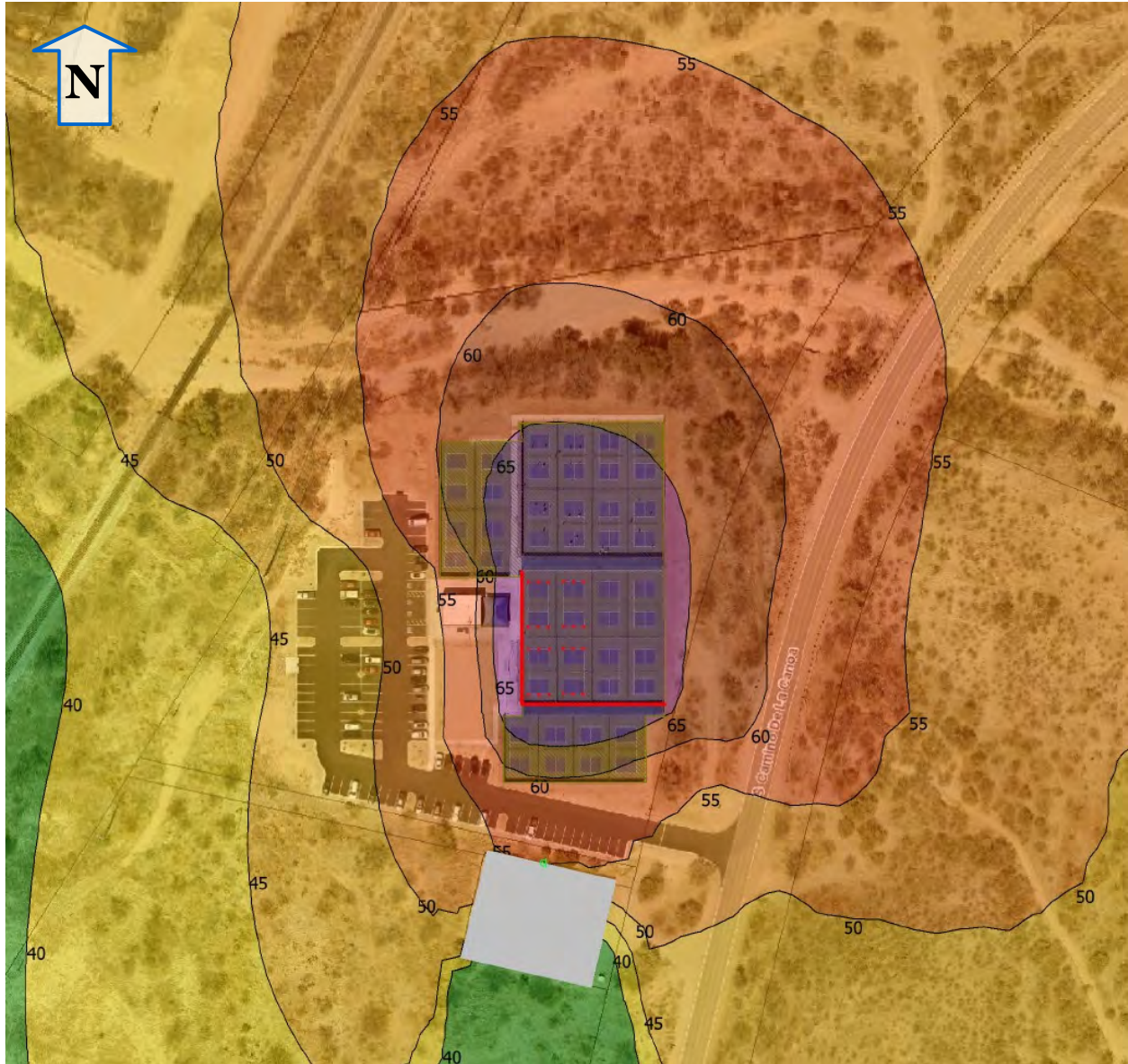


Figure 7.5. Adjusted Sound Pressure Level Contours, Four Courts, 10 Foot Wall, 15 Foot Elevation

7.3 Ground

7.3.1 Attenuation

Some amount of attenuation can occur for sound passing over porous ground. This will mostly include friable soil with vegetation growing on it. Hard surfaces like concrete and asphalt are reflective. Painted concrete surfaces like sports courts are very reflective.

This should be considered when placing a noise barrier on a particular ground type. The barrier will block the ground wave and remove the ground effect. This will affect the performance of the noise barrier. Blocking the ground wave over hard ground will enhance the insertion loss, the difference in before and after sound levels, of the barrier while blocking the ground wave over absorbing ground may cause the insertion loss of the barrier to be less than expected.

7.3.2 Refraction

Refraction caused by temperature gradients over certain ground can effectively cause sound to travel farther. Refraction is the bending of the path sound travels towards regions of lower sound speed, e.g. cooler air. This can be the result of temperature stratification of the atmosphere or wind. In low lying places where cool air tends to collect in the evenings or over irrigated ground where evaporative cooling can occur such as a golf course, a temperature lapse condition can develop with warm air above and cool air below. This will result in sound arcing down toward the ground. Refraction caused by a temperature lapse condition can result in sound arcing over obstacles on the ground that would normally impede its propagation thereby making it louder at farther distances.

7.3.3 Valleys

Parks located at the bottom of a valley can pose a particular challenge as they tend to experience temperature stratification conditions regularly. Further, the sides of the valley may trap sound and send it echoing back to locations on the opposite side. Valleys often require a detailed propagation study to understand how sound moves through the area at different times of the day.

7.3.4 Water

Bodies of water such as a pond or lake are a special type of ground that is highly reflective. It also tends to form a layer of cool air near its surface causing refraction effects similar to those described above. Sound propagation over water can be difficult to predict as its surface changes with wind and weather conditions. In calm conditions sound carries long distances over the surface of water. If a significant portion of the ground between a sound source and receiving property is water a detailed propagation study may be needed to determine the ground attenuation.

7.4 Reflective Surfaces

Surfaces that reflect sound that are close to the pickleball courts can redirect sound in undesirable directions. These surfaces can be building facades, retaining walls, or even noise barriers. Mass-loaded vinyl (MLV) fence covers are particularly reflective and may not be appropriate in some applications. Unpainted masonry walls retain some porosity and will absorb a small amount of sound, but should be considered reflective for the purposes of outdoor sound propagation.

Reflected sound from a single surface may increase the total sound pressure level as much as 3 dB over the level of the sound coming directly from the source. (Due to the short duration of the impulse produced by a paddle impact and its short wavelength it is difficult to get the reflected

sound to sum coherently with the direct sound) The positions of noise barriers must be planned strategically to prevent sound from going in unwanted directions and creating a new noise issue.

Parallel reflective surfaces can severely degrade the performance of a noise barrier. See Section 9.2.3 for more information on this design issue.

8. Noise Assessment Procedures for Pickleball Sound

8.1 Inaccuracies of Simple Averaging Techniques

8.1.1 Equivalent-continuous Sound Pressure Level

The equivalent-continuous level (L_{eq}) is a type of average sound pressure level over the entire period of a measurement. It represents a sound pressure level that has the same total energy as a measured sound pressure level that may vary over the time of the measurement.

While the equivalent-continuous sound pressure level includes all acoustical events and background noise that occur during the time of a measurement, including short impulsive events such as pickleball paddle impacts, it only gives an indication of the average level. It is not strongly influenced by peak sound pressure levels. For example, four pickleball courts may produce 50 to 60 paddle impacts each minute. That is one impact about every second. Equivalent-continuous averaging will therefore spread the energy of each paddle impact over a period of about one second. The result is that the paddle impacts will usually be indistinguishable from the background noise due to their very short duration. This, however, will not be what is reported by observers near the courts.

The main issue with using equivalent-continuous sound pressure level with pickleball is that it cannot be used to assess impulsive sound. This is the primary concern of neighbors living close to pickleball courts. A different metric that can account for the noise impact of the paddle impacts must be found.

8.1.2 Exponential Time Weighting

Sound level meters will typically have two smoothing filters called fast and slow time weighting having time constants of 0.125 and 1.0 second respectively. These are first order lowpass filters applied to the square of the sound pressure and are known as exponential time weighting. Some meters will also have an impulse peak hold filter with a 35 millisecond time constant on the rise of the sound pressure level and a slow 1.5 second decay to assist in reading the maximum level.

Fast exponential time weighting is often recommended for assessing impulsive sound. For highly impulsive sounds having short durations this metric does not work well. When the averaging time of the time weighting is longer than the duration of the impulse, the impulse is in the stopband of the lowpass filter. In other words, the time weighting is filtering out the impulsive sound source being measured. That is the purpose of a smoothing filter.

Figure 8.1 demonstrates the filter response to a burst of sound just long enough to achieve a reasonably accurate reading within 0.5 dB of the true sound pressure level. The red curve represents the envelop of a burst of sound 0.277 seconds in duration. This is the time required for

the output of the fast exponential time averaging filter (blue curve) to rise to within 0.5 dB of the actual sound pressure level of the sound burst. When the sound burst ends, the output of the exponential time averaging filter begins to decay. The peak value in the output of the fast exponential time averaging filter, after being converted to sound pressure level, is known as the L_{max} level.

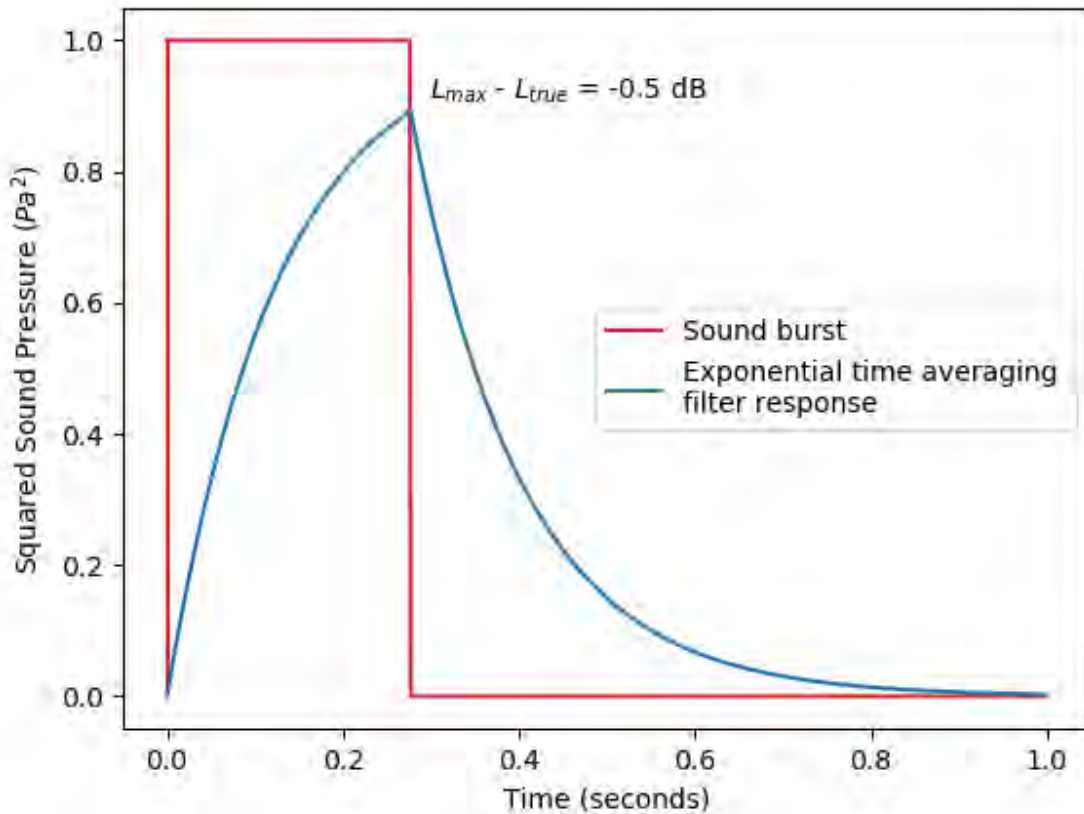


Figure 8.1. Fast Time Averaging Filter Response to a 0.277 Second Sound Burst

Figure 8.1 shows the behavior of the fast exponential time averaging filter and L_{max} when used properly. Figure 8.2 illustrates how the fast exponential time averaging filter responds to a typical pickleball paddle impact. Note that the time scale has been reduced for clarity. At the end of the 0.002 second impulse, the fast exponential time averaging filter has only had time to rise to a level that is 18 dB below the true sound pressure level of the impulse. The pickleball paddle impulse is so much shorter than the time constant of the averaging filter that the exponential

curvature of the filter response is not even visible. It is clear that fast exponential time weighting, much less slow exponential time weighting, cannot be used to assess the noise impact of pickleball paddle impacts.

