Appendix E

Bioacoustics Analysis of Potential Effects of Highway Noise on Wildlife of Great Salt Lake

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E.1 Introduction

Noise, defined as unwanted or annoying sound, can affect wildlife in a number of ways. Many animals detect and use sound to communicate, navigate, avoid danger, and find food (Bowles 1997; Bradbury and Vehrencamp 1998; Forman et al. 2003). Human-made noise, including highway noise, can interfere with these functions by blocking or masking important sounds and/or by inducing stress in the animals (Sarigul-Klin et al. 1997). These adverse affects can potentially alter the reproductive success, survivorship, habitat use patterns, distribution, abundance, and genetic composition of affected species.

Studies of the ecological effects of highways on grassland bird communities in the Netherlands (Reijnen et al. 1995; Reijnen et al. 1996) showed declines in both species diversity and abundance of birds near highways. Disturbance distances varied from 65 m (0.04 mi) to 3,530 m (2.19 mi) out from highways with traffic volumes of 50,000 vehicles per day (veh/d). Within this range, species experienced estimated population losses of between 12 and 52% at 500 m (0.31 mi) and between 14 and 44% out to 1,500 m (0.93 mi). In these studies, traffic noise was identified as the principal cause of these effects. Both visual disturbance and vehicular pollutants were found to extend only a short distance out from the roads, whereas traffic noise and reduced bird densities extended much farther (Reijnen et al. 1995). Both road-kill of birds and losses from predators moving along the road corridors have a comparatively negligible effect on avian diversity; moreover, such occurrences are evident only for a short distance from the road (Mumm et al. 2000). These occurrences are not, therefore, considered an important cause of most road-avoidance zones.

Additional studies on grassland birds in open patches near roads in a suburban landscape in Massachussetts showed significant reductions in reproduction up to 1,200 m (0.75 mi) from roads (Forman and Deblinger 2000; Forman et al. 2002). Road effects studies on amphibians, reptiles, and small mammals have shown similar population effects out to 2,000 m (Getz et al. 1978; Bowles 1997; Findlay and Houlahan 1997; Rudolph et al. 1999). Soil vibration and road-kill were suggested as the primary causes for the highway effects on amphibians, reptiles, and small mammals (Getz et al. 1978; Fahrig et al. 1995; Bowles 1997).

Comparable survey data are not available for the project study area. However, the effects described above are likely to be representative, if not conservative, estimates of the range of effects that noise disturbance resulting from the Proposed Action could have on local wildlife. The project study area includes large areas of pasture and agricultural lands that support many grassland species (Appendix A). Moreover, the projected traffic volume for the proposed Legacy Parkway project is significantly higher (approx. 72,000 veh/d vs. 50,000 veh/d) than that in the Netherlands study. Because noise levels increase with traffic volume (Forman et al. 2003), the area of potential noise disturbance from the proposed project would likely be comparable, if not higher than, those reported in the above described studies.

In a review of the Netherlands bird studies, however, Sarigul-Klijn et al. (1997) noted that such multi-species survey studies can potentially produce spurious conclusions because they lump species together and do not consider effects on the individual species level. Species in different environments have developed highly species-specific levels of vocalization complexity that vary widely in their acoustic properties (Dooling 1982; Bradbury and Vehrencamp 1998). While the Netherlands and other multi-species studies do show a wide range of responses to traffic noise, Sarigul-Klijn et al. recommended that before adopting noise limiting criteria [mitigation], it would be prudent to evaluate species-specific auditory capabilities and their behavioral responses to different background stimuli (e.g., natural sounds and highway noise). To examine how highway noise can potentially affect species directly, the following analysis considers species-specific characteristics.

E.2 Bioacoustics Background Information

This section presents an overview of acoustics terminology and concepts fundamental to understanding the complexities of highway noise analysis. A description of the methods used for this analysis follows.

E.2.1 Terminology

- **Sound.** A vibratory disturbance created by a vibrating object, which, when transmitted by pressure waves through a medium such as air, is capable of being detected by a receiving mechanism, such as a bird or mammal ear or a microphone.

- **Ambient Sound.** The all-encompassing sound associated with a given community site, usually being a composite of sounds from many sources, near and far, with no particular sound being dominant.

- **Frequency.** The pitch or tone of a sound. Technically, the number of times per second a sound wave passes a reference point, expressed as cycles per second or hertz (Hz). One hertz equals one cycle per second. High frequencies are more commonly expressed in kilohertz (kHz), or thousands of hertz. The normal range of frequencies that can be heard by the healthiest human ears is from 16 Hz to about 20,000 Hz (20 kHz). High-pitched sounds produce high frequencies; low-pitched sounds produce low frequencies.

