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Noise Assessment of Drive-through Kiosk

Innovation Park Starbucks

Prepared for

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1. Summary

This report assesses the noise impact of a Starbucks drive-through kiosk at the northeast corner of Tangerine Road and Innovation Park Drive with respect to Section 25.1 of the Oro Valley Zoning Code. Drawings and specifications for the planned drive-through kiosk have been provided and are analyzed for noise impact.

In the daytime use case, kiosk sound levels were found to decrease faster than and fall below the roadway noise levels at the adjacent properties. In the nighttime use case, kiosk sound pressure levels were found to meet the limits in Table 25-1.A of the Zoning Code. Overall the operation of a drive-through kiosk on the proposed site is compatible with surrounding land uses. Recommendations are made to meet the acoustical performance analysis given in this document.

2. Site Summary

2.1 Proposed Site Development

A commercial retail and office center is proposed at the corner of Tangerine Road and Innovation Park Drive (see Figure 2.1). The project will consist of five stand alone buildings hosting office space and two restaurants. One restaurant is planned to be a Starbucks with a drive-through. Of interest for acoustical analysis is the drive-through kiosk planned for the Starbucks restaurant (labeled 'SBUX' in the drawing).

2.2 Area Summary

The land uses surrounding the proposed site are shown in Figure 2.2. There are no residential land uses within 250 feet of the Starbucks drive-through. To the northwest approximately 800 feet distant is the Oro Valley Hospital. Other adjacent properties are commercial uses. The closest is across Tangerine Road at a distance of about 550 feet.

2.3 Zoning

Zoning in the area is shown in Figure 2.3 [Pima County ArcGIS Online <https://pimamaps.pima.gov/geoapps/main>]. The proposed site and adjacent properties are zoned PAD, Planned Area Development.