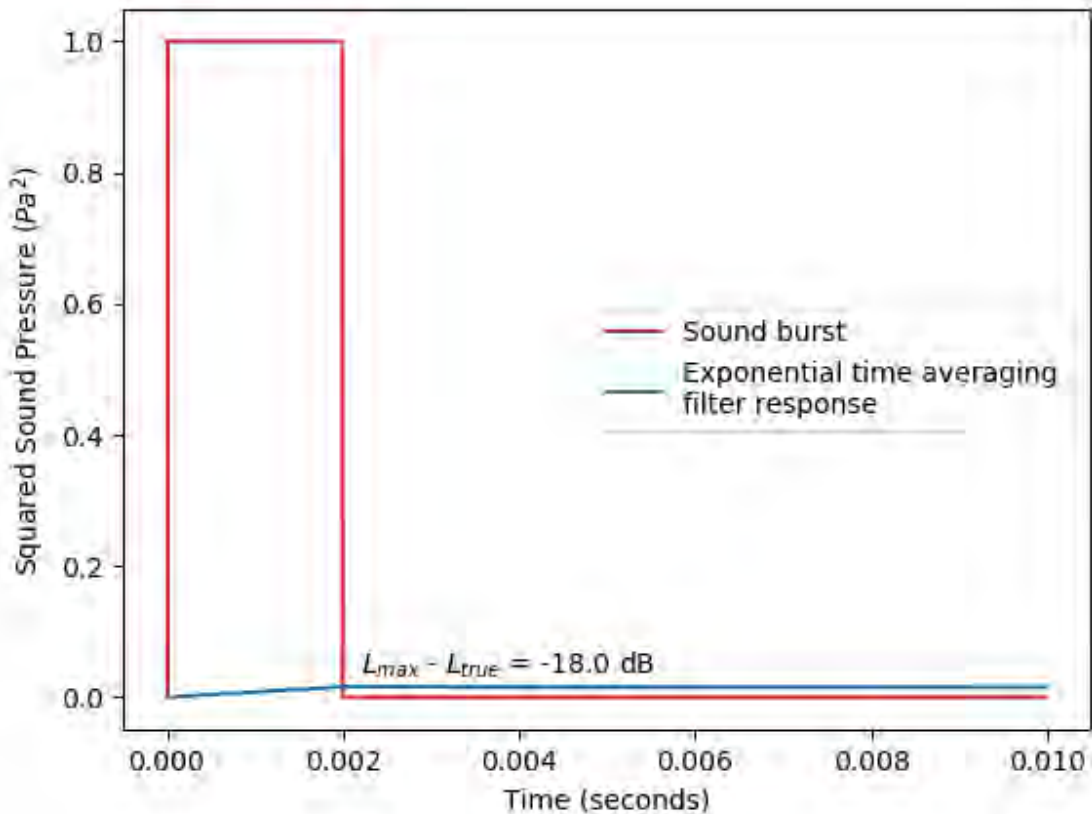


Figure 8.2. Fast Time Averaging Filter Response to a Typical Pickleball Paddle Impact

8.1.3 Percentile Sound Pressure Levels

Another common method of analyzing sound pressure level over time is to rank the levels by the percentage of time that a given level is exceeded. Percentile sound pressure level is described in Section 5.1.5. For impulsive sound, percentile levels suffer from the issues of both equivalent-continuous and exponential time weighted levels.

The majority of the energy in pickleball paddle impacts constitutes a very small percentage of the total measurement time. Even very low percentile levels like LA_{01} , the sound pressure level

exceeded 1% of the time, are little influenced. Further, percentile levels are usually calculated from the fast exponential time weighted level, a metric that already strongly attenuates the short duration impulses of the paddle impacts. Like the previous averaging methods, percentile sound pressure levels do not distinguish paddle impacts well from background noise and correlate poorly with the community response to this type of sound source.

8.2 Best Practices for Assessment of Impulsive Sound

Assessment of impulsive sound is multi-dimensional. In addition to loudness, other characteristics like onset rate, duration, and frequency range need to be considered as well to gauge the true noise impact. Due to the short duration of paddle impacts, averaging sound pressure level metrics such as equivalent-continuous level (LAeq), maximum fast exponential time weighted level (LAm_{ax}), and impulse time weighting (LAI) fail to accurately represent the perceived loudness and annoyance of the paddle impacts and impact processes in general. To get a better correlation with the actual response of the surrounding community to this type of sound metrics with a shorter time scale are needed.

The paddle impact sound pressure level is better represented by a combination of peak sound pressure level and sound exposure level (SEL). Using the sound exposure level involves windowing the measured sound pressure in time to include only the paddle impact and reflections from nearby surfaces as seen in Figure 6.1. The equivalent-continuous sound pressure level of the windowed impact is then normalized to the length of the window giving a representation of the energy in the impact alone. Appropriate adjustments for impulsive sounds can then be applied to the impacts as described next.

Most acoustical standards for sound pressure levels with regard to compatible land use provide adjustment factors for different types of sound, e.g. impulsive, tonal, time of day, etc. Each of these categories of sound produces different levels of community impact and annoyance due to their temporal or spectral characteristics in comparison to a broadband sound that does not vary in level or frequency content with time. The purpose of the adjustment factors is to normalize these types of sound to a neutral broadband sound pressure level so that they can be reasonably compared to a defined sound pressure level limit.

ANSI S12.9 Part 4 and ISO 1996 Part 1 give criteria for assigning adjustment factors to a variety of sound classifications. Sounds produced by impact processes are typically classified as ‘highly impulsive’ due to their high onset rates and intrusiveness and assigned a 12 dB adjustment. Experience has shown that pickleball paddle impacts should be adjusted as highly impulsive sounds in order to set appropriate performance goals for abatement treatments. Inadequate abatement treatment may lead to ongoing complaints, strained relations with neighbors, legal action, the need for continued involvement on the part of authorities, retrofitting, and possibly demolition costs to improve the abatement later.

8.3 Measurement Procedures for Highly Impulsive Sound

8.3.1 Measuring the Paddle Impacts

General procedures for conducting and reporting acoustical measurements have been covered in Chapter 5. For pickleball, the sound level meter should be set up to record continuous audio. This will be needed for assessing the impulses produced by the paddle impacts. The audio should be written to an uncompressed file format such as WAV with the following properties.

- Encoding: linear PCM WAV file format or other suitable lossless audio file format
- Sampling rate: 48 kHz (minimum)
- Resolution: 24 bit (minimum)

Audio recordings of the field calibration tone should be made as well and the Leq noted for future reference.

Logged data should be sampled at no more than one second intervals and include for each log interval,

- Peak sound pressure levels
 - LApk (A-weighted peak level)
 - LZpk (unweighted peak level)
- For speech assessment
 - LAm_{ax} (maximum A-weighted fast exponential time weighted level)
- For background level
 - LA_{eq} (A-weighted equivalent-continuous level)
 - LA_F (A-weighted fast exponential time weighted level)
 - LA_S (A-weighted slow exponential time weighted level)

8.3.2 Measuring Background Levels

Background noise level measurements should be made without pickleball activity at each measurement location. In practice it has been found that background levels should be performed either before or after the pickleball courts are in use so as not to disrupt the rhythm of play by starting and stopping or otherwise interfering with the use of the courts. For noise monitoring situations where the sound level meter is left to run all day it may be necessary to find a time in the recorded data where the pickleball courts were not being used in order to assess the background noise level at different times of day.

8.3.3 Data Analysis

Analysis of the measured data is performed on the sound exposure levels of the individual, A-weighted paddle impacts. A minimum of 30 paddle impacts should be obtained at each test location.

Sound Exposure Level

Some analysis and reporting software packages that work with a particular sound level meter may be able to do sound exposure analysis; however, they must be able to work on time scales less than one second. While the main part of the acoustical energy occurs within about a 10 millisecond window, later reflection and reverberation must also be included in the sound exposure window. The sound exposure should include all of the initial impulse and reverberant decay tail. See Sections 5.1.6 and 5.5.3 for more information on calculating sound exposure level.

Background Noise Correction

A background correction should be applied to each paddle impact. Since these are short impulses, only a small sample of the background noise immediately before, or if necessary after, the paddle impact is needed. This will give a more accurate correction in areas of high activity where the background noise level is fluctuating between paddle impacts. The procedure for background noise correction is explained in Section 5.3.2. It should be carried out on the equivalent-continuous level of the individual paddle impact, not on the sound exposure level directly. The background corrected equivalent-continuous level of the paddle impact is then converted to a sound exposure level for further analysis.

Adjusted Sound Pressure Level

There are two adjustments that will normally apply to pickleball paddle impacts, highly impulsive and day of week. The highly impulsive adjustment is 12 dB.

Noise assessment should be performed for the most impactful use case. A 5 dB adjust is therefore applied to account for the additional noise sensitivity during times when neighbors tend to be at home such as weekends and evenings.

This brings the total adjustment to 17 dB. The adjustment can be applied directly to the calculated sound exposure levels.

Now that the sound exposure levels have been adjusted, the adjusted sound pressure level can be calculated. This procedure is explained in Section 5.5.3. The adjusted sound pressure level can now be compared to applicable maximum permitted sound levels.

8.4 Noise Assessment of Spectator Speech

For larger crowds of people such as found at a tournament, ANSI S3.5 provides standard speech power levels for different vocal efforts. The loud vocal effort may be most appropriate for most events.

Sound pressure level measurements of spectators at a tournament would be a better estimate where possible. Differences in the number of spectators present during the measurement and the number expected at the proposed venue should be taken into account.

8.5 Site Simulation

An ISO 9613 or other suitable outdoor sound propagation standard can be used to calculate sound pressure levels at neighboring properties. Other more detailed environmental noise simulation methods exist and are also acceptable; however, ISO 9613 is simple and widely used with reasonable accuracy in most situations. There are many software packages available that implement this standard propagation model such as SoundPlan and iNoise.

8.5.1 Modeling Distributed Sound Sources

Figure 8.3 shows the dimensions of a pickleball court. Most paddle impacts occur between the baseline and no volley zone on each half of the court; however, serves are required to be made from behind the baseline.

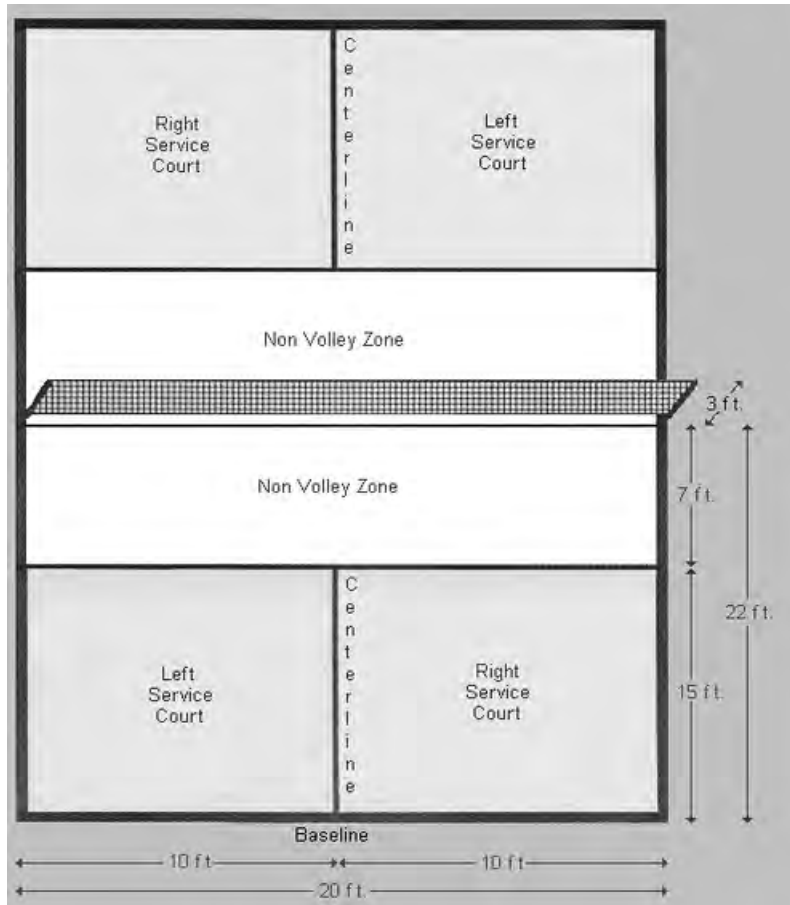


Figure 8.3. Pickleball Court Dimensions

Sound radiated from pickleball courts will not follow the inverse square law until the distance to the point of observation is large compared to the dimensions of the court or group of courts. The inverse square law states that sound radiated from a point source will decrease in level at a rate of 6 dB for every doubling in distance. As seen in Figure 8.4, this does not hold true for distributions of sound sources at close range. The figure compares two sound sources at the opposite baselines of a pickleball court to a single source approximation located at the center of the court. The vertical dashed green lines represent the edges of the concrete pad. The lower graph is the difference between the two curves in the graph above. The point of observation must be almost three court lengths before the level difference is within 0.5 dB.

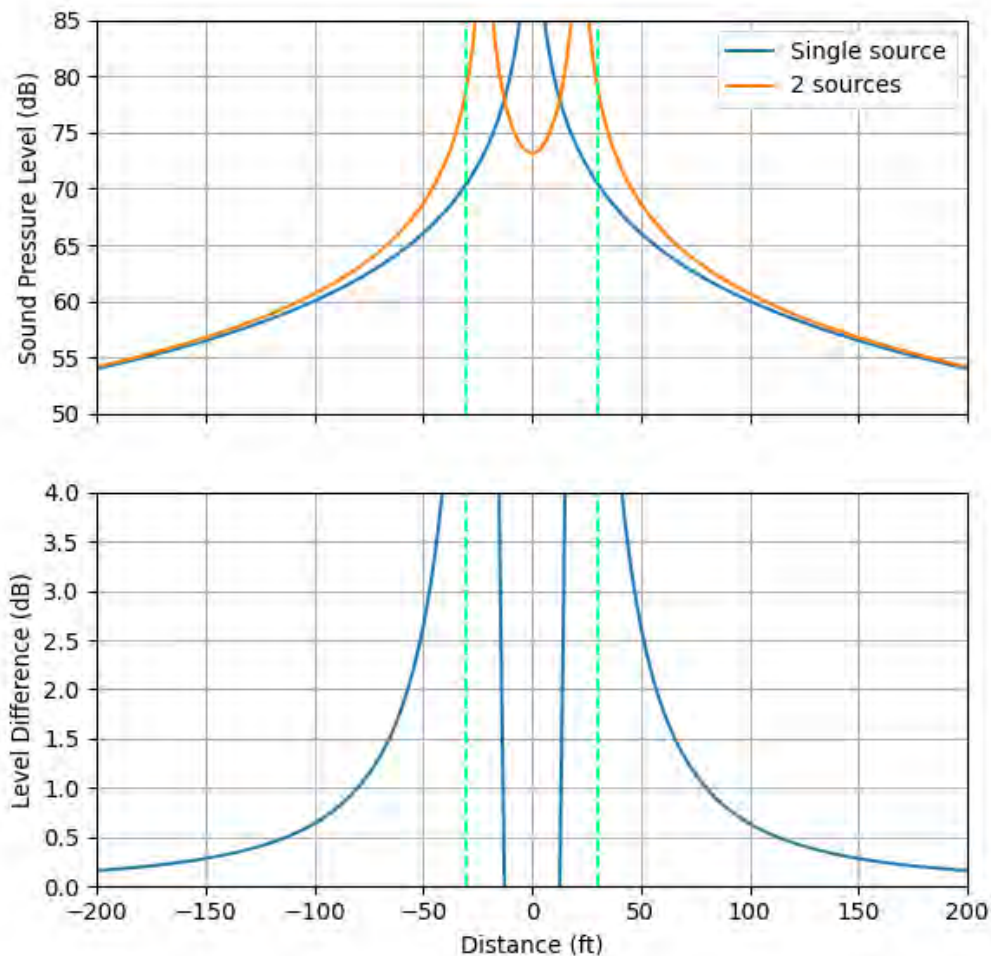


Figure 8.4. Sound Pressure Level at Distance from Court Center for One and Two Sources

For this reason, it is recommended to use multiple sound sources on each pickleball court when constructing an acoustical model of the courts. A vertical area source, i.e. a distribution of sound sources on a vertical plane located at the baseline at each end of each court extending the width of the baseline and from the playing surface to a height of 8 feet, is recommended. This arrangement is chosen for simplicity and to better ensure that the extents of noise barriers are not underestimated in the noise abatement planning stage.