- **Amplitude.** The loudness of sound, measured in decibels.

- **Decibel (dB).** A unitless measure of sound on a logarithmic scale, which indicates the squared ratio of sound pressure amplitude to a reference sound pressure amplitude. The reference pressure is 20 micro-pascals, the absolute threshold of hearing in healthy young adults. When using this reference threshold the measure dB is followed by SPL (Sound Pressure Level). Some sample sounds and their measured amplitudes are listed below.

- Rustling leaves 10 dB

- Quiet rural nighttime, soft whisper 20 dB

- Quiet urban nighttime, purring cat 30 dB

- Large conference room (background) 40 dB
- Classroom, nearby bird singing 50 dB
- Normal conversation, heavy traffic (at 300 ft) 60 dB
- Noisy urban area, gas lawn mower 70 dB
- Diesel truck (at 50 ft at 50 mph) 80 dB
- Roaring lion 90 dB
- Echolocating little brown bat 100 dB
- Thunder, rock band 110 dB
- Jet taking off nearby 120 dB

The decibel is a logarithmic measure of actual sound pressures. It is therefore important to recognize that the sound levels produced by two or more sources cannot simply be added to give the total combined sound level. Instead, the sum of the two sound levels must be computed as the root mean square (RMS) of the combined pressures. For example, if the sound of a distant truck passing by is 60 dB SPL by the time it reaches you, and that of car passing at the same time is 40 dB SPL at your ear, the amplitude of the combined sound you hear is not 100 dB SPL. The sound pressure of the truck is 1,000 times greater than the threshold of human hearing at 1 kHz, or about 0.2 dynes/cm^2. The sound pressure of the passing car is only 100 times greater than the same threshold, or about 0.02 dynes/cm^2. The combined noise level would be:

Combined pressures (RMS) = $\sqrt{(0.2)^2 + (0.02)^2}$ = 0.201 dynes/cm^2 = 60.04 dB SPL

This example shows that the additive affect of the noise from the car, which is only 10% of the pressure of the truck, contributes relatively little to the overall noise level of the combination. As a practical matter, the sum of two sound levels that differ by more than 10 dB is not affected by the lower sound level.

E.2.2 Noise Descriptors

- **dB(A).** A-Weighted Decibel. An overall frequency-weighted sound level in decibels that approximates the frequency response of the human ear.
- **Lmax.** Maximum Sound Level. The maximum sound level measured during the measurement period.
- **Lmin.** Minimum Sound Level. The minimum sound level measured during the measurement period.
- **Leq.** Equivalent Sound Level. The equivalent steady-state sound level that, in a stated period of time, would contain the same acoustical energy.

- **Lxx.** Percentile-Exceeded Sound Level. The sound level exceeded "x" percent of a specific time period. L10 is the sound level exceeded 10% of the time.

E.2.3 Bioacoustics Concepts

Sound Propagation and Attenuation

When an animal calls, the sound wave emitted can be envisioned as a sphere that expands as it moves away from the animal. The amount of energy being propagated by that sphere is fixed, equaling the energy used by the animal to give the call. With expansion, the area of the sphere increases (spherical spreading), but the intensity of the sound falls off proportionally as the square of the distance from the calling animal. The sound level attenuates, or drops off, at an ideal rate of 6 dB for each doubling of distance. Excess attenuation is the additional falloff in intensity due to sound absorption and scattering resulting from local variation in air temperature, wind, humidity, and habitat and substrate composition.

If the sound source is long in one dimension, such as traffic on a highway or a long train, the sound source is considered to be a line source. As a general rule, the sound level from a line source will drop off at a rate of 3 dB per doubling of distance. If the intervening ground between the point or line source and the receptor is acoustically *soft* (e.g., ground vegetation, scattered trees, clumps of bushes), the rate of attenuation increases by 1 to 2 dB per doubling of distance.

Meteorological effects such as wind, temperature, and humidity can also have a substantial effect on how sound propagates over large distances (i.e., greater than about 152 m [500 ft]). These effects can either increase or decrease sound levels depending on the orientation of the source and receptor and the nature of the particular effect. As a practical matter, these effects cannot be reasonably evaluated in environmental noise predictions. Understanding these effects, however, can help explain variations that occur between calculated and measured sound levels.

The science of highway traffic noise analysis has traditionally focused on the effects of noise on humans. Accordingly, sound-level meters and traffic noise models have been developed primarily to provide A-weighted sound levels. Because the hearing response curves of nonhuman species are different from those of humans, A-weighted sound levels may not be appropriate for assessing noise impacts on wildlife. In this discussion, A-weighted sound levels are used to generally describe the traffic noise environment because this is the primary single number result that is provided by the traffic noise model. For the purposes of assessing noise impacts on wildlife, a more specific discussion, using the un-weighted 1/3 octave spectra generated by the model, is also provided.