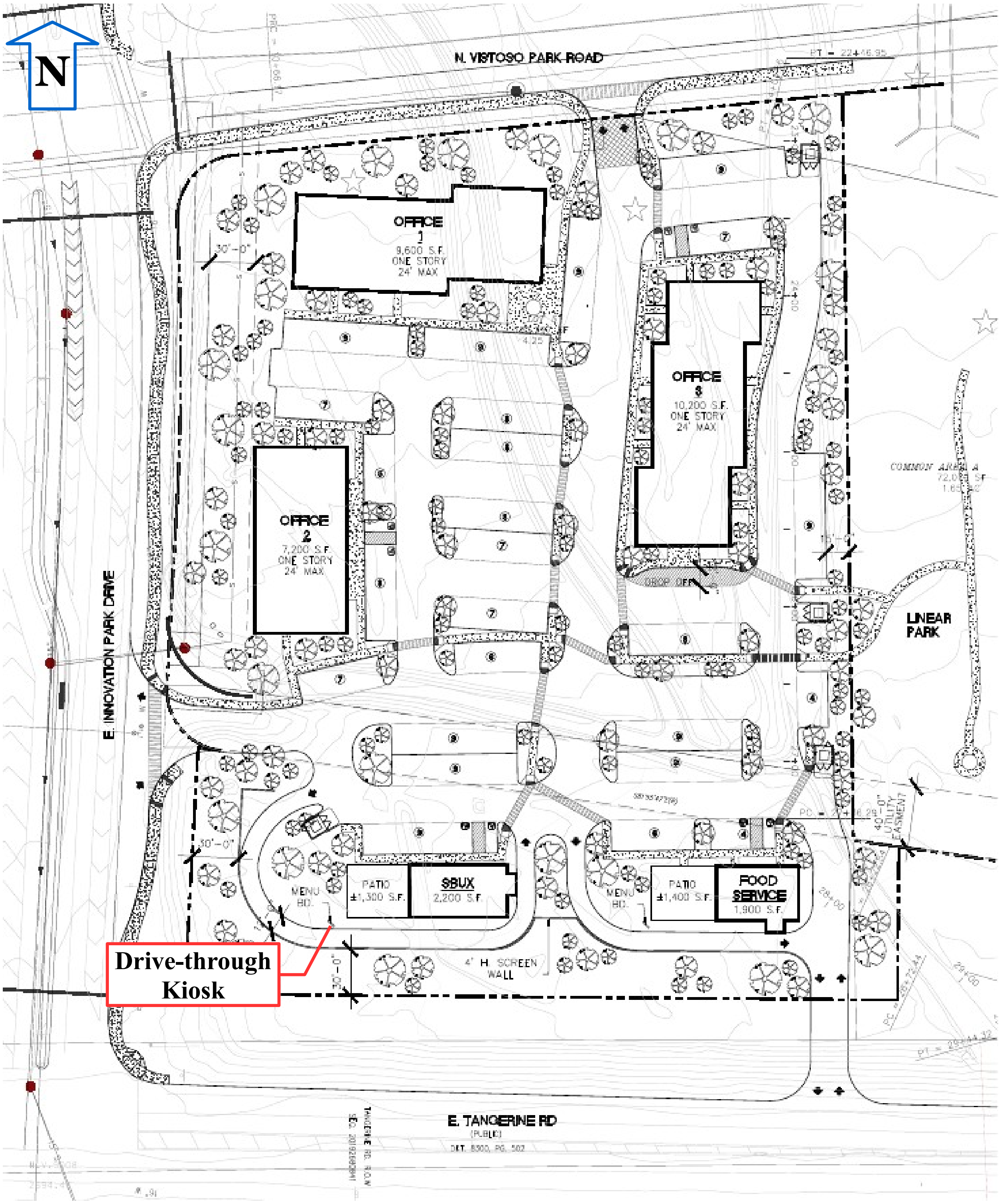

Figure 2.1. Proposed Site Plan

Figure 2.2. Proposed Site and Surrounding Area

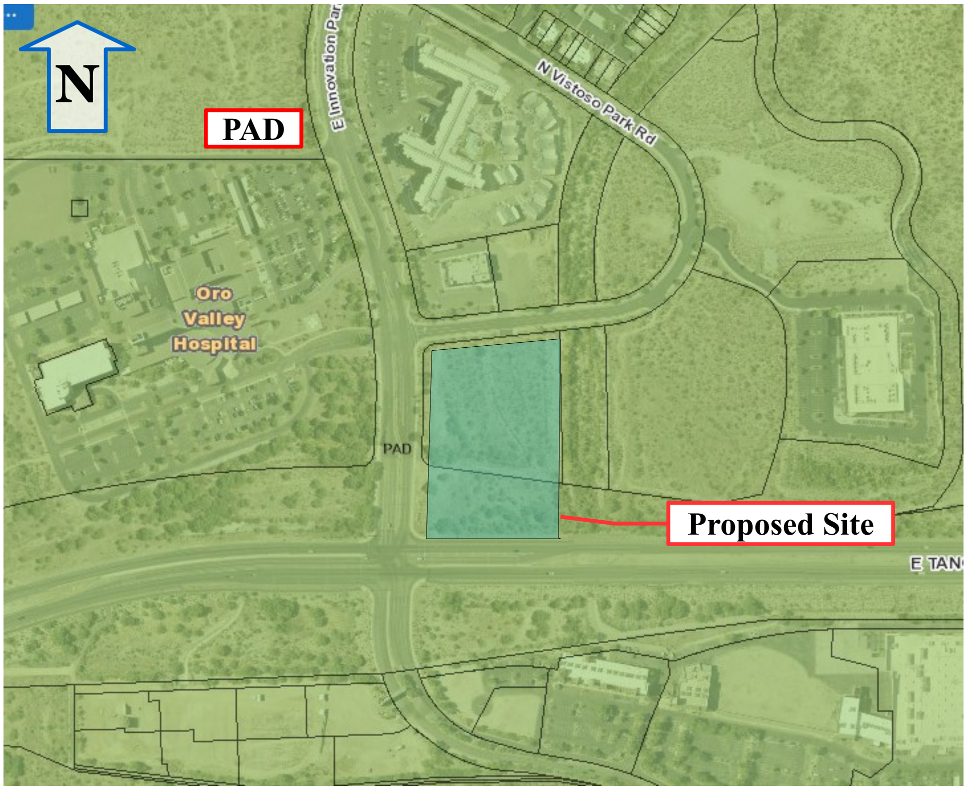

Figure 2.3. Zoning

2.4 Drive-through Kiosk

Starbucks has provided specifications for the kiosk to be installed. The loudspeaker is attached to the bottom of menu board as shown in Figures 2.4 and 2.5. The height of the loudspeaker is approximately 18 inches above grade.

Figure 2.4. Drive-through Kiosk

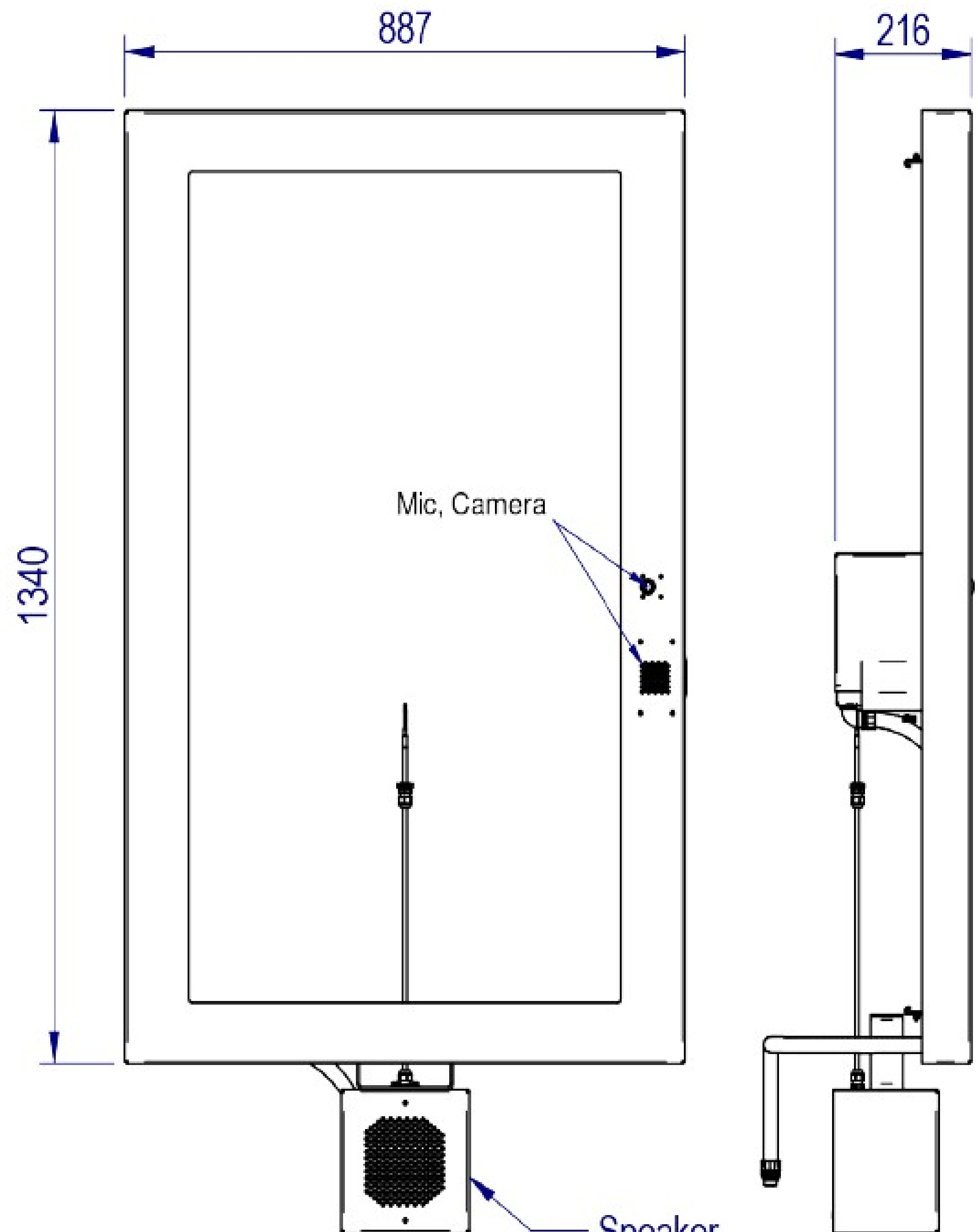

Figure 2.5. Kiosk Mechanical Drawings

3. Site Plan Analysis

3.1 Methodology

The acoustical site model has been constructed using the iNoise package version 2022.01 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 Drive-through Kiosk Sound Source