8.5.2 Pickleball Court Directivity

As described in Section 6.4, pickleball courts have a directivity pattern that is bidirectional. Measurements at numerous pickleball courts have shown that the directivity pattern can be

approximated as shown in Table 8.1 or by using Eq. 8.1 where θ is the angle of the receiver with respect to the direction of play and D is the attenuation in decibels from the directivity.

$$D=20 \log_{10}(\sqrt{(\cos^2(\theta)+10^{(-5.5/10)} \sin^2(\theta))}) \quad (8.1)$$

Angle (deg)	Attenuation (dB)
0	0.0
10	-0.1
20	-0.4
30	-0.8
40	-1.4
50	-2.2
60	-3.1
70	-4.0
80	-4.7
90	-5.0
100	-4.7
110	-4.0
120	-3.1
130	-2.2
140	-1.4
150	-0.8
160	-0.4
170	-0.1
180	0.0

Table 8.1. Pickleball Court Directivity Pattern

9. Noise Abatement Methods

When a noise impact assessment indicates that activities planned for a site exceed the limits set in the noise regulations, a noise abatement plan to bring the site into compliance should be prepared by a qualified acoustical engineer.

9.1 Setbacks

A noise abatement plan begins with sufficient setback to noise sensitive areas to make abatement treatments effective. Any given noise abatement treatment will produce a limited amount insert loss or attenuation. A noise abatement plan for a site generally consists of a number of different treatments that work together to achieve an acceptable sound level in the surrounding area. Any deficit in the amount noise reduction achievable through mitigation treatments must be made up for in setback. In short, the setback is what makes the rest of the noise abatement plan possible.

One approach to setbacks is to simply prescribe a minimum setback with regard to all residential land uses. This has been done recently by Park City, Utah. Under their new pickleball code amendment [Park City], proposed pickleball courts within 600 feet of residential properties must have a noise abatement plan prepared. Pickleball courts within 150 feet of residential properties are not permitted.

This approach has the advantage of being easy to understand and apply; however, there are some situations where it may not be possible to create an effective noise abatement plan at 150 feet due to elevation differences or multi-story housing that make sufficient shielding by a sound wall impractical or impossible. In some special cases it may be possible to mitigate pickleball courts closer than 150 feet. Thus a 150 foot setback requirement would be overly restrictive in these applications.

Pickleball courts within 100 feet of residential land uses have proven to be problematic resulting in lawsuits, strict limitations on usage, and court closures. Courts within 150 feet of residential land uses require careful noise abatement planning using modern methods of noise assessment for highly impulsive sound such as ANSI S12.9 Part 4 described in previous chapters and strict adherence to design specifications.

9.2 Noise Barriers

9.2.1 Performance Requirements

Sound walls and fence covers are the main noise abatement treatments utilized for pickleball noise control. Sound walls are a more permanent and aesthetic solution while fence covers have lower material and installation costs. Both types of barriers can have reflective or sound absorbing surfaces.

There are a variety of materials and products available that are acceptable for pickleball mitigation. It is important that they meet a few minimum requirements.

Sound must not be able to penetrate through the barrier material. For pickleball, this means the barrier material must have a minimum sound transmission class (STC) of 20. This is not difficult to achieve with many solid materials that can include many options from mass-loaded vinyl (MLV) fence covers to masonry walls. Materials such as wind screens attached to court fencing and vegetation in the form of a hedges provide a level of visual privacy, but should not be considered noise abatement treatments.

In order to maintain the integrity of the barrier transmission loss, penetrations in the barrier surfaces cannot exceed 1% of the surface area. There can be no gaps between the bottom of the barrier and the ground or between barrier sections. Fence covers must be installed with the manufacturer's recommended amount of panel overlap.

9.2.2 Fence Cover Safety Notice

IMPORTANT

Standard chain link court fencing may not be rated for wind loading with a solid material attached. This can pose a danger of fence collapse in high winds. Many fence manufacturers produce reinforcement kits to stabilize fencing for this type of loading. It is important to consult with the fence manufacturer or a structural engineer prior to attaching MLV, sound blankets, or anything other solid material to an existing open link fence.

9.2.3 Parallel Surfaces

A common problem encountered when designing a noise barrier system for pickleball courts is the need to shield homes on opposite sides of the courts. Arranging reflective noise barriers so that they have parallel faces creates a situation where the sound is trapped between the interior surfaces and cannot dissipate. It has nowhere to go but over the noise barrier. This will significantly degrade its acoustical performance. If this layout cannot be avoided by changing the relative positions of the two walls, sound absorption will be needed on the interior surfaces to control acoustical energy buildup.

Figure 9.1 shows a performance comparison of several surface materials on opposite sides of two pickleball courts arranged end to end. Carsonite is a sound wall system with integrated sound absorption. It is commonly used for noise mitigation along roadways and absorbs well at 1,000 Hz, the critical frequency for pickleball paddle impacts. AudioSeal is an outdoor sound absorbing blanket material that can be attached to a fence. It does not absorb as well as the Carsonite at higher frequencies, but still performs adequately. The MLV curve is notably higher than the AudioSeal and Carsonite curves due to its high reflectivity at 1,000 Hz.

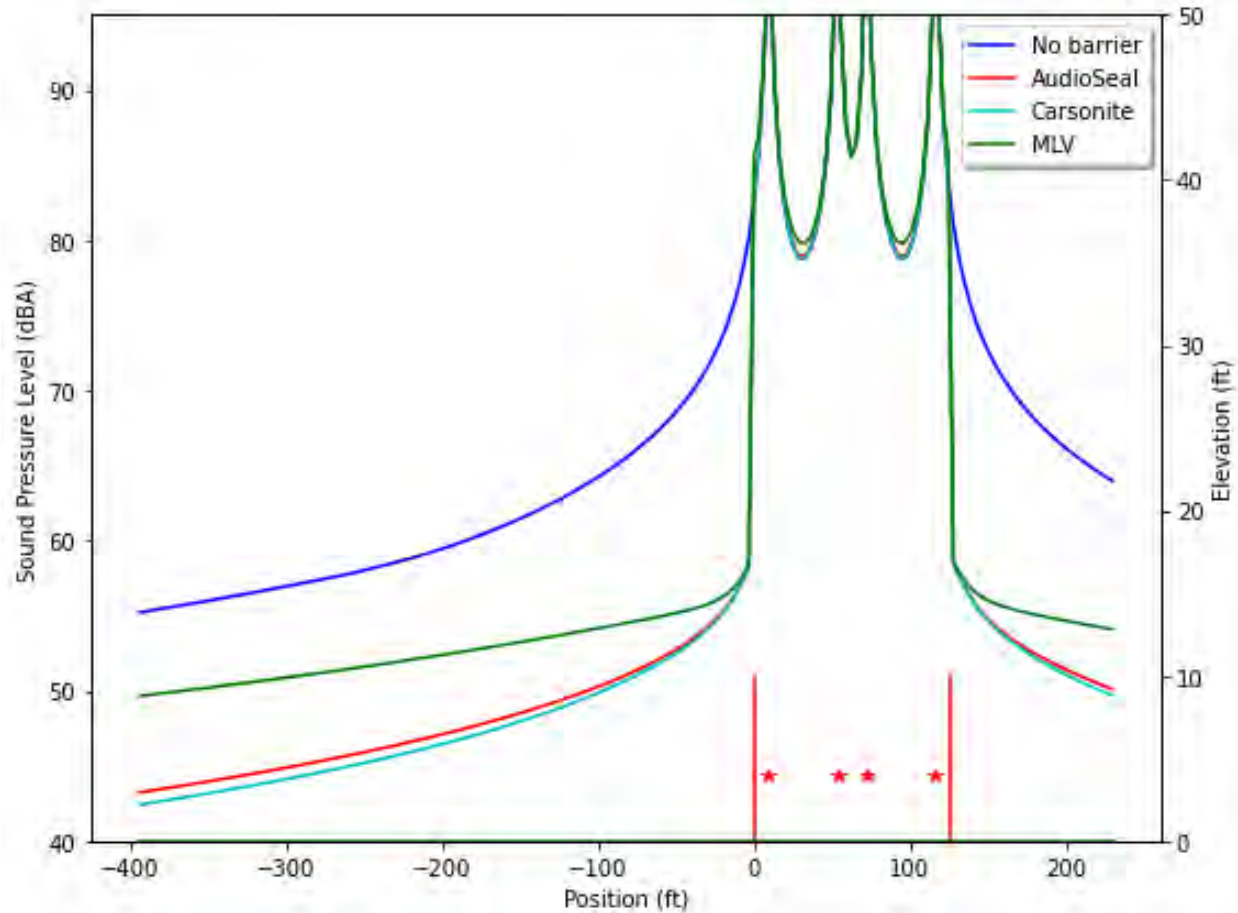


Figure 9.1. Performance Comparison of Interior Parallel Surfaces of Noise Barriers

It should also be noted that the slopes of the AudioSeal and Carsonite curves are almost identical to the slope of the curve for no noise barrier. The MLV curve has a notably shallower slope that trends toward the no barrier use case at distances farther from the noise barrier. This is the result of the large number of high amplitude image sources produced by reflective interior surfaces of the MLV.

Note: The ISO 9613 standard contains provisions for only one reflection. Acoustical simulation software implementing this standard will not calculate the case of parallel walls accurately. The above figure was created using multiple image sources and 40th order reflections for the MLV surfaces in order to get convergence on a solution.

9.2.4 Lowering Pickleball Courts

One approach to free standing sound walls is to lower the elevation of the pickleball courts by excavating the soil at the location of the courts and using it to create a berm next to the courts. While this can have some acoustical benefits in some situations, it is more of a cost saving design choice. By constructing the sound wall on top of the berm, a lower wall height will be

required and the wall will be less expensive to build.

9.2.5 Ventilation and Air Flow

In summer, pickleball courts, like any outdoor sport played on a hard court, can become hot. Sound walls and fence covers will impede the air flow over the courts and make the courts feel even warmer. It may be possible to alleviate this to a degree by using overlapping wall sections that allow some breeze to pass through. This usually requires an overlap of at least four times the width of the gap between the wall sections. Sound absorbing material may also be needed in the gap to control flutter reflections that allow sound from the pickleball courts to work its way through the overlap. There must be no line of sight to players on the courts possible through the gap. If necessary, add a wall extension to shield the outside opening of the overlap. This wall layout can also be used as a passageway for ingress and egress.



Figure 9.2. Sound Wall Overlap

9.3 Court Orientation

From the examples of pickleball court directivity in Section 7.1, it is apparent that the orientation of pickleball courts can be used as a noise mitigation measure. By turning the courts so that a noise sensitive area is to the side of the courts, sound levels in that direction can be reduced 3 to 5 dBA.

This may not be an ideal solution in some situations. It is preferable to have the direction of play roughly north-south to reduce glare from the sun during play. It is, however, worth the effort to take advantage of this characteristic of pickleball paddle radiation when it will not interfere with the use of the courts.

9.4 Sound Masking

9.4.1 Masking Requirements

Masking of a sound source refers to changing the threshold of hearing by introducing another

sound source such that the first sound source can no longer be heard. This is difficult to achieve with impulsive sounds because of their high peak sound pressure levels. Since impulsive sound is by nature intermittent and of limited duration, a masking source would have to operate continuously at a high amplitude in order to mask the impulse. This will often create a new noise issue.

Pickleball paddle impacts produce sound mostly in the 1,000 Hz octave band. The masking source must therefore also produce sufficient sound in the 1,000 Hz octave band to cover the sound of the paddle impacts.

9.4.2 Roadways

Roadways are a broadband, continuous sound source. In general, even busy highways are not able to mask pickleball courts due to the high peak sound pressures of the paddle impacts. Traffic noise tends to be mostly low to mid frequency sound and does not have sufficient energy in the 1,000 Hz octave band to effectively mask pickleball.

It appears to be a common perception that placing pickleball courts in neighborhoods located close to main arteries or interstates will prevent noise issues due to the sound from the roadway. In practice, this has not proven to be the case as seen at Glenhaven Park in La Cañada Flintridge, California [La Cañada Flintridge]. This neighborhood park is located adjacent to Interstate 210 on the north side of Los Angeles.