Sound Perception

Most people have difficulty distinguishing the louder of two sound sources if they differ by less than 1.5–2.0 dB. Research into the human perception of changes in sound level indicates the following parameters.

- A 3-dB change is just perceptible.
- A 5-dB change is clearly perceptible.
- A 10-dB change is perceived as being twice or half as loud.

A doubling or halving of acoustic energy changes the resulting sound level by 3 dB, which corresponds to a change that is just perceptible. In practice, this means that a doubling of traffic volume on a roadway or doubling the number of wind turbines in a wind farm will, as a general rule, only result in a 3-dB (or just perceptible) increase in noise.

Sound Masking

Sound masking is the mechanism by which one sound (e.g., highway noise) interferes with the hearing of another sound (e.g., animal vocal signals). Species that have evolved complex vocalizations may be subject to significant biological impacts if they cannot hear their own species' signals because of masking by noise (Sarigul-Klin et al. 1997). Also, species that rely on hearing to detect danger (especially the presence of predators) and to navigate could be adversely affected if this ability is impaired by noise interference.

Spectrum Level Analysis

In contrast with the broad-spectrum noise analysis approach typically employed in noise impact analysis for effects on human receptors, bioacoustic scientists that study auditory masking in wildlife commonly measure noise levels in terms of power per hertz or power per cycle (Dooling 2002). This per-hertz energy distribution in a noise is referred to as the *spectrum level* of noise. It is different from the broad-spectrum measure described above in that the spectrum level reflects the amount of energy in a single frequency, not that present in a broad frequency range. If a noise is relatively constant in amplitude, the difference between these two measures (i.e., broad-spectrum vs. spectrum-level) is approximately 40 dB. The spectrum level can be calculated by subtracting ten times the log of the bandwidth of the noise (or 40 dB) from the overall noise level (65 dB). In this example—where the overall noise level registering on the sound level meter is 65 dB SPL—the spectrum level (i.e., the energy in a single cycle of noise) is approximately 40 dB lower than the broad-spectrum level, or about 25 dB SPL, given that the energy is distributed equally across the entire band.

This difference between these analysis methods is important because, while the overall sound pressure level readings from a sound-level meter are commonly used to describe highway noise, the auditory system of wildlife potentially affected by this noise is only concerned with those frequencies in the noise immediately surrounding the signal. The two measures are not the same. The spectrum level analysis more accurately allows measurement of how far out from the highway traffic noise can mask the vocal signals of different species or different signals of the same species (e.g., songs as opposed to soft calls in birds). The spectrum level in the region of the animal's signal is the most useful in calculating signal-to-noise ratios and determining whether the signal can be detected above the noise by other animals at biologically important distances.

Wildlife Audibility Curves

The minimum audible sound that can be detected in quiet across an animal's frequency range of hearing defines its audibility curve. Audibility curves are unique to each species and differ between and within species. Figure E-1 shows typical variation in the audibility curves of assorted bird species.

Birds hear best at frequencies between about 1 and 5 kHz (Dooling et al. 2002), with absolute sensitivity approaching 0–10 dB SPL at the most sensitive frequency—generally 2–3 kHz (Dooling 1980, 1982, 1992). Owls can generally detect softer sounds than either songbirds or non-songbirds over their entire range of hearing (Dooling et al. 2002). Songbirds hear better at high frequencies than non-songbirds, and non-songbirds hear better at low frequencies than songbirds. On average, the sound “space” available for birds for vocal communication extends from about 0.5 kHz to 6.0 kHz (the frequency range 30 dB above the most sensitive region of the typical audibility curve). Studies also show that there tends to be a correlation between hearing sensitivity at high frequencies and the highest frequencies contained in the species’ vocalizations (Dooling 1980, 1982; Dooling et al. 2002).

Signal Detection, Discrimination, Recognition, and Identification

Signal detection only may not be sufficient for wildlife species to respond appropriately to different behavioral contingencies. It is also important that the listener be able to discriminate the sound from other similar sounds and to recognize the sound. For example, the listener must be able to determine whether the sound is a natural sound or if it originates from a conspecific or from a potential predator; additionally, it is necessary to discriminate between, for example, a neighboring territorial male’s defense song, a potential mate’s availability signal, and a begging call from a chick (Sarigul-Klign et al.1997). It is important to recognize, therefore, that different levels of highway noise may affect these different levels of perception unequally. While loud traffic noise may make all of these perceptual functions impossible, an intermediate level of noise could permit detection, but hamper discrimination and prevent recognition and identification. Low-level noise might have minimal effects on detection and discrimination, interfere moderately with recognition, but make accurate identification difficult. This differential masking effect is potentially very important for species that use complex vocal signals (e.g., bird songs) that contain a variety of signals of different amplitudes, as well as for species that have multiple calls used in different behavioral situations requiring variable distances for effective communication (e.g., a parent-offspring warning call at or near the nest contrasted with a territorial male singing from an elevated perch to a rival male in a neighboring territory). The potential masking effects of the highway noise is therefore not only a function of the amplitude, frequency, and acoustic characteristics of the noise, but also the communication requirements of the species under consideration and the acoustic variability of their signals.