3.2.1 Location

The drive-through kiosk will be located west of the Starbucks building. The height of the loudspeaker is approximately 18 inches above grade. The distance from the loudspeaker to the customer vehicle is 6 feet in the acoustical model.

3.2.2 Use Cases

A well designed kiosk will often have an automated gain control (AGC) function to adjust the output of the loudspeaker based on the background noise level. The AGC reduces the amount of sound produced at times when the background noise is low such as during nighttime hours. This is useful for kiosks located in areas where there is a large variation in background noise at different times of day such near a highway.

This leads to two use cases. One is when the loudspeaker volume is determined relative to the background noise level. The other is when the background noise is not a factor and the kiosk output is set to achieve a normal conversation level. In the former case, the equivalent-continuous sound pressure level, LAeq, will be set at 15 dBA above the background noise level. This is a common setting for good speech communication in the presence of noise. In the latter case, LAeq will be set to an ANSI S3.5 standard speech level at the customer position.

3.2.3 Zoning Code Requirements

The Oro Valley Zoning Code Section 25.1 gives specific recommendations for maximum allowable sound pressure levels according to receiving land use, time of day, and the characteristics of the sound produced. Speech is considered regular impulsive sound. All equivalent-continuous levels will be adjusted by 5 dBA. This includes the one hour broadband and one minute octave band levels. Neither the restaurant employee speaking or the loudspeaker used will produce noticeable sound in the 16, 31.5, or 63 Hz octave bands as these bands are outside of the speech spectrum discussed in the next section. The one minute level limits will therefore not be exceeded in this application.

The level limits in Table 25-1.A of the Code that apply are the one hour average limits and maximum sound limits. These limits are adjusted upward in the presence of background noise levels that exceed the limits. This will apply in the use case where the kiosk level is set 15 dBA above the roadway noise. Here the concern will be whether the one hour average and maximum sound pressure levels exceed the background noise level at the adjacent properties or are masked by it.

3.2.4 Source Characteristics

An ANSI S3.5 normal effort speech spectrum will be used for the loudspeaker. Table 3.1 shows the unadjusted and unweighted octave band speech sound pressure levels that will serve as the starting point for the kiosk source model.

Octave Band (Hz)	Sound Pressure Level (dB)
125	48.1
250	56.9
500	59.1
1000	54.1
2000	48.8
4000	43.5
8000	37.0

Table 3.1. Normal Effort Speech Levels at 1 Meter

The loudspeaker enclosure is a small box close to the ground. A cardioid directivity pattern with a 10 dB rear null will be assumed as shown in Figure 3.1. The loudspeaker faces southwest.

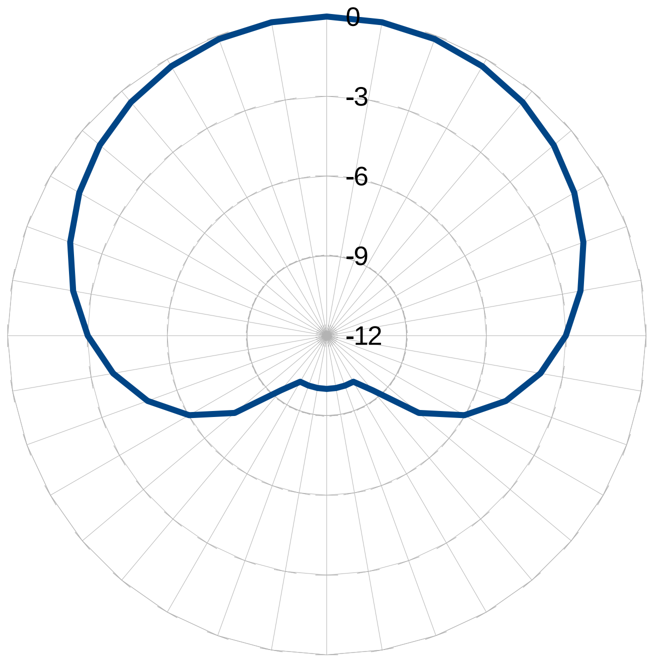

Figure 3.1. Kiosk Directivity Pattern

The relative difference in the unadjusted LAeq and LAmax will be assumed to be 15 dBA. This is a conservative estimate of the fast exponential time weighted speech crest factor and does not take into account a number of factors that will tend to decrease the level difference. These may include power compression by the loudspeaker driver and audio compression in the signal processing (not including the AGC).

Other undefined factors that will tend to reduce the amount of sound leaving the property include the directivity of the kiosk and obstacles, mainly the customer's vehicle, that will block sound traveling in that direction.

3.3 The Model Space

Figure 3.2 gives an overview of the acoustical model. The drive-through kiosk is located on the west side of the Starbucks (SBUX) building. Four receiver field points outside the shopping center and two points at adjacent businesses have been selected to verify sound pressure levels at nearby land uses. These are,

- Outside shopping center
    - Tucson Orthopaedic Institute
    - Meggitt
    - Carbon Health Urgent Care

- Oro Valley Hospital
- Inside shopping center
  - Office 2
  - Food Service

The heights of the receivers are at 5 feet above grade.