9.4.3 Fountains

There is some evidence that water fountains can be beneficial under certain conditions. As discussed above, a masking source must produce sufficient sound in the 1,000 Hz octave band and operate at all times in order to mask pickleball. Water falling on water can produce significant sound in the 1,000 Hz octave band.

Fountains located close to a noise sensitive area such as a back patio that is several hundred feet from pickleball courts may produce partial masking of paddle impacts from the courts. It may be possible to reduce this distance with a sound wall system at the pickleball courts.

For noise sensitive areas close to pickleball courts this is not likely to be an effective noise abatement treatment. Larger noise sensitive areas or larger numbers of homes will require multiple fountains in order to keep the distance from the fountains to the individual homes relatively small compared to the distance to the pickleball courts.

9.5 Full Enclosure of Pickleball Courts

For outdoor pickleball courts that cannot be mitigated because of insufficient available setback, topography, elevation features of the surrounding structures, or some other reason, the only remaining noise abatement option may be a full enclosure to contain the sound. Any penetrations in the building shell will need to be analyzed for sound leakage including doors, windows, ventilation, exhaust fans, etc. Vestibule doors may be necessary in some applications where ingress and egress face noise sensitive areas.

Indoor courts with bay doors opening away from noise sensitive areas can also work in some instances. In this use case, a room analysis of the reverberant field will need to be done and the amount of sound power exiting through the bay doors calculated from the direct and reverberant sound fields. Buildings can be much higher than free standing wall and provide a better performing noise barrier.

9.6 Noise Control Policy

9.6.1 Hours of Operation

Limiting the hours of operation of the pickleball courts to certain times of the day or days of the week can sometimes be an effective noise control strategy. These arrangements are often negotiated with neighbors.

9.6.2 Restrict Players Allowed to Use Courts

In some cases, restricting court usage to, for example, club members and their accompanied guests can increase accountability for how the courts are used. While this may also reduce the amount of players that use the courts, noise abatement planning should assume the courts will be used at full capacity.

9.6.3 Speech

A pickleball court properly mitigated for paddle impacts will generally not have noise issues related to the loudness of speech on the courts. Noise issues with speech are for the most part related to content rather than sound level. If this is the case, a prohibit on swearing and other offensive speech may be necessary.

9.6.4 Restrictions on Equipment

Quieter Equipment

In practice, the enforcement of the use of specific types of pickleball equipment, paddles and balls, has proven to be difficult to manage for home owners associations, country clubs, parks, and most other types of pickleball facility. In order for this to be considered a noise abatement measure, there must be a clear policy in place and personnel dedicated to monitoring activity on the courts to ensure unsanctioned equipment is not in use.

Paddles

There has been an effort in the pickleball paddle industry to move to quieter designs and most players are already using this “green list” equipment as it is referred to. Measurements by Spendiarian & Willis at a number of pickleball facilities have found that the mean sound exposure level of paddle impacts, when normalized to distance and ground type, is very consistent. This indicates that, in aggregate, most players are either using essentially the same equipment or that there is not a significant acoustical difference in the equipment used. During

testing where the make and model of the paddles in use have been recorded, it has been found that most players were using green list paddles. At the present time green list paddles should not be considered a noise control measure since most players are already using this equipment anyway.

Foam Balls

Measurements by Spendiarian & Willis comparing foam pickleballs to common regulation balls has shown that the foam balls can be 8 to 9 dB quieter than regulation balls. While the use of foam balls is an effective noise abatement measure, it is undesirable for pickleball players as the foam balls play very differently from the regulation balls and cannot be used in tournaments or to train for them.

10. Site Planning Considerations for Pickleball

10.1 When a Noise Impact Assessment Is Needed

Courts located within 350 feet of residential properties in most cases require noise abatement. Pickleball court sites within 500 to 600 feet of noise sensitive areas should be reviewed by a qualified acoustical engineer in the site selection phase of the project. In the case that the ground between the pickleball courts and receiving property is water this distance may extend 800 to 1,000 feet in some cases. Courts located within 150 feet of homes require careful and often extensive noise abatement design to avoid complaints. Placing open air pickleball courts within 100 feet of residential properties is not recommended.

10.2 Site Selection

10.2.1 Available Setbacks

The most important factor to consider in selecting a site for pickleball courts is the distance to adjacent residential land uses. While a noise barrier such as a sound wall or mass-loaded vinyl fence cover can be effective in reducing noise impact, it can only provide a limited amount of insertion loss, usually between 8 and 12 dB depending on the ground it is installed on, flanking paths, reflecting surfaces, and other factors. The rest of the noise reduction required to meet acceptable sound levels must mostly be gained through distance. It is important to ensure that there is enough buffer so that noise abatement installed can be adequately effective. Other site conditions that may increase the setback required are discussed in the following subsections.

10.2.2 Proximity to Multi-story Residential Structures

In order for a noise barrier to be effective it must be able to block the line of sight from the sound source to the receiving land use. Pickleball paddle impacts can occur from near the elevation of the playing surface to a height of about 8 feet above it. Multi-story housing located close to the proposed pickleball courts may not be adequately shielded a wall system. This can affect upper level windows, balconies, raised decks, other amenities located above ground level. These need to be included in the noise impact assessment of the proposed pickleball courts.

10.2.3 Topography

Similar to housing with floors above ground level, homes sitting at an elevation higher than the proposed pickleball courts can also be difficult to shield with a noise barrier.

In addition, refraction caused by temperature gradients over certain ground can effectively cause sound to travel farther. Refraction is the bending of the path sound travels towards regions of

lower sound speed, e.g cooler air. This can be the result of temperature stratification of the atmosphere or wind. In low lying places where cool air tends to collect in the evenings or over irrigated ground where evaporative cooling can occur such as a golf course, a temperature lapse condition can develop with warm air above and cool air below. This will result in sound arcing down toward the ground. Refraction caused by a temperature lapse condition can result in sound arcing over obstacles on the ground that would normally impede its propagation thereby making it louder at farther distances.

Parks located at the bottom of a valley can pose a particular challenge as they tend to experience these conditions regularly. Further, the sides of the valley may trap sound and send it echoing back to locations on the opposite side. Valleys often require a detailed propagation study to understand how sound moves through the area at different times of the day.

10.3 Tournaments

The main difference in sound from pickleball courts during tournaments will be spectators. The noise assessment and abatement planning should include a speech analysis based on the number and location of spectators. This has been described in Section 8.4.

If a PA system is to be used for announcements, limits on the system gain should be established to ensure sound levels reaching the surrounding properties remain acceptable. Noise monitoring may also be employed at the property boundaries. This involves placing one or more microphones near noise sensitive areas so that the sound system operator can monitor sound levels in real time and make any necessary adjustments.

11. Conclusions

11.1 Best Practices in Noise Assessment and Regulation

Basic methodologies and best practices for community noise assessment, environmental acoustics measurements, and noise regulation documents have been discussed. The group of ANSI standards in S12.9 represents the current best practices in community noise assessment. The measurement methodology and sound classifications in Part 4 of the standard (harmonized with International Organization for Standardization standard ISO 1996) have been implemented under European Union Directive 2002/49 and in a number of Asian countries. ANSI S12.9 Parts 4 and 5 have been used as the basis for the recommendations in this document.

11.2 Characteristics of Pickleball Sound

The most notable sounds from pickleball courts are the popping sound produced when a pickleball contacts a paddle and speech. It is the popping sound of the paddle impacts that produces the greatest number of noise complaints. This sound has been classified as highly impulsive for the purpose of noise assessment under ANSI S12.9 Part 4.

11.3 Noise Impact Assessment of Pickleball

It has been shown that averaging techniques such as equivalent-continuous and maximum fast exponential time weighted sound pressure levels (LAeq and LAmax) are not well suited for assessment of short duration impulsive sound like that produced by the impact of a pickleball on a paddle. These metrics can be expected to substantially underestimate the community response to this type of sound. Measurement procedures based on the adjusted sound exposure level according to ANSI S12.9 Part 4 have been described as a more accurate methodology for noise impact assessment of pickleball.

11.4 Noise Abatement Planning

Setbacks are an important first step in mitigating pickleball courts. A noise abatement plan usually consists of a number of treatments that each contribute a certain amount of noise reduction. Any difference between the total noise reduction of the abatement treatments and that required to meet target sound levels must be made for with setbacks.

Topography and multistory structures near the courts will also influence the amount of setback required. In order for a noise barrier to be effective it must block the line of sight from the sound source to the point of observation. Upper level bedroom windows and decks that are able to overlook the noise barrier will not be shielded and will likely experience a greater noise impact than at ground level.

Testing at numerous pickleball courts has found that the sound radiated from the paddles is directional. More sound goes in the direction of play than to the sides of the court. This characteristic can be used as a noise abatement measure by orienting pickleball courts so that the direction of play is not directed toward noise sensitive areas.

Sound masking in the form of water fountains has been found to be somewhat helpful in certain situations. This is mainly where the masking sound source is much closer to the noise sensitive area than the pickleball courts and the noise sensitive area is not too close to the pickleball courts. Roadways have not been found to be effective masking sources for pickleball.

In most cases, the noise abatement installed for the paddle impacts will be sufficient for speech from the courts as well. Noise complaints about speech on pickleball courts are most often related to content rather than sound level. This is best addressed through policy.

11.5 Site Planning

Site review and feasibility analysis for pickleball begins by looking at available setbacks and sight lines. This will determine what noise abatement treatments may be needed and whether they can be effective on a particular site. Topography and the presence of nearby multistory housing are also important considerations that may affect required setbacks. The noise impact assessment of impulsive sound is a complex task that should be done using modern standards and best practices by an acoustical engineer with experience in psychological acoustics and signal analysis.

References

ANSI S1.4-1983, *Specification for Sound Level Meters*, American National Standards Institute, 1983.

ANSI S1.4-2014, *Electroacoustics – Sound Level Meters – Part 1: Specifications*, American National Standards Institute, 2014.

ANSI S1.11-2004, *Specification For Octave-Band and Fractional-Octave-Band Analog and Digital Filters*, American National Standards Institute, 2004.

ANSI S1.13-2005, *Measurement of Sound Pressure Levels in Air*, American National Standards Institute, 2005.

ANSI S1.42-2001, *Design Response Of Weighting Networks For Acoustical Measurements*, American National Standards Institute, 2001.

ANSI S1.43-1997, *Specifications For Integrating-Averaging Sound Level Meters*, American National Standards Institute, 1997.

ANSI S3.5-1997, *Methods of Calculation of the Speech Intelligibility Index*, American National Standards Institute, 1997.

ANSI S12.9-2013, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 3: Short-term Measurements with an Observer Present*, American National Standards Institute, 2013.

ANSI S12.9-2021, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long Term Community Response*, American National Standards Institute, 2021.

ANSI S12.9-2007, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 5: Sound Level Descriptors for Determination of Compatible Land Use*, American National Standards Institute, 2007.

ANSI S12.62-2012, *Attenuation of sound during propagation outdoors – Part 2: General method of calculation*, Nationally Adopted International Standards, Acoustical Society of America (ASA), 2012.

Buchta, Edmund, "A field survey on annoyance caused by sounds from small firearms," *Journal of the Acoustical Society of America*, vol. 88 (3), September 1990. p. 1459.

City of La Cañada Flintridge, "Pickleball Program at Glenhaven Park to End October 28," <<https://cityoflcf.org/pickleball-program-at-glenhaven-park-to-end-october-28/>>, October 27th, 2022.

Dittrich, Kerstin and Oberfeld, Daniel, "A comparison of the temporal weighting of annoyance

and loudness," *Journal of the Acoustical Society of America*, vol. 126 (6), December 2009. p. 3168.

Harris, Cyril M. (Ed.), *Handbook of Acoustical Measurements and Noise Control, 3rd Edition*, Acoustical Society of America, 1998.

ISO 226-2003, *Acoustics - Normal equal-loudness-level contours*, International Organization for Standardization (ISO), 2003.

ISO 1996-1, *Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures*, International Organization for Standardization (ISO), 2016.

ISO 9613 Part 2, *Acoustics - Attenuation of Sound During Propagation Outdoors - Part 2: General Method of Calculation*, International Organization for Standardization (ISO), 1996.

Park Cty, Utah, Municipal Code 15-4-22 Outdoor Pickleball Courts In Residential Areas. Adopted April, 2022.

Schultz, T. J., "Synthesis of Social Surveys on Noise Annoyance," *Journal of the Acoustical Society of America* v. 64, pp. 377-405, 1978.

Smoorenburg, G. F., Vos, J., "Rating of impulse noise, in particular shooting noise, with regard to annoyance," *Journal of the Acoustical Society of America*, suppl 1, vol. 73, Spring 1983. p. S48.

Vos, Joos, "On the annoyance caused by impulse sounds produced by small, medium-large, and large firearms," *Journal of the Acoustical Society of America*, vol. 109 (1), January 2001. p. 244-253.

Vos, Joos and Houben, Mark M. J., "Enhanced awakening probability of repetitive impulse sounds," *Journal of the Acoustical Society of America*, vol. 134 (3), September 2013. p. 2011.

Vos, Joos and Smoorenburg, Guido F., "Penalty for impulse noise, derived from annoyance for impulse and road-traffic sounds," *Journal of the Acoustical Society of America*, vol. 77 (1), January 1985. p. 193.

World Health Organization (WHO), *Night Noise Guidelines for Europe*, <http://www.euro.who.int>, 2009.

Zwicker, E. and Fastl, H., *Psychoacoustics Facts and Models, 2nd Edition*, Springer, 1999.

NEWS RELEASE 17-MAY-2024

Pickleball courts in a legal pickle #ASA186

When advising on the noise associated with pickleball, loudness is just one of many concerns, and solutions require infrastructure or limitations on play.