Acoustic Variation in GSLE Birds

Table E-1 summarizes the acoustic characteristics of many of the bird species identified as occurring or potentially occurring within the project study area. These species have been sorted in ascending order by the lowest frequency characteristic of signals in each species’ vocal repertoire. The shaded cells in the Vocalization Frequency Range columns provide a visual summary of the vocal diversity within and across these species. The repertoires of species at the top of the chart have the lowest-frequency sounds, but these repertoires may also include high-frequency signals. The species at the bottom of the chart tend not to have low-frequency signals in their repertoires.

These data show that while some species, such as owls, bitterns, herons, and some passerines (e.g., Mourning Doves), tend to use low-frequency signals, and others, such as many songbirds and shorebirds, have songs and calls that include signals with much higher frequencies, there is no clearly discernable pattern defining vocal patterns used in specific habitats. There is essentially a continuum of vocal signals used by the birds in all habitats within the project study area.

Active Space

Many birds use a variety of different vocal signals to communicate with conspecifics, including loud songs used for territorial defense and mate attraction, high-pitched predator warning calls, inter-mate and flock contact calls, and the soft begging calls of nestlings. The distance over which these signals can be heard varies with their function. Songs are believed to have evolved to provide optimal long-distance transmission to attract mates and deter rivals (Marler 1955; Wiley and Richards 1982; Klump et al.1986). Softer calls are mostly limited to short-distance communication. When the amplitude of the signal is attenuated over distance to a level equal to the sensory threshold of the receiver, the maximum transmission distance of the signal has been reached. The three-dimensional volume in which these signals can be detected and recognized by a receiver is referred to as the *active space* of the signaler (Marten and Marler 1977; Brenowitz 1982).

E.3 Methods

E.3.1 Approach

The nature and extent of noise disturbance associated with highway traffic depends largely on the acoustic characteristics (e.g., frequency, duration, loudness, periodicity) of the noise; the sound attenuation properties of the adjacent habitat; the hearing capacity and sound requirements of the species potentially affected; their stress response levels; and the distance the animals are from the highway. Because birds communicate vocally and are the wildlife group most likely to be most affected by road noise, they were selected as the focus of this analysis. Three species—American Bittern, Black-necked Stilt, and Brewer's Sparrow—were selected for this analysis because they represent the breadth of avian vocal capabilities of the species occurring in the Proposed Action area. American Bitterns use intense, low-frequency calls to communicate with conspecifics (Gibbs et al. 1992). This acoustic pattern is well suited for transmission of sound through dense vegetation typical of the bittern's emergent marsh habitat (Bradbury and Vehrencamp 1998). Black-necked Stilts are open area flocking birds that use loud, high-frequency calls (Robinson et al. 1999). Brewer's Sparrows are territorial, desert scrub birds that use complex songs of varying frequency and intensity to maintain their territories (Rottenberry et al. 1999). Additional analysis was conducted on the acoustic requirements of Barn Owls and domestic cats to assess the potential effects of road noise on masking important environmental sounds used by local Barn Owls and cats for predator/prey detection.

The principal objective of this analysis was to estimate the area of potential effects of noise on wildlife within the project study area. To do this it was first necessary to measure the existing background sound levels, then model the potential future noise conditions associated with each project alternative. The main criterion used to evaluate noise effects in this analysis was the masking potential of the highway noise. This measure is a function of not only the acoustic properties of the highway noise, but also of the vocalizations/environmental sounds that could be affected. Based on measurements of these properties and determination of the critical ratios of hearing for different species (see *Background Information* below), masking thresholds were determined for the highway noise at varying distances from the proposed rights-of-way. All these factors were evaluated for effects on the sound detection ability of individuals at varying distances from the proposed rights-of-way, as well as between pairs of communicating individuals (e.g., neighboring territorial birds) at varying distances between each other and from the highway. When the highway noise level exceeded the amplitude of the vocalization, it was considered to have a potential effect on that species. The approximate distance from the highway that this effect could occur was estimated, and an area of potential indirect effects was calculated. Various aspects of predictable variability in the highway noise and behavioral adaptations used by wildlife to reduce the masking thresholds, and hence the effective impact area, were also evaluated.