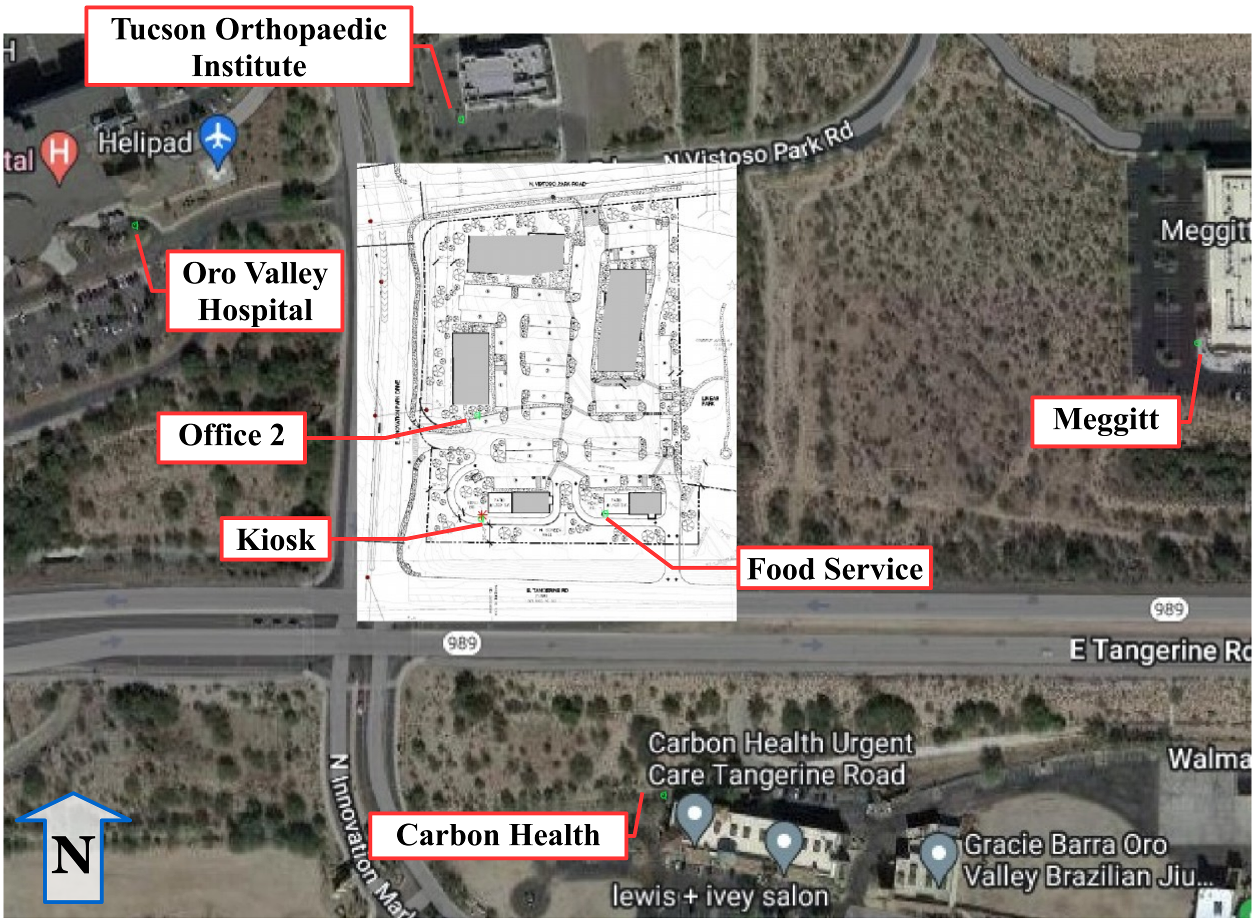

Figure 3.2. Model View

3.4 Sound Pressure Level Contour Maps

Sound pressure level contours in the figures below are displayed in 5 dBA increments. The legend identifying the map symbols is in Figure 3.3. All sound pressure levels are A-weighted. Sound walls are labeled as barriers in the iNoise software. The height of the grid points is 5 feet above grade.

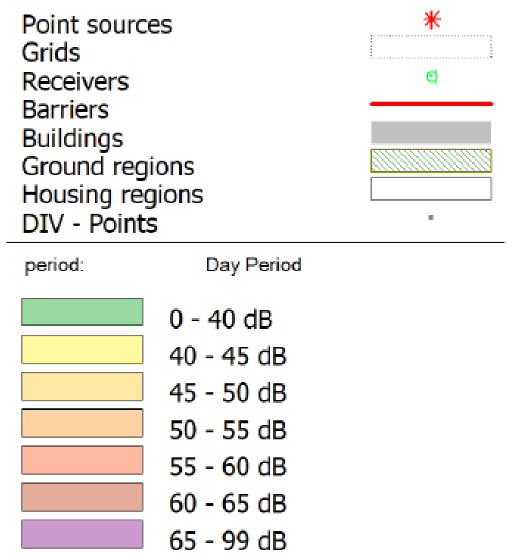

Figure 3.3. Legend for Sound Pressure Level Contour Maps

3.5 Low Background Noise Use Case

In the kiosk use case where background noise levels do not interfere with speech intelligibility, a normal conversation level at the customer vehicle is sufficient. Sound pressure level contours for the adjusted LAeq are shown in Figures 3.4 and 3.5.