Reports and Proceedings

ACOUSTICAL SOCIETY OF AMERICA

OTTAWA, Ontario, May 17, 2024 – Pickleball Legal Consultant is a job title that likely did not exist a decade ago, but as pickleball courts infiltrate neighborhoods to satiate an appetite for a sport whose namesake is a snack, communities take issue with the resulting influx of noise. Now homeowners' associations and city councils face litigation by those whose lives are disrupted by pickleball's din.

Charles Leahy, an attorney, retired mechanical engineer, and former HOA board member became interested in this issue after his HOA dismissed the recommendations of noise consultants and failed to install noise absorbing barriers. Litigation over noise nuisance ensued and threatens closure of the courts.

Leahy sought to understand how acoustic engineers assess the noise, how they fashion their recommendations, and what best practices engineers can employ to persuade the community that the noise is real and needs to be mitigated.

He will present his work Friday, May 17, at 8:35 a.m. EDT in a session dedicated to pickleball as part of a joint meeting of the Acoustical Society of America and the Canadian Acoustical Association, running May 13-17 at the Shaw Centre located in downtown Ottawa, Ontario, Canada.

“Compared to tennis, pickleball is a much smaller court, easier to learn, and especially accessible to seniors,” said Leahy. “Each tennis court can become up to four pickleball courts. Tennis involves a soft and compressible ball and a racket with strings. Pickleball is a hard plastic ball and a hard paddle. Tennis produces a ‘thunk’ sound versus pickleball ‘pop,’ which is louder, sharper, more piercing, and more frequent. Thus, more annoying.”

Communities looking to invest in – and those facing lawsuits because of – the courts often seek out engineering consultants to advise them. Leahy examined over 70 pickleball consultant noise reports and compared their recommendations with the American National Standard Institute. He found many reports



IMAGE:

EXPERTS RECOMMEND HOAS AND COMMUNITIES CONSIDER THE “POPPING” NOISE ASSOCIATED WITH PICKLEBALL WHEN DECIDING TO BUILD COURTS NEAR HOMES.

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considered only the decibels associated with the noise, but other factors are important too.

"It's not just the loudness, it's the impulsive sharpness and randomness of the 'pops,'" said Leahy. "It's the persistence and repetition of the random noises over many hours a day, usually seven days a week."

His best recommendation is to build courts far from homes, at least 600-800 feet away to allow the sound to naturally dissipate. Less desirable (or more difficult or costly) solutions include enclosing the courts within a building or wall barriers or using less noisy paddles and balls.

"Pickleball has a highly impulsive noise, with each court generating about 900 pop noises per hour," said Leahy. "It's incompatible with residential living. Cities can also locate pickleball in industrial and commercial neighborhoods rather than close to homes."

"The benefits of pickleball to the players are undeniable, and the demand for more pickleball courts is real and genuine. However, there needs to be more research, more planning and prevention, and more effort to avoid ending up in front of the judge and jury."

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A survey of the community impact of pickleball noise: A pilot study

Kathleen M. Romito  ; Jamie Banks



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**A survey of the community impact of pickleball noise: A
pilot study**

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As pickleball grows in popularity, pickleball noise in residential settings is increasingly recognized as a potential acoustic intrusion and health hazard to neighbors. Current recommendations for appropriate mitigation are currently based on expert opinion from sound professionals and industry leaders. While expert recommendations have provided valuable guidance, a lack of publicly accessible data—particularly from those living near the courts—can present a challenge for local decision makers, who must balance the harm resulting from pickleball noise with the interests of a growing player base. This study aims to help fill that gap through a survey of residents living within 1000 feet of public, club-operated or homeowners association (HOA)-managed pickleball courts. Survey questions gathered data on the number of courts, exposure duration across time, sound levels, the existence of mitigation means, and the respondents' current levels of annoyance, disturbance, and/or other harms. This research on the lived experience of communities is essential to evidence-based decision making that protects the health and well-being of the neighboring residents while also providing the desired access to pickleball recreation.

1. INTRODUCTION

Pickleball is an increasingly popular racquet sport played with hard paddles and plastic balls that produce loud “pops.” These repetitive impulse sounds introduce a new and distinctive source of unwanted and potentially harmful noise in residential environments, exposing residents living near busy courts to thousands of sharp “pops” each day. An audio recording of the noise from 4 pickleball courts can be heard at <https://doi.org/10.5281/zenodo.15566001> (1).

In 2024, 18,455 new courts were built in an estimated 4,000 new locations (2). As new courts are constructed, pickleball noise is disrupting the soundscape in residential areas, leading to conflicts and complaints. One Google Map identifies more than 500 pickleball noise hotspots across North America (3). The issue has been covered in hundreds of news reports, generated countless social media posts, and led to approximately 200 legal claims in the United States (4).

Although local decision makers and acoustic professionals responsible for decisions regarding court locations usually understand the health and social benefits of pickleball recreation, they are less likely to be familiar with the potential harm to residential neighbors who are chronically exposed to pickleball noise. A previous content analysis of self-reported health concerns linked to pickleball noise found significant issues amongst residents exposed to chronic pickleball noise, including trauma-like symptoms, phantom sounds (pops), and severe psychological distress (5).

This pilot study aims to better understand the impacts of pickleball noise on the lives and health of community members who are exposed and to inform guidelines for court locations and noise mitigation strategies.

2. METHODS

A. SURVEY DEVELOPMENT

An eighteen-question online questionnaire was developed using Survey Monkey (SurveyMonkey Inc, San Mateo, CA; www.surveymonkey.com). The survey questions were drafted based on scientific literature on the effects of noise and on impacts reported by affected community members. The draft survey underwent face validation with a focus group, was revised accordingly, and submitted to an ethics committee for approval.

The first ten questions focused on the respondent’s zip code location and details of the physical arrangement of the courts located nearby, including geographic features and existing noise mitigation measures. Participants were instructed to estimate the distance between their residence and the courts using Google Earth or by pacing the distance, with each step approximating three feet. The remaining eight questions addressed the nature and severity of the impacts experienced, as well as respondents’ concerns about their noise exposure. Free text comments were permitted in Questions 3, 6, 7, and 10-18 without restrictions on the number of comments. Open-ended responses for questions 11 & 12 were analyzed using thematic analysis. Responses were coded, grouped into categories, and synthesized into higher-order themes reflecting common experiences and perspectives. No demographic information was requested from respondents.

B. SURVEY SAMPLE AND DISTRIBUTION

The survey was open for three weeks in September–October 2025. The survey was directed at individuals who currently live, formerly lived, or anticipate living within 1000 feet of pickleball courts. “Exposed” individuals are defined as those respondents who currently live or have lived near courts and who hear or have heard chronic pickleball noise. Respondents were instructed to submit one survey only. Duplicate responses from the same device were not allowed and IP addresses were scanned for multiple responses.

To recruit neighbors with both ongoing concerns as well as successfully resolved concerns, two acoustic firms that regularly address pickleball noise were invited to share the survey with past clients. Four community advocates were invited to distribute the survey link to community members who had previously reached out to them regarding pickleball noise. The survey was also posted on two Facebook groups: Pickleball Noise Relief (focused on affected neighbors) and Pickleball Sound Mitigation (administered by an acoustic firm, focused on finding technical solutions). The author also posted messages in each group soliciting successful noise mitigation experiences.

C. ANALYSIS

For this paper, survey responses were analyzed using descriptive statistics only. A detailed statistical analysis is underway to determine the contribution of co-variates, such as distance from courts and duration of noise exposure, on the impacts of pickleball noise on the lives and health of the surrounding residents.

3. RESULTS

A. SURVEY RESULTS

Within the three-week open survey period, 440 responses were received from 264 communities, 229 of which were from the United States, evenly distributed across the North, South, East, and West. In four zip codes, there were two distinct locations (i.e., sets of courts) where noise concerns occurred. International responses came from 29 postal codes in Canada, and from one postal code each in Australia and New Zealand.

Three hundred eighty-six of the 440 surveys received were from community members who were exposed to pickleball noise in their neighborhood, either presently or in the past. Thirty-three of the survey participants reported that courts were planned nearby, 11 reported they had never lived near existing or planned courts, and 10 declined to state whether they had lived near courts (Question 2). Overall, 87.7% of respondents met the study’s definition of “exposed” individuals. Fifteen submissions were received from respondents living more than 1000 feet from courts and their responses are included in the results.

Results from exposed respondents were analyzed and described in the following tables: the physical characteristics of courts (Tables 1–2), amount of exposure (Table 3), acoustic and non-acoustic factors affecting the experience of the sound (Table 4), annoyance (Tables 5, 6, 7), interference with daily activities (Figures 1–5), consideration of moving (Figure 6), and health concerns (Figure 7). The remainder of the questions were analyzed using all community responses.

The physical characteristics of the neighborhood courts are shown in Table 1 and the presence of noise mitigation currently in place is shown in Table 2.

Table 1. Characteristics of pickleball courts

Q3. Type of courts (n=365)		Q4. # of courts (n=383)		Q5. Setback distance (n =385)		Q6. Geography (n=302)	
Public	220 (60.3%)	1	23 (6.0%)	<100 ft	167 (43.4%)	Home above courts	139 (46.0%)
HOA*	92 (24.9%)	2-4	229 (59.8%)	100-300 ft	119 (30.9%)	Body of water	15 (5.0%)
Private/Club	33 (9.0%)	4-8	92 (24.0%)	300-500 ft	46 (11.9%)	Geography focuses noise	65 (21.5%)
Neighbor	21 (5.8%)	>8	39 (10.2%)	500-1000 ft	38 (9.9%)	None	114 (37.5%)
				>1000 ft	15 (3.9%)		

*Homeowner Association

Table 2. Existing noise mitigation (n=374)

Thick vinyl sound barriers	57 (15.2%)	Mesh netting	70 (18.7%)
Limited hours, recommended	66 (17.7%)	Limited hours, enforced	31 (8.3%)
Quiet paddles, recommended	54 (14.4%)	Quiet paddles, enforced	5 (1.3%)
Quiet balls, recommended	45 (12.0%)	Quiet balls, enforced	6 (1.6%)
No mitigation in place	172 (46.0%)		

*Multiple responses allowed

Qs. 8, 9. What is the duration of exposure to pickleball noise? While some courts are used only occasionally, many public courts—due to pickleball’s popularity—are in near-constant use from daybreak to sunset. The addition of lights, in some situations, can extend the hours of play into the late-night hours. Pickleball is a relatively new sport and most respondents have less than 5 years of exposure to the noise. See Table 3.

Table 3. Exposure to pickleball noise

Hours per week, courts open (n=379)	Responses (%)	Years of exposure (n=382)	Responses (%)
<30 hours per week	32 (8.4%)	< 1 year	41 (10.9%)
30-50 hours per week	50 (13.2%)	1-3 years	162 (43.1%)
50-70 hours per week	76 (20.1%)	3-5 years	119 (31.6%)
>70 hours per week	221 (58.3%)	>5 years	54 (14.4%)

Q10. Which of the following can be used to describe your experience with pickleball noise? While 2/3 of respondents described the noise as loud, almost 90% described the noise as repetitive pops or clicks. Almost 3/4 of participants reported being able to hear the noise inside their home or office and almost 2/3 reported being exposed to nighttime pickleball noise. Nearly half of all residents reported experiencing harassment from pickleball players after raising concerns about the noise. Several respondents further described incidents involving “assault,” “threats,” or “being accosted,” and at least three indicated that police involvement was required.

Table 4: Acoustic and non-acoustic factors affecting residents’ experience of the sound (n=384)

Acoustic Factors: How Residents Describe the Sound	Responses (%)	Non-Acoustic Factors: How Residents Experience the Sound	Responses (%)
Repetitive (e.g., pops, clicks)	377 (88.1%)	Noise heard inside home or office	316 (73.6%)
Chronic	286 (66.8%)	Being ignored by decision makers	280 (65.4%)
Loud	282 (65.9%)	Courts visible from home	275 (64.3%)
Unpredictable	254 (59.4%)	Noise during the night, 6 pm-8 am	274 (64.0%)
Intermittent	189 (44.2%)	Harassment from pickleball players	203 (47.4%)

*Multiple responses allowed

Q11. Does the word “annoyance” adequately describe your experience of pickleball noise? (n=358)

While the term “annoyance” is used by acousticians to define a sound problem that requires a remedy, lay people, including local decision makers, more often use the term to describe an irritant, without the implied need to remedy the situation. More than half of respondents reported “no” when asked if the word “annoyance” was adequate to describe their experience. Of the twenty-eight (7.5%) respondents who skipped the “yes/no” question, 26 left comments describing their experience as more than an annoyance using phrases such as “tortuous”, “unbearable”, and the “popping sound triggers PTSD from the military”. Their responses are included as “no” in the table below. See Appendix, Table A1.

Table 5. The word “annoyance” adequately explains the experience of pickleball noise (n=386)

The word “annoyance” adequately explains the experience	Respondents (%)
Yes	157 (40.7%)
No	229 (59.3%)

A total of 206 respondents provided an open comment to the question about the adequacy of the term “annoyance,” with nearly 2/3 of them communicating severe psychological or emotional distress, mirroring the 26 comments from those who did not answer the structured question. See Appendix, Table A2.