E.3.2 Analysis Methods

The methods used in this analysis are summarized and described below.

- The noise levels in the project study area were measured to determine existing conditions. This analysis included both short-term (1-hour) and long-term (3-day) measurements at selected locations.
- Using data on expected traffic loads during peak hours on the proposed highway, future noise levels were modeled to evaluate how the project alternatives would change the traffic noise environment.
- The area of potential noise impact adjacent to the proposed highway was determined by plotting absolute noise level contours and noise change contours over the wildlife habitat map.
- The acoustic characteristics of the highway noise (frequency and amplitude profiles over distance from the highway) were detailed to provide baseline information from which to calculate potential masking thresholds.
- The general hearing capacities (auditory curves) of representative birds, mammals, amphibians, and reptiles were determined from literature research.
- The critical ratio profiles of these vertebrate groups were estimated.
- The masking thresholds for birds were calculated and plotted.
- The source amplitudes of vocalizations of each of the study birds was calculated, and the frequency range of each species' acoustic signals was determined from the literature.
- Highway noise impact distances were estimated by simultaneously plotting the highway masking thresholds and the acoustic profiles of each species.
- Based on comparison of the acoustic properties of each study species and the masking thresholds, the potential for highway noise to mask other species of wildlife within the project study area was evaluated.
- Using similar analysis methods, the potential impact distances of highway noise on predator/prey detection by owls, bobcats, and mice were estimated.

E.3.3 Existing Sound Environment

Short-Term Field Measurements

Field noise measurements were taken on July 1 and 2, 2003, in the open space and wildlife areas west of the project study area (Figure E-2). A series of short-term measurements, typically 10–15 minutes in length, were taken at selected locations over the 2-day period. The short-term measurements were made using a Larson-David Model 812 Type 1 sound-level meter. The meter was placed on a tripod with the microphone 1.5 m (5 ft) above the ground. The calibration of the meter was checked before and after each measurement with a Larson-Davis Model CA250 calibrator. Local meteorological conditions at each measurement position were noted using a Kestral Instruments Model 3000 handheld weather meter. Sound-level data were sampled in 1-minute intervals at each position. Acoustical events that occurred during each minute were noted. At selected positions, sound level data were also collected at 1-second intervals so that discrete variations in sound levels could be observed. Figure E-2 depicts the measurement positions.

Skies were clear during both days. On July 1, high wind conditions (average wind speed of 9–24 kph [8–15 mph]) generally prevailed throughout the afternoon. In the early evening, winds reduced to 3–6 kph (2–4 mph). On July 2, winds were relatively calm. During the high winds, local noise levels were typically elevated by wind blowing through vegetation. In addition, at wind speeds above approximately 19 kph (12 mph), noise generated by wind blowing across the microphone can begin to contaminate the measurement. During the high wind conditions, there was little if any bird activity, and therefore little if any sound generated by birds. On July 2, when winds were substantially reduced, there was a marked increase in bird activity and audible bird vocalizations. Because of the proximity of the measurement positions to the airport, noise from aircraft overflights occurred during many of measurements.

Long-Term Field Measurements

Long-term measurements were taken over a 34-hour period beginning at 11:00 a.m. on July 1, 2003. The long-term measurements were conducting using Larson-Davis Model 700 sound-level meters. Figure E-2 depicts the measurement positions. Hourly wind speed data were taken from data collected by Salt Lake City International Airport.

E.3.4 Legacy Parkway Traffic Noise Modeling

Projected future traffic noise levels for the Legacy Parkway were estimated using the Federal Highway Administration Traffic Noise Model (TNM) Version 2.1. Based on predicted peak traffic volumes given in the Legacy Parkway Final EIS, a traffic volume of 1,800 vehicles per hour per lane, or 7,200 for four lanes (72,000 veh/d), was used. This model assumes neutral meteorological conditions and therefore does not take into account the effects of wind, temperature, or other meteorological factors on noise level. The noise level contours generated by the TNM have not yet been verified beyond 305 m (1,000 ft). The locations of contours beyond this distance are projected estimates only and could vary significantly depending on existing background noise, atmospheric conditions, and substrate type.

E.3.5 Sound Masking Threshold Determination

Bird Auditory Curves

The auditory threshold curves, established on the basis of behavioral responses, have been obtained for 14 species of birds, comprising songbirds, non-songbirds, and nocturnal predators (Dooling 2002). An average curve for 10 species of birds was developed as part of the Dooling study. In practical terms, the auditory curve is the absolute threshold level in decibels above the *spectrum level* (power per hertz) of the background noise that a pure tone must be in order to be heard. Table E-2 summarizes the decibel values reported for the 10-bird average (Dooling 2002).