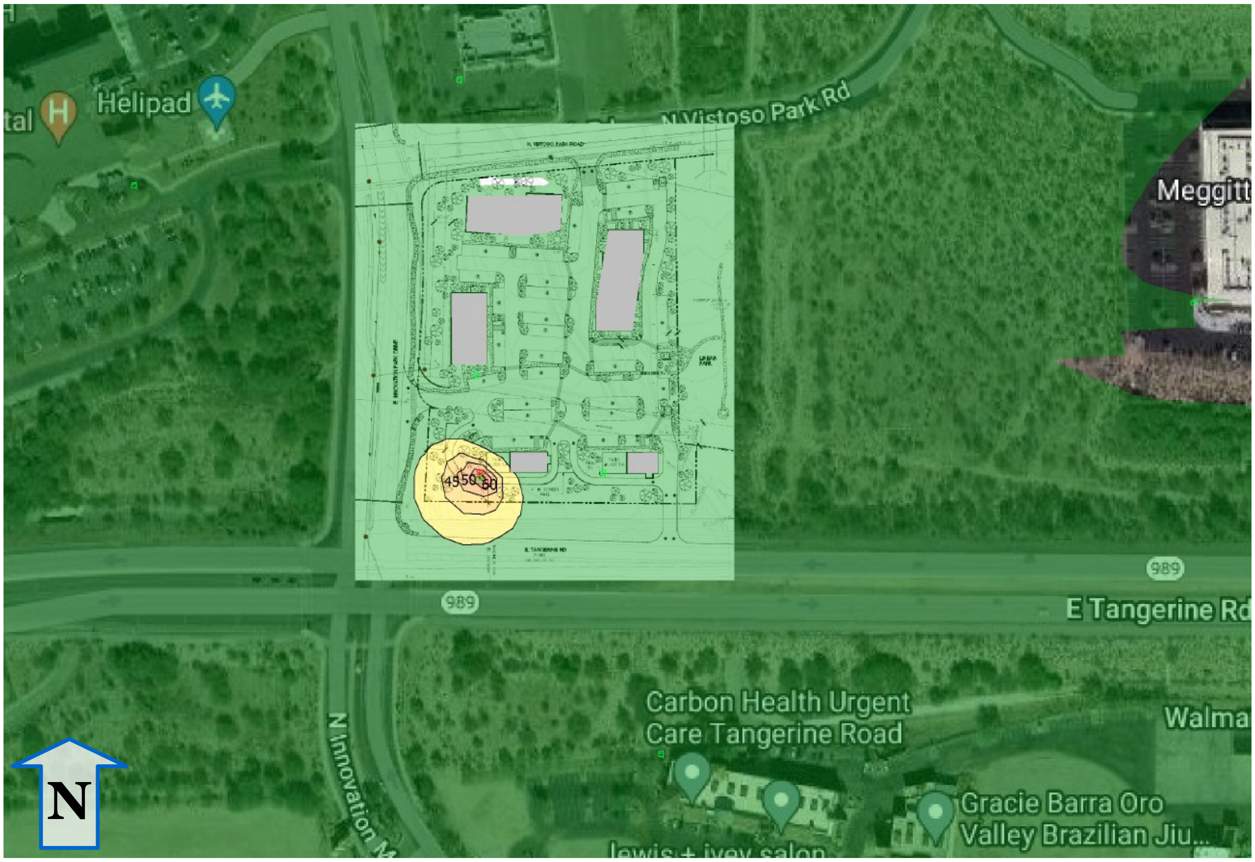

Figure 3.4. LAeq Sound Pressure Level Contours with No Background Noise

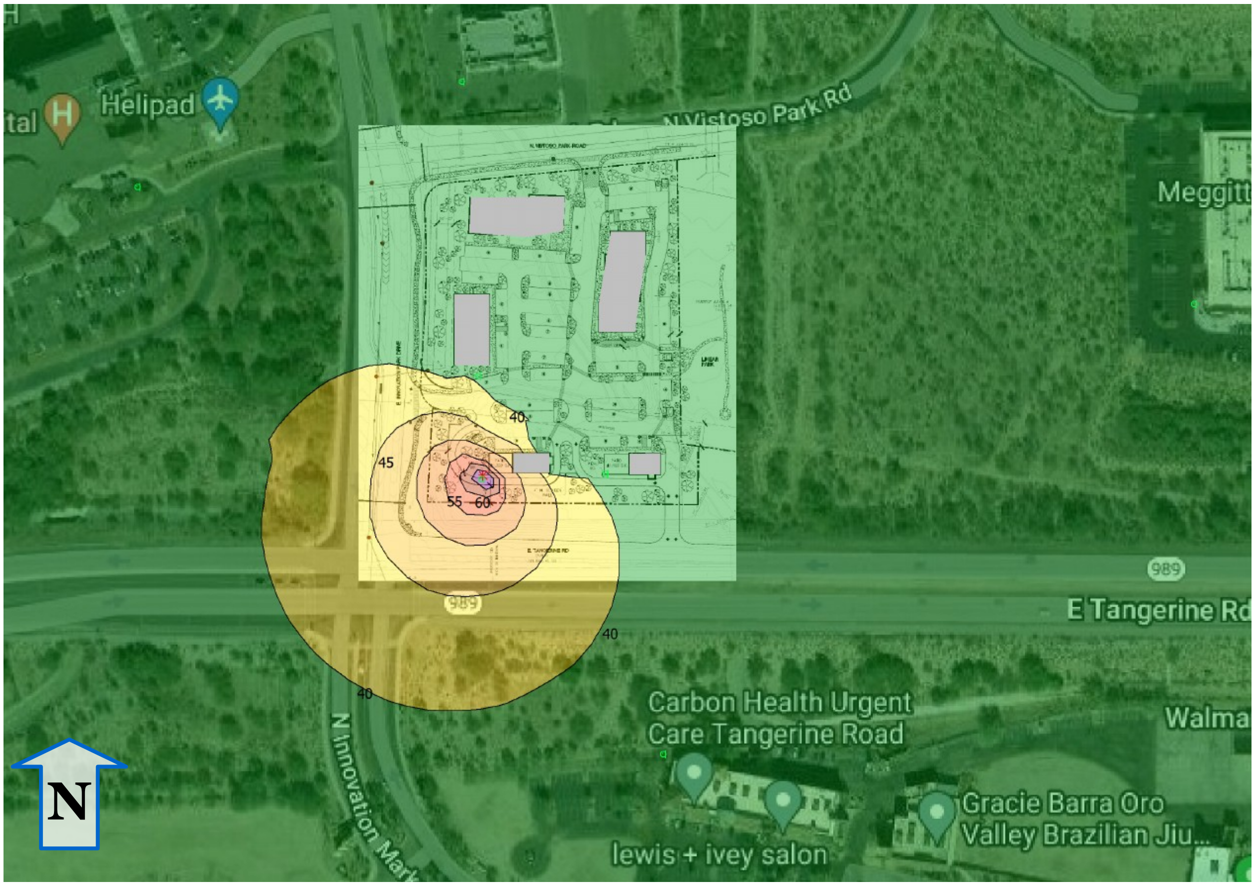

Figure 3.5. LAmax Sound Pressure Level Contours with No Background Noise

As seen in the above figures and in Tables 3.2 and 3.3 below, with moderate kiosk settings the adjusted average (LAeq) and maximum (LAmax) sound pressure levels are below the nighttime limits of 55 and 75 dBA respectively for hospitals in Table 25-1.A of the Code. The sound levels also meet the commercial limits of 65 and 85 dBA for LAeq and LAmax for the adjacent commercial land uses.

Location	Land Use	Height Above Grade (ft)	Adjusted Sound Pressure Level (dBA)	0700 – 1900 Hourly Limit (dBA)	Exceeds 0700 – 1900 Hourly Limit	1900 - 2200 Hourly Limit (dBA)	Exceeds 1900 – 2200 Hourly Limit	2200 - 0700 Hourly Limit (dBA)	Exceeds 2200 – 0700 Hourly Limit
Carbon Health Urgent Care	Commercial	5	25.8	65	no	65	no	65	no
Food Service	Commercial	5	29.9	65	no	65	no	65	no
Meggitt	Commercial	5	0.2	65	no	65	no	65	no
Office 2	Commercial	5	29.4	65	no	65	no	65	no
Oro Valley Hospital	Hospital, Hotel	5	21.6	65	no	60	no	55	no
Tucson Orthopaedic Institute	Commercial	5	4.3	65	no	65	no	65	no

Table 3.2. LAeq Levels at Adjacent Land Uses with No Background Noise

Location	Land Use	Height Above Grade (ft)	LAFmax (dBA)	0700 – 1900 Max Limit (dBA)	Exceeds 0700 – 1900 Max Limit	1900 - 2200 Max Limit (dBA)	Exceeds 1900 – 2200 Max Limit	2200 - 0700 Max Limit (dBA)	Exceeds 2200 – 0700 Max Limit
Carbon Health Urgent Care	Commercial	5	35.8	85	no	85	no	85	no
Food Service	Commercial	5	39.9	85	no	85	no	85	no
Meggitt	Commercial	5	10.2	85	no	85	no	85	no
Office 2	Commercial	5	39.4	85	no	85	no	85	no
Oro Valley Hospital	Hospital, Hotel	5	31.6	85	no	80	no	75	no
Tucson Orthopaedic Institute	Commercial	5	14.3	85	no	85	no	85	no

Table 3.3. LAmax Levels at Adjacent Land Uses with No Background Noise

3.6 Use Case with Road Noise Interference

Acoustical measurements of the roadway noise have not been performed on the proposed site to quantify the background noise levels throughout the day. This part of the analysis will look at the difference between ambient and background sound pressure levels as defined in the Zoning Code at the adjacent properties when the road noise drives the kiosk output to higher levels.

The kiosk is a point source whose sound pressure level decreases 6 dB with every doubling of distance. The roadways generating most of the background sound are line sources. Sound radiating from a line source will decrease 3 dB with every doubling in distance from the centerline of the roadway. Because the sound from the kiosk decreases more rapidly than the roadways, there will be a distance from the kiosk where the sound from the roadways becomes dominant. The purpose of this analysis is to determine whether the noise assessment locations receive more sound from the kiosk or the roadways and if it would be possible to measure the kiosk sound in the presence of the roadway sound.