Q12. How often does the issue of pickleball noise interfere with your ability to do the following activities? Most respondents reported that pickleball noise either often or constantly interferes with the ability to be mindful, enjoy their home, communicate at home, or work productively (Fig 1-4). Almost half report it often or constantly interferes with sleep (Fig. 5)

How often does the noise affect your ability to:

Fig.1 Be mindful, rest, be calm or think (n=377)

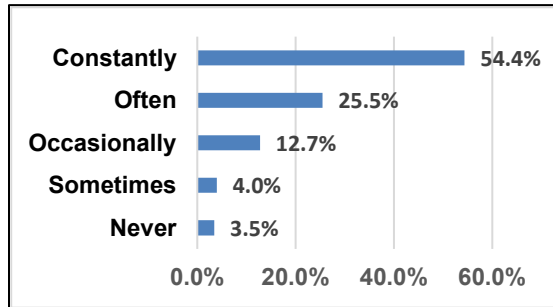


Fig.2 Enjoy indoors/outdoors at home (n=374)

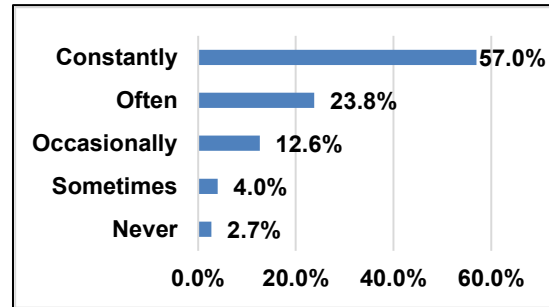


Fig.3 Talk, socialize, do activities at home (n=368)

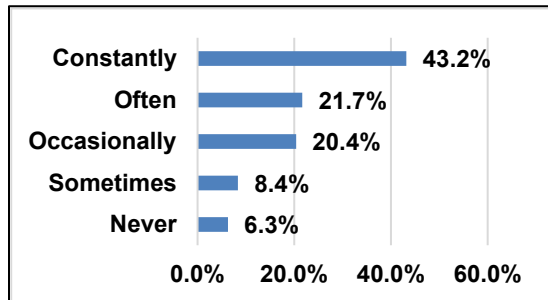


Fig.4 Concentrate or work productively (n=364)

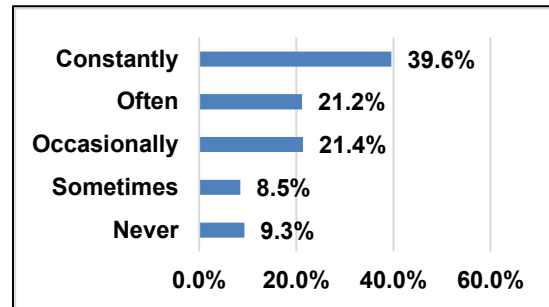
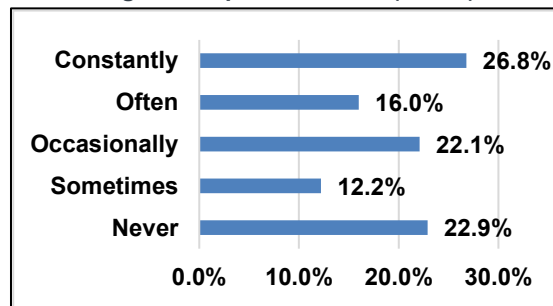


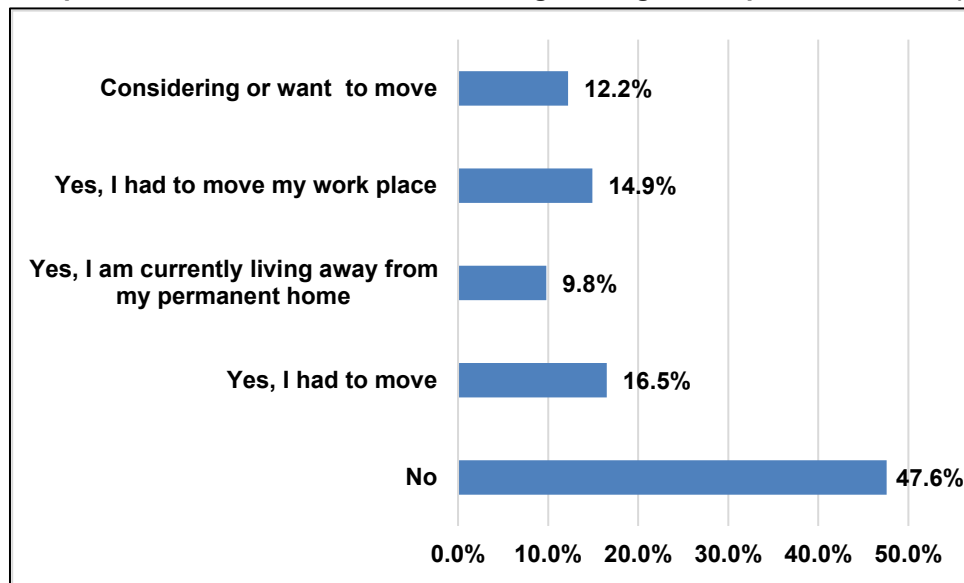
Fig.5 Sleep undisturbed (n=362)



Open ended comments from 84 respondents further describe disruption of rest, well-being, and quality of life among those exposed to pickleball noise. See Appendix, Table A3.

Q 13 Have you had to significantly modify your life because of pickleball noise? 226 of 386 participants responded to the given response options. Of the remaining 160 (41.5%), 31 provided open-ended comments that expressed a desire to move with some unable to and others considering or preparing to move. These responses are included in the results below. More than half of the respondents reported either having to move or wanting to move. See Figure 6.

Fig 6. Proportion who moved or are considering moving due to pickleball noise (n=257)



Q14. What feelings best describe your response to pickleball noise? Almost all respondents reported at least one type of negative emotional response to pickleball noise. Frustration, feeling anxious/agitated, stress, and feelings of powerlessness were all reported by more than 2/3 of respondents. See Table 6.

Table 6. Emotional responses to pickleball noise (n=418)

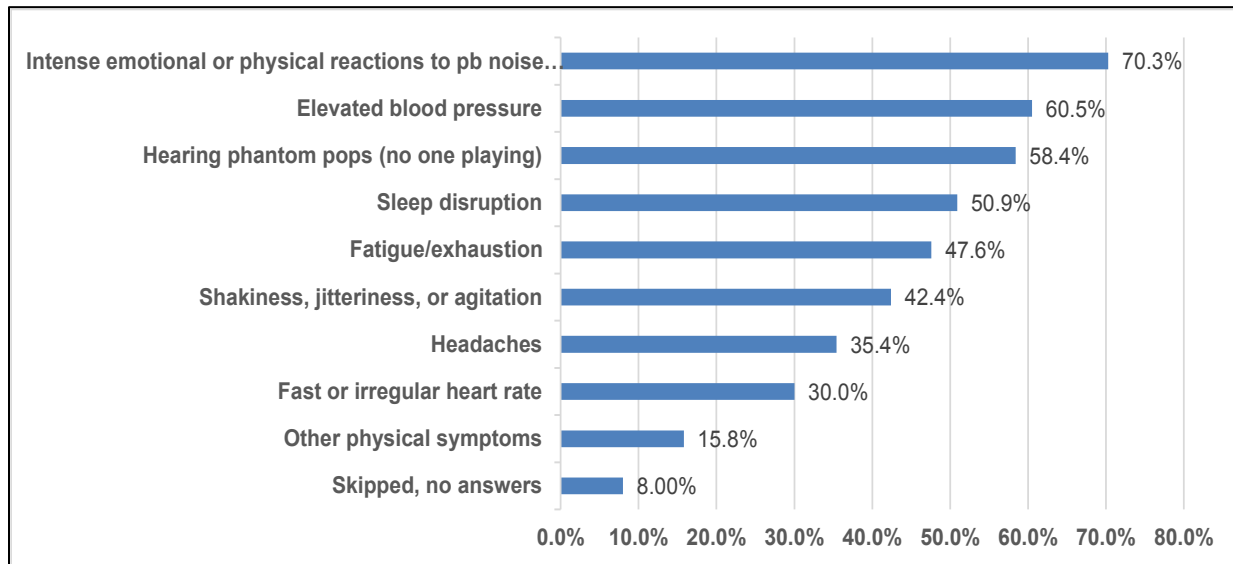
Feelings	Responses (%)
Frustration	343 (82.1%)
Stress	312 (74.6%)
Feeling of Powerlessness	302 (72.3%)
Anxious/Agitated	302 (72.3%)
Anger/Rage	269 (64.4%)
Resentment	265 (63.4%)
Hopeless	186 (44.5%)
Depressed	151 (36.1%)
Fear	75 (17.9%)
No strong feelings	19 (4.6%)

*Multiple responses allowed

65 respondents left additional comments, reflecting the above themes. One commenter reported “feeling suicidal” and another was so enraged they thought they would “end up in prison due to violence”. Many reported trauma-like responses using descriptive terms such as “trauma”, “torture”, and “PTSD.” One respondent commented, “It honestly made my PTSD from my military service much worse. The constant high pitch in a random and irregular pattern was just nerve-wracking all the time inside and outside my home”.

Q15 What concerns do you have about the possible effects of pickleball noise on your health or that of your family members? More than 90% of all respondents reported at least one health concern. More than 2/3 of respondents reported intense emotional or physical reactions to pickleball noise or its reminders. See Figure 7.

Figure 7. Health concerns from pickleball noise (n=393)



*Multiple responses allowed

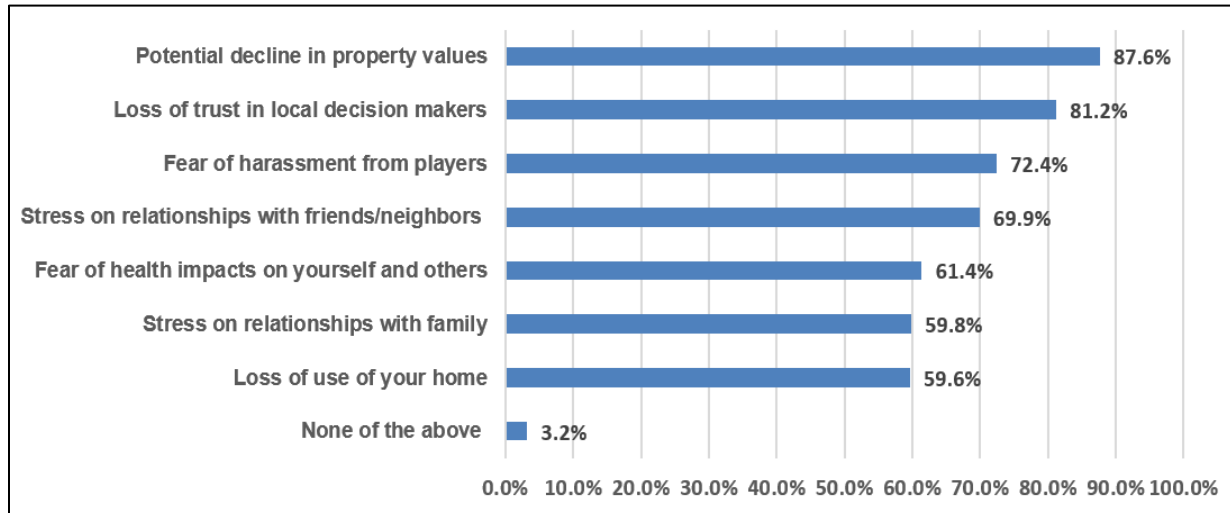
Q16. How concerned are you about the impacts of pickleball noise on your community? More than half of the community reported being extremely concerned about the impact on each of the following: children or infants, seniors, veterans or others with PTSD, and people with learning disorders, neurologic disorders, or other disabilities. See Table 7.

Table 7. Level of concern about specific impacts on community from pickleball noise (n=430)

Answer choices	Not concerned	Not very concerned	Moderately concerned	Very concerned	Extremely concerned
Impact on children or infants	42 (11.7%)	25 (7.0%)	56 (15.6%)	50 (13.9%)	186 (51.8%)
Low income and/or minority populations	87 (26.1%)	36 (10.8%)	61 (18.3%)	38 (11.4%)	111 (33.3%)
Effect on environmental quality and ecosystems	29 (7.9%)	20 (5.4%)	59 (16.1%)	69 (18.9%)	189 (51.6%)
Impact on seniors, especially those with pre-existing conditions	20 (5.4%)	9 (2.4%)	36 (9.7%)	66 (17.7%)	242 (64.9%)
Impact on veterans or others with PTSD	22 (6.2%)	15 (4.3%)	36 (10.2%)	47 (13.3%)	233 (66.0%)
Children and adults with learning and/or neurological disorders, e.g., autism, sensory deficit disorders	27 (7.7%)	18 (5.1%)	43 (12.2%)	56 (15.9%)	208 (59.1%)
Children and adults living with disabilities	34 (9.6%)	16 (4.5%)	52 (14.7%)	53 (15.0%)	198 (56.1%)

Q 17. What other impacts of pickleball noise concern you? Property values, fear of harassment and health impacts and stress on relationships both with family members and within the community were all areas of significant concern to the respondents, with more than 60% of respondents indicating a concern for each issue. See Figure 8.

Figure 8. Other concerns about impact of pickleball noise (n=435)



*Multiple responses allowed

Q18. Are there any other details about your experience that you think are important to know? 280 open-ended responses to this question were received and mirrored the hundreds of other open-ended responses received to the above questions.

B. SURVEY RESULTS ON NOISE MITIGATION STRATEGIES

Physical sound barriers, quiet paddles and balls, and setbacks from homes are often recommended by acoustic professionals. The authors have not found any published research regarding the effectiveness of these strategies that include input from residents living near courts. A limited descriptive analysis is provided below. A detailed statistical analysis is underway to determine the contribution of co-variables, such as noise mitigation strategies and duration of noise exposure, to the impacts of pickleball noise on the well-being of the surrounding residents and will be the subject of a separate manuscript.

I. VINYL SOUND BARRIERS

Sixty-seven respondents reported that their local courts have thick vinyl sound barriers with setbacks ranging from less than 100 feet to more than 1000 feet. Sixty-one of these respondents provided comments, of which almost all (n= 59, 96.4%) suggested the barriers are not adequately addressing the noise problem.

II. SETBACKS

About 1 in 8 respondents (53) report living more than 500 feet from courts. A significant proportion of this group reports a notable impact on their ability to be mindful (n=31, 62%), enjoy being indoors/outdoors at home, (n=31, 62%), or communicate/socialize at home (n=22, 46%). Almost half of this group said the term “annoyance” is not adequate to describe their experience of pickleball noise (n=24, 49%). Almost 2/3 of this group report concerns about intense emotional or physical reactions to pickleball noise or its reminders (n=27, 65.9%) and almost half report concerns about high blood pressure (n=20, 48.8%).