Highway Sound Masking Thresholds

TNM calculates 1/3 octave traffic sound pressure levels. The traffic noise spectrum level at various distances from the highway has been estimated by assuming that traffic noise is broadband in nature (i.e., equal energy across the 1/3 octave band). With this assumption, the spectrum level of the predicted traffic noise can be estimated by calculating 10 times the logarithm of the 1/3 octave bandwidth and subtracting this value from the 1/3 octave sound pressure level. The masking threshold for a given traffic noise 1/3 octave traffic noise spectrum is then calculated by adding the masking threshold for each 1/3 octave band determined from Table E-2 to the 1/3 octave band traffic noise spectrum levels. The 1/3 octave band masking thresholds were interpolated from the octave thresholds presented in Table E-2.

Bird Vocalization Profiles

To assess whether highway noise could potentially mask wildlife vocalizations in the project study area, information on the acoustic characteristics of species with known or potential occurrence in these areas was obtained from the literature where possible. For birds, this information was obtained from *The Birds of North Americ*a species accounts (Poole and Gill). Information obtained included the minimum, maximum, median, and range of frequencies used in all described vocal signals; an index of structural complexity; and a notation of whether the vocalizations included marked frequency modulation and/or harmonics. Because contrasting signals can often be detected against background noise below the masking threshold (Klump 1996), the information on the vocal signal structural complexity, frequency modulation, and use of harmonics was used to evaluate whether the vocal signals of each species could be detected at greater than expected distances due to these properties.

Masking Distance Calculations

To estimate masking distances for each bird species, a spectral analysis was conducted of prerecorded calls for each bird. Spectral analysis was conducted for the loudest part of the call and the softest part of the call. The peak frequency of the call was identified through this analysis. Because the prerecorded calls were simply recorded audio signals with no sound-level calibration, source amplitudes for each species were estimated using a body size-to-sound power output formula presented by Calder (1990):

$$P = 0.042m^{1.14}$$

where P is the sound power output in milliwatts adjusted to a distance of 1 m (3.3 ft) from the bird and *m* is the body mass in kilograms. These power outputs were converted to SPL (dB) values, and the overall sound level of the bird call spectrum was then scaled up to match the reference value. The corresponding pea- frequency sound level was taken as the reference value at 1 m (3.3 ft) for the peak frequency of the call. To evaluate the sound level of the call between two birds at various distances, simple point source attenuation of 6 dB per doubling of distance was applied to the call reference value. Figures E-10 and E-11 show the bird call sound level as a function of the distance between two birds. The highway noise masking level at various distances from the freeway for the peak frequency of the call is also plotted. A comparison of the call sound level to the masking level indicates the distance between birds at which calls would be masked.

E.3.6 Noise Effects and Impact Area Analysis

Highway noise was considered to have a potential impact on birds if:

- there was an overlap in frequency/amplitude spectrum of the highway noise and the vocal signals of species or environmental sounds on which they depend for normal survival and social behavior, and
- the amplitude of the highway noise exceeded the masking threshold of the species for vocal signals such that it could potentially impede the normal behavior of the species in a biologically significant way.

Noise Effects Area

From the model results, absolute noise level contours (A-weighted) were developed for each of the alternatives (Figure E-3). The noise contours, when placed over the wildlife habitat map, allow calculation of the extent to which each habitat can be affected by noise levels defined by the contours. In addition to the modeling analysis described above, TNM was used to develop 1/3 octave band traffic noise levels at various distances from the roadway.

Other Wildlife Species Potentially Affected by Noise

Wildlife habitats that could potentially be affected by noise from the Legacy Parkway project were identified by overlaying the GIS noise level contours (as described above) onto the wildlife habitat map (Figure 2-6 in the *Legacy Parkway Wildlife Impact Analysis* [Technical Memo]) and identifying all habitats that occur within these contours. Wildlife species that are known to occur or could potentially occur within these areas and that were consequently subject to noise impacts were identified by filtering the species-habitat matrix (Appendix A) for species that use the habitat types found within the noise contours. To evaluate the range of possible effects on different wildlife species, three bird species—American Bittern, Black-necked Stilt, and Brewer's Sparrow—were selected because their vocal signals span a range of frequencies potentially affected by highway noise. For analysis of the potential effects of highway noise on predator/prey detection sounds, the acoustic hunting requirements and environment of Barn Owls and cats were evaluated.