Roadway line sources have been added to the acoustical model. According to the PAG Travel Data and Forecasting website <https://pag.public.ms2soft.com/tcds/tsearch.asp?loc=Pag&mod=>, Tangerine Road has a daily traffic count of 11,439 while Innovation Park Drive has a daily count of 9,484. This is a sound power level difference of 0.8 dBA. The absolute sound power of the road sources has been set arbitrarily since no measurements are available.

The spectrum levels for the roadway noise are based on CNOSSOS heavy truck reference data at 48 mph for Tangerine Road and 30 mph for Innovation Park Drive.

Table 3.4 lists the differences between ambient sound pressure level (unadjusted LAeq) and background level with the kiosk operating at 15 dBA above the background level at the customer position. Unadjusted levels are used here because they are not being compared to the Code limits, but to the background noise level in order to determine whether a measurement of LAeq would be possible. At each noise assessment location the difference of the ambient noise level minus the background noise level is less than 3 dBA. It would therefore not be possible to measure the one hour equivalent-continuous sound pressure level and apply a background noise correction. The maximum sound pressure level, LAmax, is also never exceeds the roadway LAeq background noise level by more than 3 dBA at each of the field points.

Location	Land Use	Height Above Grade (ft)	Ambient – Background (Leq, dBA)	Maximum Level – Background (Lmax, dBA)
Carbon Health Urgent Care	Single Family	5	0.0	-8.5
Food Service	Single Family	5	0.0	-5.2
Meggitt	Single Family	5	0.0	-30.2
Office 2	Single Family	5	0.0	-5.4
Oro Valley Hospital	Single Family	5	0.0	-9.2
Tucson Orthopaedic Institute	Single Family	5	0.0	-28.1

Table 3.4. Sound Pressure Level Differences at Adjacent Land Uses in Comparison to Roadway Noise

4. Conclusions and Recommendations

An investigation of the noise impact of a proposed drive-through kiosk at Tangerine Road and Innovation Park Drive has been carried out for two use cases. In one case, for daytime hours, the kiosk loudspeaker must overcome the background noise produced by the two adjacent roadways. In the other use case for nighttime hours, moderate conversational sound pressure levels produced by the kiosk were evaluated against the sound pressure level limits in Section 25.1 of the Oro Valley Zoning Code. In the daytime use case, kiosk sound levels were found to decrease faster than and fall below the roadway noise levels at the adjacent properties. In the nighttime use case, kiosk sound pressure levels were found to meet the limits in Table 25-1.A of the Code.