III. QUIET EQUIPMENT

Six respondents reported that playing with quiet balls was enforced at their neighborhood courts. All six had homes located within 100 feet of courts. Only one commented “no impact on daily activities”. The other five reported “a nightmare”, “tortuous”, “it has ruined the enjoyment of our home”, “unbearable annoyance”, and “abusive noise”.

4. DISCUSSION

The results of this pilot survey show that pickleball noise has a substantial impact on the health and well-being of people in the nearby community.

A. ACOUSTIC AND NON-ACOUSTIC FACTORS

Characteristics other than decibel levels can affect human response to noise; for example, frequency (in Hz), number of noise events, and impulsivity (6,7,8,9). Pickleball courts can generate up to 900 pops per court per hour, with four busy courts producing over 35,000 pops per day in irregular patterns at ~1,200 Hz—a frequency to which the human brain is highly sensitive. Respondents highlight that it is “not just decibels.” A higher percentage of respondents described the sound as *repetitive pops* compared with *loud* (88% vs 66%, respectively).

More than 3/4 of respondents reported possible exposure to the noise for more than 50 hours per week. Although courts may not be in constant use, residents emphasized the uncertainty of when play might begin, an anticipatory stressor that prevents relaxation. Nearly 90% have lived near active courts for more than one year. While it is commonly believed that noise tolerance increases with continued exposure, research suggests that in some situations, annoyance increases with extended exposure (10).

Non-acoustic factors unrelated to the physical, measurable characteristics of a sound, such as social context and stress have been found to explain up to 1/3 of the variance in noise annoyance (11). Examples from this survey include being able to hear the noise inside one’s home, reported by almost 3/4 of respondents. Another is the harassment from pickleball players after speaking up about the noise, reported by nearly half of all respondents. These results underscore the importance of considering factors other than decibels when evaluating the human response to pickleball noise.

B. IMPACTS ON DAILY LIFE

For many respondents, the noise has severely disrupted daily life and caused significant stress. Most residents report being impacted constantly or very often. People report being unable to enjoy their homes, gardens, or outdoor spaces, and many have altered routines or even relocated to avoid the noise. Comments frequently describe an ongoing sense of intrusion— “*I cannot think, I cannot concentrate, I can’t do anything in my house*” and a feeling that they are being driven indoors or away from home.

Some report major life decisions such as delaying retirement or giving up hobbies, because of the noise. Over half of respondents have either already moved, want to move, or have moved part time from their home, due to the noise. These experiences are clearly very stressful and clearly meet common definitions of an environmental nuisance: interference with the comfortable enjoyment of life or property.

C. HEALTH CONCERNS AND PHYSIOLOGIC STRESS RESPONSE

The high level of concern over the impact of pickleball noise on health and the reports of specific impacts, e.g., elevated blood pressure, sleep disturbance, anxiety and jitteriness, are consistent with extensive scientific evidence on the ability of noise to trigger the body’s stress response. Noise stimulates the amygdala and activates the autonomic nervous system leading to inflammation and oxidative stress, resulting in damage to the vascular endothelium (12). Chronic activation of the stress response increases the risk of cardiovascular, cerebrovascular, and metabolic harms as well as of mental health disturbances like anxiety and depression (13,14). In addition to these non-auditory impacts, the reported concern by well over half of respondents over “phantom pickleball pops,” i.e., hearing sound in the absence of play, may represent a trauma-related reactivity or a form of noise-induced tinnitus. It is reported that these

phantom sounds may cause sleep disruption and, for some, have lasted for weeks or months after moving away (5).

The potential for pickleball noise to trigger trauma-like responses warrants further consideration. Previous research found that a self-reported sense of trauma, feeling tortured, and/or severe distress was noted frequently by people who spoke publicly about their concerns with pickleball noise (5). More than 2/3 of survey respondents reported intense emotional or physical reactions to pickleball noise or its reminders—a measure designed to assess trauma-like symptoms. Evidence for this possibility is further supported by the finding that 2/3 of respondents expressed extreme concern about the effects of pickleball noise on veterans and individuals with PTSD, the highest concern among all vulnerable groups. Such trauma-like responses may arise when individuals or communities face persistent, uncontrollable, and distressing noise that overwhelms coping capacity, leading to chronic distress, hypervigilance, or sleep disruption.

D. COMMUNITY LEVEL IMPACT

Significant community and social disruption was reported in relation to pickleball noise, with a majority reporting stress on relationships with neighbors, friends, and relatives. Fear of harassment from pickleball players and a loss of trust in local decision makers, reported by most respondents, are factors that exacerbate disruption of community and social relationships.

Beyond individual effects, respondents describe broader concerns for the community. Significant majorities expressed concern for other vulnerable groups, including children and infants, children and adults with disabilities including neurologic and cognitive issues, as well as the elderly.

E. ROLE OF MITIGATION

Current guidance, based on expert opinion, has suggested that full relief is unlikely within 100 feet of active courts, and significant multi-faceted mitigation is needed within 400 feet (5). Most respondents in this survey live within 300 feet of courts which might suggest that the impacts are greater closer to courts.

However, preliminary results suggest that while proximity may increase the percentage of people affected, meaningful impacts persist for residents living at even greater distances from the courts. Initial results also suggest that current implementation of various mitigation techniques, including quiet paddles/balls or sound barriers, may not provide adequate relief in many situations.

Further statistical analysis is needed to better understand the multifactorial relationships between setbacks, geography, mitigation, and duration of exposure and how these factors affect the significant impact currently being reported by many residents.

F. LIMITATIONS

Purposeful sampling, used in this pilot study, is commonly used in exploratory and early-stage environmental health research to document the existence of a new problem and characterize the range of responses. Given inherent response bias, typical in surveys of this type, participation was likely weighted toward those most impacted. Additionally, two experienced acoustics firms were invited to share the survey with their clients to solicit examples of successful implementations. One firm declined to participate, although it allowed the survey to be posted on its Facebook page. As a result, the pool of potential success cases may have been reduced, which may have increased bias. Random sampling is not included in this methodology but can be used in subsequent studies to help measure the prevalence of concerns.

The survey underwent face validation but no other psychometric testing. The study relied on self-reported data, and no objective measurements were collected to validate respondents' estimates of factors such as distance from courts, duration of exposure, or noise intensity.

Statistical analyses are ongoing and not included in the current paper; the lack of demographic data (e.g., age, gender, time spent at home) prevents assessment of potential variation across population subgroups.

G. POLICY IMPLICATIONS

As pickleball continues to grow in popularity, acoustic professionals and local policy makers must be made aware of the potential negative impacts on pickleball noise on the daily lives, health, and well-being of surrounding community members. For many, the effects extend beyond simple annoyance. Decisions about appropriate court locations must rely on factors that are meaningful to the lived experience of communities. In addition to assessing loudness (e.g., decibels), other characteristics of the sound must be considered including impulsivity, number of noise events/day, and total duration of exposure. It is equally critical to account for non-acoustic factors that shape human perception of noise such as the intrusion of sound into the interior of the home and the presence of social conflict. A framework for planning and zoning that incorporates these considerations has been proposed (15), but further development and broader dissemination of evidence-based guidelines for court siting and mitigation strategies are needed.

5. CONCLUSION

Survey responses from 264 communities show that pickleball noise has a substantial impact on nearby residents. Residents describe both loss of enjoyment of home and property from chronic noise exposure and significant health concerns consistent with a physiological and psychological noise-induced stress response. Municipalities and local leaders tasked with providing opportunities for pickleball recreation are also responsible for protecting the well-being and health of neighbors living in proximity to pickleball courts. Evidence-based guidelines are needed to help guide these decisions.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Rob Mastroianni, Nalini Lasiewicz, Lance Willis, and Pickleball Sound Mitigation.

7. APPENDIX

Table A1. Comments from the respondents who skipped the “annoyance” question (Q.11, n=26)

<i>The popping sound triggers PTSD from the military</i>	<i>Racquet noise and yelling</i>	<i>Tortuous</i>
<i>Aggressive, oppressive</i>	<i>Irritating, impulsive</i>	<i>Anxiety trigger</i>
<i>Daily torture</i>	<i>Disturbing</i>	<i>Constant nightmare</i>
<i>I flinch</i>	<i>Unwanted noise</i>	<i>Nuisance against our covenant</i>
<i>Unbearable</i>	<i>Obnoxious</i>	<i>Noise piercing</i>
<i>Worse than annoyance, health risk</i>	<i>Unbearable</i>	<i>Absolute torture</i>
<i>Annoyance + health impact</i>	<i>Tortuous</i>	<i>Extremely annoying, disruptive</i>
<i>Torturous</i>	<i>Difficult to have a conversation</i>	<i>Drives a person crazy</i>
<i>Stressful</i>		<i>Enjoyment, exercise</i>

Table A2. All open comments to the question about “annoyance” (Q.11, n=206)

Category	% of total	Representative Comments
Severe psychological distress emotional distress	65.0%	<i>“Psychologically damaging is more like it!”, “auditory assault”, “Sonic harassment or torture”, “Absolute torture”, “CRIMINAL ASSAULT”, “soul destroying”, “abusive”</i> <i>“Painful, PTSD inducing, nails on chalkboard”.</i>
Impacted quality of life	23.3%	<i>“It sounds dramatic, but it affects my quality of life.”</i> <i>“It has ruined the enjoyment of our home”,</i> <i>“It is impossible to live in our home”, “I think nuisance is better word.”</i> <i>“I would call the sound maddening. Have to go inside.”</i>

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Impacted health	8.7%	"We both have been diagnosed with health issues due to the noise", "Documented health risk affecting each family member differently "Mental health and overall well-being was extremely affected to the point of a breakdown."
Positive or neutral	2.9%	"Joy, fun", "Enjoyment, exercise"

Table A3. Open comments to question about interference with daily activities at home (Q12, n=84)

Category	% of responses	Representative comments
Impacted daily activities	58.3%	"Stopped playing outside with my child", "I cannot think, I cannot concentrate, I can't do anything in my house", "We are retired so forced to leave our house on a daily basis multiple times a day", "Interferes with my ability to read, converse with my spouse, work in my yard, use the front half of my house for anything at all"
Stress and/or health effects	13.1%	"Anger", "Blood pressure risen", "Hallucinations", "It's nerve wracking and it's impossible to relax" "I'm now triggered just by the mention of the P word"
Sleep disturbed	11.9%	"We cannot sleep in the master bedroom". "Even when they are not playing, you wake up in the night thinking you hear it"
Coping	8.3%	"Fighting court expansion near my home is a part time job", "You man up and do what you have to"
Other	8.3%	"Traffic"

8. REFERENCES

- Leahy, C. Audio: Pickleball paddle strikes recorded courtside, California, 2024. MP3 file.
- 2024 USA Pickleball annual facts & highlights, USA Pickleball, accessed April 2, 2025. <https://usapickleball.org/about-us/organizational-docs/pickleball-annual-growth-report/>.
- Google Map of Pickleball Noise Hot Spots, created by Nalini Lasiewicz. Google Maps accessed March 28, 2025. https://www.google.com/maps/d/u/1/viewer?entry=yt&ll=40.430090946430944%2C79.90188363766478&mid=1obf5UNxqSbADZn7kj_OeZYwWQCKcTx8&z=14.
- "I was stunned to find out there are over 200 lawsuits that I've been able to find throughout the nation, all pertaining to HOA's and local municipalities concerning pickleball courts." Hillsborough County Commission, Josh Wostal 1:49:36 <https://www.youtube.com/watch?v=XQ27sRYMzBg>
- Romito, K., Fink, D. Pickleball noise: The physiological and psychological effects on nearby residents. Proc. Mtgs. Acoust. 56, 050001 (2025) <https://doi.org/10.1121/2.0002030>
- SAE. Alarm - Backup Electric Laboratory Performance Testing. 2009 Warrendale, PA, USA Society of Automotive Engineering SAE J994.
- Quehl J, Basner M. Annoyance from nocturnal aircraft noise exposure: Laboratory and field-specific dose response curves, J Environ Psych. 2006; 26 (2) pp127-140. <https://www.sciencedirect.com/science/article/abs/pii/S0272494406000302?via%3Dihub>.
- Banks, J., O'Rourke, P.J. The community impact of aviation noise: A pilot study. J Exposure Sc. & Environ. Epidemiology(2025) <https://doi.org/10.1038/s41370-024-00737-z>
- Rajala V, Hongisto V, Annoyance penalty of impulsive noise-The effect of impulse onset. BuildingEnvir.2020;168. <https://www.sciencedirect.com/science/article/abs/pii/S0360132319307516?via%3Di%20hub>.
- Lefèvre M, Chaumond A, Champelovier P et al. Understanding the relationship between air traffic noise exposure and annoyance in populations living near airports in France. Environment International, 2020; 144. <https://doi.org/10.1016/j.envint.2020.106058>.
- ISO/TS 16755-1. "Acoustics — Non-acoustic factors influencing the perception, interpretation and response to environmental sounds — Part 1: Definition and conceptual framework" (ISO, Geneva, Switzerland, 2025).
- Münzel T, Sørensen M, Schmidt F, et al. The Adverse Effects of Environmental Noise Exposure on Oxidative Stress and Cardiovasc. Risk. Antioxid Redox Signal. 2018 Mar 20;28(9):873908. <https://doi.org/10.1089/ars.2017.7118>
- Hahad O, Bayo Jimenez MT, Kuntic M., et al. Cerebral consequences of environmental noise exposure. Environ Int. 2022; 165:107306. <https://doi.org/10.1016/j.envint.2022.107306>
- Basner M, Babisch W, Davis A., et al. (2014). Auditory and non-auditory effects of noise on health. The Lancet. 2014;383(9925):1325 <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3988259>
- Leahy, C. Managing pickleball noise through zoning. Zoning Practice. American Planning Association. November 2025, Vol 42, No 11.