E.4 Results

E.4.1 Short-Term Noise Measurements

Table E-3 summarizes the sound levels for the short-term measurements at each sampling location in the study area. The loudest noise values (Lmax) ranged between 53 and 79 dB(A) (Mean +/- Standard Deviation = 64.3 +/- 7.6); the lowest noise values (Lmin) ranged between 31 and 45 dB(A) (Mean +/- Standard Deviation = 35.4 +/- 4.7). During the measurement periods, the sound levels exceeded, on average, 51 dB(A) 10% of the time (L10), 43 dB(A) 50% of the time (L50) and 39 dB(A) 90% of the time (L90). The highest Lmax values were generally associated with plane overflights; the highest wildlife signals (duck vocalizations) were approximately 52 dB(A) (at approximately 30 meters from the microphone). The mean equivalent steady state sound level (Leq) across the entire study area was 48.6 dB(A) (S.D. = +/- 6.6) with a minimum value of 37.1 dB(A) and a maximum value of 59.9 dB(A).

E.4.2 Long-Term Noise Measurements

Figure E-4 shows the long-term hourly sound levels and the local wind speeds measured at survey location L1. The wind speed profile shows the wind speeds recorded at Salt Lake City International Airport for July 1–3, 2003; this profile is the same in each figure.

Table E-4 presents the mean, standard deviation, minimum, and maximum sound levels measured at the three long-term measurement stations in the study area (Figure E-2). The highest noise level (81 dB[A]), was recorded at location L1, closest to I-15; the lowest value (32 dB[A]) was recorded at L2. The mean equivalent steady state sound level (Leq) across the entire study area (L1–L3) was 50 +/- 10 dB(A), with a minimum value of 36 dB(A) and a maximum value of 78 dB(A). Overall, sound levels exceeded 51 +/- 11 dB(A) 10% of the time, 45 +/- 8 dB(A) 50% of the time, and 40 +/-7 dB(A) 90% of the time. There were no significant differences in the mean values for Leq, L10, L50, or L90 between the long-term sound level measurements (Table E-4) and the short-term measurements (Table E-3) ($P > 0.1$; df = 148 for all comparisons). However, the ranges of sound levels recorded for these values (Leq, L10, L50, L90) were significantly larger for the long-term measurements ($P < 0.01$; df = 6). On average, the noise levels (Leq, L10, L50, L90) recorded at L2 were significantly lower than those recorded at L1 ($P < 0.001$; df = 88) and at L3 (Student's t test; $P < 0.001$; df = 88). The same values recorded at L1 and L3 were not statistically different ($P > 0.1$; df = 88).

E.4.3 Modeled Legacy Parkway Traffic Noise

Existing Noise Levels

Figure E-3 shows the background noise-level contours for the No-Build Alternative. Background noise levels for the project study area would be identical to those described above for existing conditions.

Projected Noise Levels

Figure E-3 shows the projected future noise level contours modeled for the Alternatives A, B, C, and E. Differences in the patterns of noise level for each alternative are a function of the physical alignments of each right-of-way. The baseline traffic noise data used for modeling the noise contours were the same for each alternative.

Change in Noise Level

Wildlife can be affected not only by the intensity of noise, but by the relative change in intensity. For example, species already experiencing high levels of noise may not "notice" a 10–15 dB(A) change from highway noise. However, species currently experiencing only low-level natural background noise could readily notice a change in noise level that could interfere with communication.

E.4.4 Highway Noise Impacts

Species Hearing Capacity

Figure E-1 shows the amplitude-frequency masking profiles of highway noise adjusted to accommodate the amplitude profiles of an average songbird. Also shown in this figure is an average hearing curve of a non-passerine bird, as well as those of an owl, a cat, and a human. These curves indicate the amplitudes at each frequency above which the species represented can theoretically (under laboratory conditions) detect an acoustic signal. Any vocal signal above this threshold and above the traffic noise masking threshold at each survey distance can be detected by the subject species. If the vocal signal falls below the hearing curve, it cannot be heard by that species. If it is above the hearing curve, but below the masking threshold line of the highway noise, it cannot be detected due to masking. For example, a 30 dB 200 Hz signal (Point A) could not be heard by a non-passerine bird because it is below the hearing curve (Figure E-1). A 30 dB 1 kHz signal (Point B) could be detected by the non-passerine bird because it is above this curve, but would be masked by highway noise at distances closer than 1,219 m (4,000 ft). Finally, a 75 dB 1425 Hz signal (Point C) could be heard by the non-passerine bird at distances closer than 38.1m (125 ft) and would be minimally affected by highway noise.