If the kiosk is operated during evening or nighttime hours an automated gain control (AGC) system may be needed to reduce the kiosk sound level when the background noise level decreases.

The following are guidelines for minimizing the noise impact of the loudspeaker on the surrounding area and optimizing communication with the customer.

- Place loudspeakers as close as possible to the customer in order to reduce the required amplification for necessary for good communication.
- Avoid placing the kiosk on a curve that will force the vehicle farther away from the loudspeaker.
- Aim the loudspeaker away from noise sensitive areas and avoid directing sound upward.
- To the degree possible, locate kiosks so as to utilize vehicles, buildings, and other structures to block the line of sight from the loudspeakers to noise sensitive areas. A menu board or wall can also be used for this purpose.
- Adjust the loudspeaker volume to the minimum necessary for good communication. In most applications, this should not be more than 15 dBA above the background noise level at the customer's vehicle (including the customer's vehicle).
- If necessary, such as may be the case for kiosks that are operated into the evening or nighttime hours, use an automatic gain control (AGC) amplifier to power the loudspeaker. This will reduce the gain to the loudspeaker during times of lower background noise level.
- Don't place the kiosk in a location with high background noise levels that will require increasing the loudspeaker volume for effective communication.

Not all of these measures may be necessary for a specific application or kiosk design. Ultimately the amplification of the loudspeakers will have to be limited as necessary to comply with the sound pressure level limits set in the Oro Valley Zoning Code. The above recommendations will reduce the amount of amplification necessary for effective communication and minimize the amount of sound going toward noise sensitive land uses.

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

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

RT_{60}: 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 other than a particular sound 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.

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.

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.

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 ($1 \text{ N} / \text{m}^2$).

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 is 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 (RT_{60}): 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.

sone: 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 μPa, squared and the reference time, one second. This quantity is used to characterize single events of short duration where the averaged level (L_{eq}) is inadequate.

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 quantifiy 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.

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

Here p is the sound pressure in Pascals. p_{ref} is a reference pressure, the threshold of hearing at 1000 Hertz (Hz), 20 x 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.