Annoyance penalty of impulsive noise – The effect of impulse onset

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Highlights

- Impulsive noise is more annoying than steady-state noise and deserves a penalty.
- Our results were against constant penalty values used in most noise regulations.
- Penalty values ranged from 0 to 8 dB depending on the prominence of the impulse.
- Prominence depends on impulse envelope: onset rate and level difference.
- Results can be used to assess the annoyance of impulsive noise in buildings.

Abstract

Impulsive sound can be perceived more annoying than a steady-state sound having the same A-weighted equivalent sound pressure level, L_{Aeq} . The difference in perceived noise annoyance can be compensated by adding a penalty or an adjustment k to L_{Aeq} (rating level). Many legislations apply a constant penalty value, such as 5 dB or more, but the validity of this procedure has been questioned. Nordtest method NT ACOU 112 identifies an impulse from the time profile of sound pressure level by using two measures describing the onset of an impulse: level difference (D_L) and onset rate (R_{on}). The purpose of this study was to determine how the annoyance penalty depends on D_L (5–40 dB) and R_{on} (5–800 dB/s) and to compare obtained results to the penalty prediction model of Nordtest method. A psychoacoustic laboratory experiment of 32 participants was conducted. Synthetic and periodic impulsive sounds were studied with two alternative spectra. The sounds were presented at 55 dB L_{Aeq} . Steady-state sounds at levels 49–70 dB were used to derive the penalty of impulsive sounds. The observed penalty values ranged between 0 and +8 dB. The penalty values depended somewhat on spectrum. The penalty deviated from zero when $D_L > 10$ dB or $R_{on} > 15$ dB/s and increased with increasing D_L and R_{on} . The penalty predicted by Nordtest method usually overestimated the observed penalty when $R_{on} \geq 200$ dB/s. The results are against constant penalty values and they can be used to develop future penalty schemes.

Introduction

National regulations for environmental noise have been prescribed to achieve sufficiently comfortable and healthy living environments. A typical limit value for the A-weighted equivalent sound pressure level (SPL) of environmental noise inside residential buildings is 35 dB $L_{Aeq,07-22}$ during daytime and 30 dB $L_{Aeq,22-07}$ during night time, e.g. Ref. [1]. For comparison, regulated level for building services is 28 dB L_{Aeq} in living rooms and 33–38 dB in other rooms within a dwelling, e.g. Ref. [2]. Very similar target values are used in the regulations of many European countries.

The regulations do not concern only the values of L_{Aeq} . Many regulations involve a penalty, k [dB], which is added to the measured or predicted L_{Aeq} in order to counteract the negative effect of a *specific feature* of the sound on annoyance. Frequently used synonyms for penalty are e.g. adjustment, sanction, bonus, allowance, and surplus. The outcome is also called rating level, $L_r = L_{Aeq} + k$ in e.g. ISO 1996-2 standard [3]. The most typical specific features are *impulsiveness* and *tonality*. E.g. in Finland, the penalty values due to impulsive sound vary between 3 and 10 dB depending on the scope of the regulation [1,2,4]. The penalty places special noise control requirements especially for residential buildings where the noise regulations are the tightest but also to other building types, such as schools, hospitals, offices, and accommodation buildings. Denmark [5] and Sweden [6] apply penalty of 5 dB for impulsive environmental noise. Instead, Italy [7] applies a constant penalty of 3 dB. For comparison, Switzerland [8] applies four alternatives (0, 2, 4, and 6 dB), Germany [9] applies two alternatives (3 or 6 dB), and Great Britain [10] applies four alternatives (0, 3, 6, or 9 dB). ISO 1996-1 [3] suggests a constant penalty of 5 dB for regular

impulsive noise and 12 dB for highly impulsive noise. However, the application of constant penalties are not always supported by laboratory studies [11].

Many regulations do not describe exact quantitative criteria for identifying the impulsiveness in sound. For example, ISO 1996-1 standard [12] does not present a mathematical method to identify and categorize impulses. At least three kinds of methods are used to identify impulsiveness in sound: subjective methods, simple rating methods, and sophisticated rating methods. Subjective methods are based on subjective assessment of the measurer. If the sound contains rapid audible level changes, the sound is impulsive. Simple ratings are based on built-in time and frequency weightings of standard sound level meters. One well-known rating quantity is $L_{AI} - L_{AS}$ where S and I denote the Slow and Impulse time weightings. The larger the value, the stronger is the impulsivity. A European council directive [13] suggested that noise is impulsive if $L_{AI} - L_{AS} \geq 4$ dB. However, the review of Rice [14] suggests that the quantity is not able to detect all impulses. Furthermore, I weighting is no longer supported in new sound level meters. Rice [14] suggested that quantities based on the analysis of time series of the signal using time weighting $L_{Aeq,10ms}$ showed promising results in the indication of impulsiveness. Furthermore, Rice [14] suggested that the maximum positive differences between successive values of $L_{Aeq,10ms}$ should be determined.

A more sophisticated rating method, which is partially meeting the suggestions of Rice [14], was introduced in NT ACOU 112 method [15]. It describes how the subjective prominence of impulsive sound could be objectively assessed by analyzing both the strength and the growth of the impulse. Nordtest method [15] describes an impulse onset by using two measures: level difference, D_L , [dB] and onset rate, R_{on} [dB/s]. The measures are described in Fig. 1 where the A-weighted SPL time profile is analyzed with Fast time weighting, L_{AF} . The method suggests that the sampling of L_{AF} is made using 10–25 ms time window, which conforms with the suggestion of Rice [14]. The starting point of an impulse is the first point where the first order linear regression slope between two consecutive SPLs is over 10 dB/s. The end point of the impulse is the first point where the slope between two consecutive SPLs is below 10 dB/s. D_L is calculated by subtracting the SPL of the end point from the SPL of the starting point. The R_{on} is calculated by fitting a first order regression line to SPLs between the starting and the ending point. The R_{on} is the slope of the regression line. It is noticeable that the method defines an impulse to be the onset of an impulsive sound, avoiding taking into account the decay of the SPL.

Nordtest method [15] defines the unitless predicted prominence, P , of the impulse by $P = 3 \cdot \lg(R_{on}) + 2 \cdot \lg(D_L)$. Penalty k [dB] is determined according to $k = 1.8 \cdot (P - 5)$, for $P > 5$ if $R_{on} > 10$ dB/s. Otherwise, $k = 0$ dB.

According to the criteria of Nordtest method [15], impulsiveness is not limited to gunfire or shooting noise, where many previous studies on impulsiveness penalty are focused, e.g. Refs. [11,16]. Impulsiveness exists in many kinds of environmental sounds, such as construction noise, music, shooting, explosion, wind turbine noise [17], and several logistic and industrial operations. Impulsivity also exists in numerous daily sounds whenever two items impact each other, such as

door closing, hand clapping, dropping of items, log splitting, or walking. Rapid fluctuations in traffic noise have been considered to be impulsive [18]. 'Human voice contains also strong temporal variations.' For example, a recording containing the previous spoken sentence in quotations includes altogether 23 onsets where $R_{on} > 10$ dB. Eleven of them also lead to a penalty according to Eq. (2). The penalties varied between 0.6 and 9.0 dB.

There is reasonably little scientific research concerning the adequate penalty of impulsive sound. Vos and Smoorenburg [11] found that the penalty for impulsive gunfire noise or impulsive metal construction noise was 12.5 dB when the background noise was absent, 10 dB when background noise was 35 dB L_{Aeq} , and 5.5 dB when background noise was 55 dB L_{Aeq} . Vos [16] studied further the penalty for gunfire noise and summarized that the penalty reduces with increasing equivalent SPL of impulses. The penalty is 10 dB for impulses at 35 dB L_{Aeq} and 0 dB for impulses at 65 dB L_{Aeq} . The review of Rice [14] covered several other studies and it supports the level dependent penalty: the penalty varies between 10 dB (low levels, e.g. 50 dB L_{Aeq}) and 0 dB (high level, e.g. 80 dB L_{Aeq}). The impulses in the previous studies were very prominent (high values of D_L and R_{on}) and the findings may not be directly applicable for impulsive sounds having a significantly slower onset rate, such as those mentioned above.

To our knowledge, only Pedersen [19] has studied experimentally how the penalty depends on the onset of the impulse, i.e. D_L and R_{on} . His model was adopted to Nordtest method [15]. However, Pedersen [19] suggested that a more thorough study is desirable since the penalty model was partially based on general experience and using only industrial noise types. Better knowledge of the variables affecting the penalty of impulsive sounds could improve our understanding about the annoyance of environmental noise and building service noise in residential environments.

The investigation of the effect of impulse onset on penalty is topical since a new standardization working group (ISO TC 43/SC 1/WG 45) has been launched in 2019. It attempts to develop a standard for the objective identification of impulsive sounds. Nordtest method [15] is already implemented in a British standard of assessment of environmental sound [10].

Impulsive sounds carry also spectral information. Hongisto et al. [20] found in a psychoacoustic experiment that wide-band sounds having strong emphasis on high frequencies were more annoying than wide-band sounds having strong emphasis on low frequencies. They conducted the study at a constant level of 42 dB L_{Aeq} . Because the impact of spectrum on annoyance was drastic, the spectrum may also have an impact on the annoyance of impulsive sounds. Contrary to the findings of Hongisto et al. [20], Vos [21] found that low-frequency impulses from firearms were more annoying than high-frequency impulses. We are not aware of previous studies investigating spectrally different impulses while keeping the D_L and R_{on} constant.

The purpose of this study is to determine how the annoyance penalty of impulsive sounds depends on the values of D_L and R_{on} and to compare the observations to the penalties predicted by Nordtest method [15]. This study focuses on periodic impulses and constant overall level of 55 dB L_{Aeq} . The

study was conducted using two different spectra of impulsive sounds to investigate a possible effect of spectrum on annoyance. This study also investigates the smallest threshold values of D_L and R_{on} above which the impulse penalty could be suggested. Therefore, this study covers an exceptionally large range of D_L and R_{on} values. The experiment has a generic nature so that the results can be applied to all kinds of built environments.

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Participants

The participants were recruited via university mailing lists and Turku University of Applied Sciences. The requirements for the participant were: age within 20–45 years, Finnish as a native language, and normal hearing. It was instructed that one should not participate the experiment during a flu or any other illness. Thirty-two voluntary persons (13 men and 19 women) participated in the experiment. The participants were native Finnish speakers and their age ranged from 20 to 44 years (mean 29, ...

Results

Fig. 5 shows the mean *annoyance* and confidence intervals for the reference sounds as a function of L_{Aeq} and the regression line fitted to the mean *annoyance* of the reference sounds. The observed mean *annoyance* of the reference sounds increased monotonically with increasing L_{Aeq} , thus providing a robust reference for calculating the penalty of the impulsive sounds. The mean *annoyance* and the 95% confidence intervals for *sounds* I1 – I66 are shown in Fig. 6. Overall, higher values of D_L and R_{on} ...

Discussion

The observed penalty increased with increasing D_L and R_{on} . This is in agreement with Eq. (2) and Nordtest method [15]. However, the dependence of penalty on D_L and/or R_{on} was not a simple function of R_{on} and D_L . The results give strong evidence that the onset of the impulse, i.e. both onset rate, R_{on} , and level difference, D_L , have an effect on *annoyance* and *annoyance* penalty of impulsive

sound. The results are against the constant penalty values for impulsive noise suggested by ISO 1996-1 ...

Conclusions

Nordtest method NT ACOU 112 [15] defines a method to identify impulses in a sound using A-weighted sound pressure level time profile with Fast time weighting. An onset is identified from the time profile when the onset rate exceeds $R_{on} = 10 \text{ dB/s}$. The predicted prominence of the impulse depends also on level difference D_L , i.e. the strength of the impulse in decibels. Nordtest defines an annoyance penalty in decibels (i.e. an adjustment to L_{Aeq} to obtain the rating level) based on the predicted ...

Declaration of competing interest

None. ...

Acknowledgements

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References (30)

C.G. Rice

[Human response effects of impulse noise](#)

J. Sound Vib. (1996)

D. Oliva *et al.*

[Annoyance of low-level tonal sounds – factors affecting the penalty](#)

Build. Environ. (2017)

V. Hongisto *et al.*

[Annoyance of low-level tonal sounds – a penalty model](#)

Appl. Acoust. (2019)

Finnish Ministry of the Environment, Government Decision on the Noise Level Guide Values (993/1992), (Helsinki,...

Finnish Ministry of the Environment

Decree 796-2017 of the Ministry of the Environment on the acoustic environment of buildings

Acoustics – Description, Measurement and Assessment of Environmental Noise – Part 2: Determination of Sound Pressure Levels

(2017)

Finnish Ministry of social Affairs and Health, Decree 545-2015 of the Ministry of social Affairs and Health on health-related conditions of housing and other residential buildings and qualification requirements for third-party experts

Delta

Environmental noise regulation in Denmark. Danish reference laboratory for noise measurements c/o DELTA

Orientering nre (Jan 2012)

Samordnade Bullerregler För Att Underlätta Bostadsbyggandet, Statens Offentliga Utredningar

(2013)

DPCM

Limiti massimi di esposizione al rumore negli ambienti abitativi e nell' ambiente esterno. Con le modifiche introdotte dal D.P.C.M. 14.11.97. G.U.-8.3.1991-n

(1991)



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...This means that Steady-state sound must be played 7.1 dB louder than Impulsive sound to produce the same annoyance rating. According to Rajala and Hongisto (2020), the annoyance penalty due to impulsive sound increases with increasing DL. DL values up to 40 dB are usual for many impulsive sounds occurring in our daily life....

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