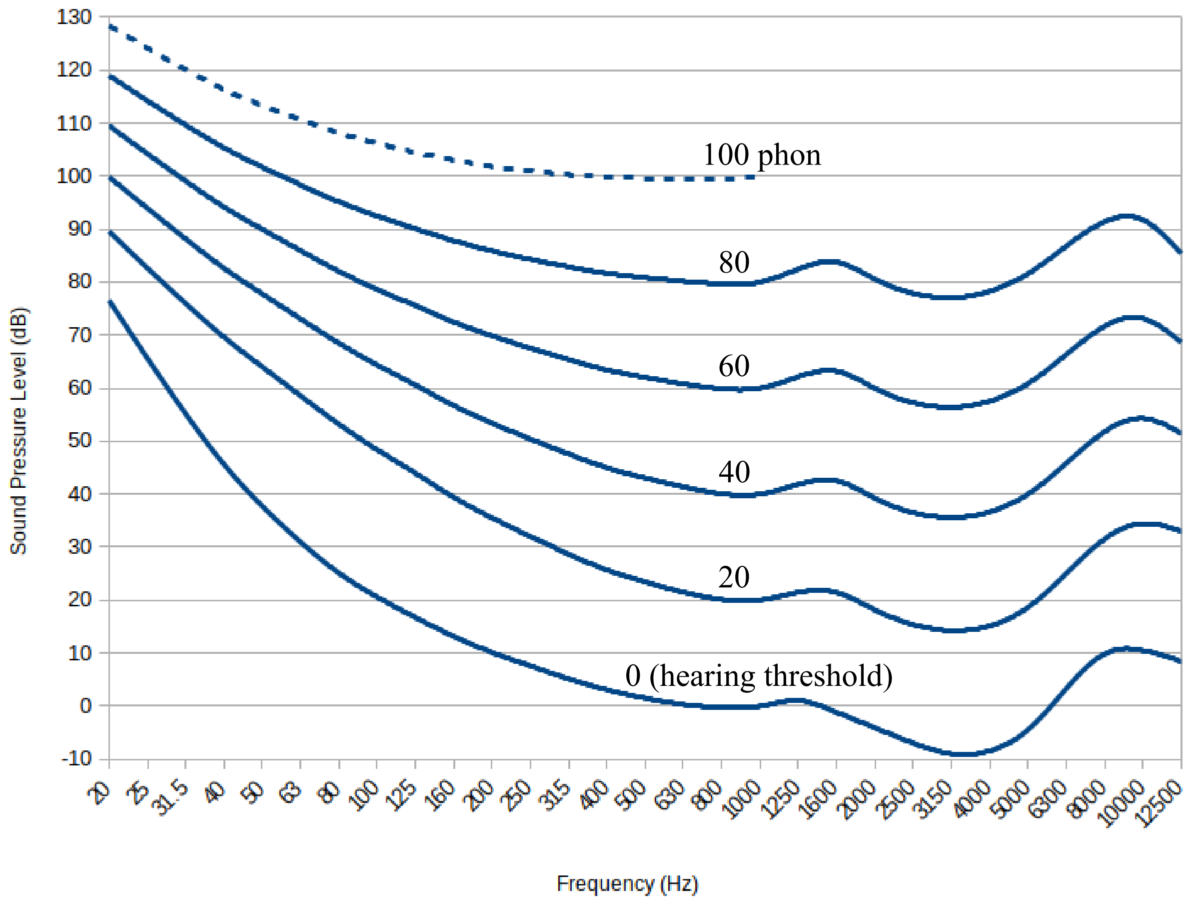

Figure A2.1. ISO 226 Equal Loudness Contours

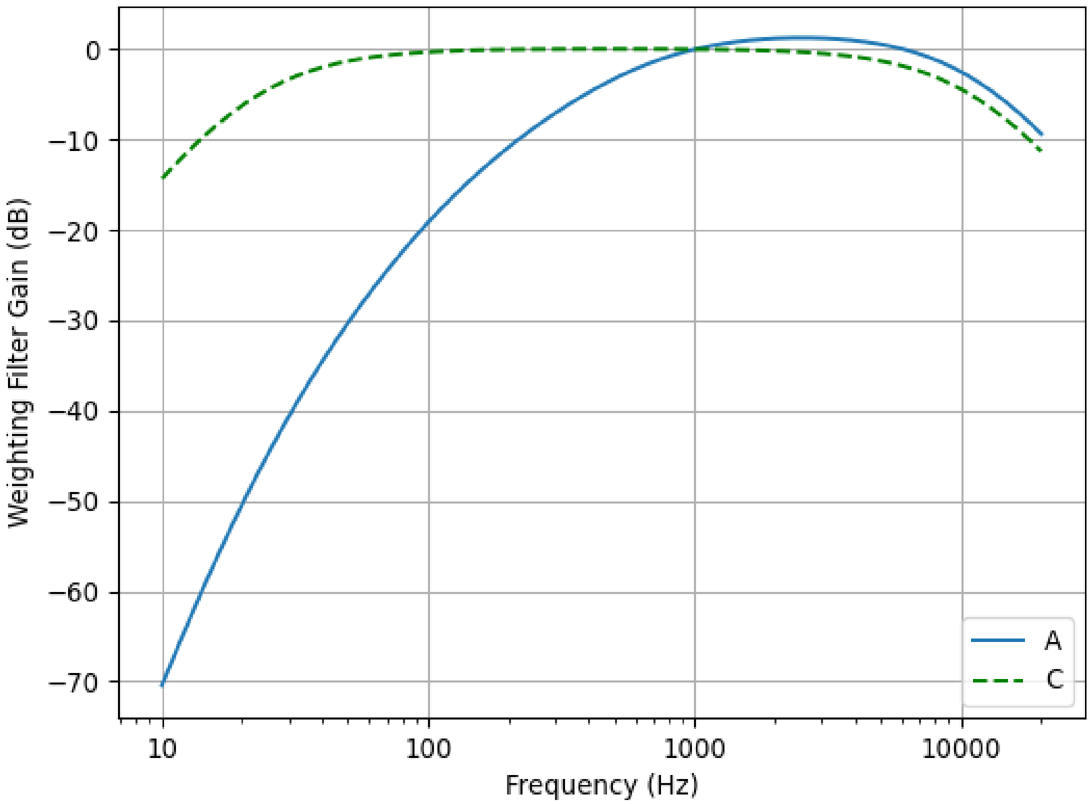

Figure A2.2. Frequency Weighting Filter Curves

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

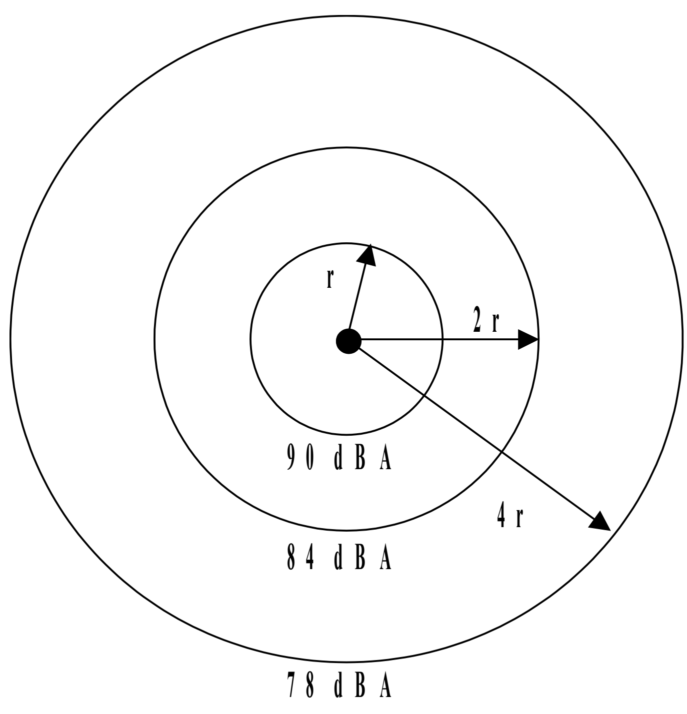

Figure A2.3. Decrease of SPL with Distance Due to Spherical Spreading

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.

$$65 \text{ dBA} + 65 \text{ dBA} \neq 130 \text{ dBA} \quad \textbf{WRONG} \tag{A2.2}$$

$$65 \text{ dBA} + 65 \text{ dBA} = 68 \text{ dBA} \quad \textbf{RIGHT} \tag{A2.3}$$

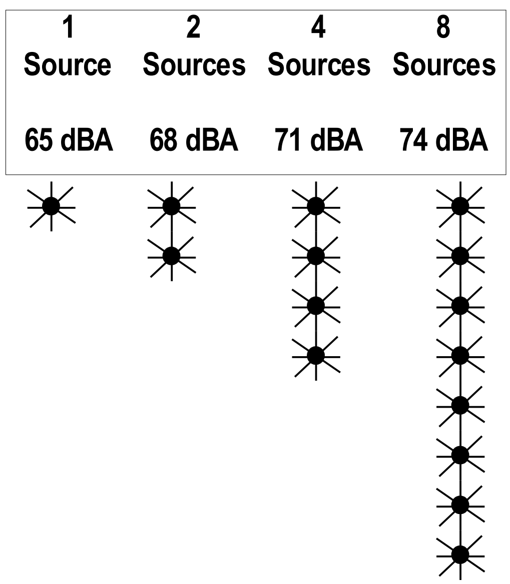

Figure A2.4. Total SPL from Multiple Sources with Equal SPL Output

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.