The differences in the shape and locations of the hearing curves reflect differences in the hearing capabilities of each species. The lower the curve on the graph, the more sensitive the species is to hearing low-amplitude sounds. The owl, for example, can hear the lowest sounds, with a peak sensitivity at 4,000 Hz. The cat is comparable in its hearing capabilities; this correlation is likely associated with the two species' similar prey detection requirements and capabilities. The non-passerine bird (e.g., a kestrel) does not have as acute hearing requirements, but is notably better able to hear lower sounds than the bird represented by the generalized top curve.

It is important to note that with regard to masking effects of the highway noise, the amplitudes of the vocal signals described above are those that the receiver hears, not those emitted by the individual giving the call. All sounds, including vocal signals, attenuate with distance. Therefore, as the distance between communicating individuals increases, the amplitude of the sound received by the listener decreases and the relative potential for highway noise to mask the signal increases. The importance of this relationship is that individuals communicating at distances sufficiently close to maintain amplitudes of the received signals above the masking thresholds can communicate effectively; however, if the same individuals move apart, vocalizations could attenuate to levels below the masking threshold, and the highway noise could impede communication. This spatial relationship is further complicated by the positions of the birds relative to the highway. If they are parallel to the highway, the attenuation of their vocal signals will follow the inverse square law for attenuation, with the highway noise remaining essentially constant. However, if the birds are aligned perpendicularly to the highway, both the vocal signals and the highway noise attenuate simultaneously over the distance between the birds, if the caller is closer to the highway. If the caller is the individual farther from the highway, the vocal signal attenuates over the distance to the receiver, but the masking threshold is higher at the receiver's location than at the caller's.

The spatial relationship is particularly important in evaluating the potential for masking of territorial defense or mate attraction vocalizations given by territorial species. Depending on the proximity of the territories to the highway, the singers may or may not be able to communicate over distances typically required for territorial maintenance. These distances may be determined by factors other than communication constraints, notably the area required to provide sufficient food and shelter resources for the female and nestlings. If highway noise precludes communication over these requisite distances, the males may not be able to effectively attract mates and/or successfully reproduce in the area. Additionally, the distances over which soft calls can be effective between adults and between adults and young may be constrained by proximity to the highway; such constraints may lead to miscommunication or missed communication, with resultant failed behaviors (e.g., failure to adequately feed nestlings, failure to warn nestlings of a predator nearby).

Species Acoustic Profiles

Figures E-5, E-6, and E-7 show the vocal signal profiles of American Bittern, Black-necked Stilt, and Brewer's Sparrow, respectively, and the traffic noise masking threshold spectrum. These charts show the peak frequencies (maximum amplitude) of each species' vocal signals relative to the masking potential of the highway noise at different distances from the highway. Also included are vocal signals of the same species as they would be heard by a conspecific at 15.2, 30.5, and 45.7 m (50, 100, and 150 ft) (the yellow, blue, and green lines). Note that the peak frequency (highest point on the signal profile) for the American Bittern is approximately 200 Hz, with a secondary peak of lower amplitude at approximately 1,000 Hz. The peak frequencies of both Black-necked Stilt and Brewer's Sparrow are approximately 4,000 Hz. When one compares the signal profiles of each bird with the traffic noise masking thresholds it is possible to determine the relative potential that the signals will be masked at different distances from the highway, as well as the maximum distances at which individuals can communicate at different distances from the highway without their signals being masked.

One important aspect of comparing vocal signals of different species is the inherent variation and complexity in the signals in each species' repertoire. Figure E-8 shows the sonograms of the three species being analyzed in this technical report. While the structure of the calls of American Bittern and Black-necked Stilt are relatively simple, that of the Brewer's Sparrow song is highly complex, with multiple signals of varying frequency and amplitude. Figure E-9 shows the power spectrum of a typical Brewer's Sparrow song. Note the variation in amplitude between element groups. This variation is an important determinant of the transmission capacity of the song as a whole and the potential for highway noise masking part or all of the song (see below). The limiting factor in both processes is the relative amplitude of the individual elements. The complete song will be successfully transmitted and received only if the intensity of the softest element is sufficient to reach the receiver and be recognized above background noise.

Vocal Signal Masking

Two important highway noise characteristics should be noted. First, the potential for masking is highest at the lower frequencies (50–225 Hz). Second, the masking effect is less at higher frequencies for all distances from the highway due to differential attenuation of sound (traffic noise) with distance. By comparing the positions of the three species' vocal signal profiles, it becomes evident that the American Bittern profile, which has the lowest peak frequency, is most aligned with the area of highest masking potential from highway noise (50–225 Hz). The Black-necked Stilt and Brewer's Sparrow profiles are shifted much farther to the right, where the masking potential is reduced at the higher frequencies. What these differences mean is that because low-frequency sound (traffic noise) travels farther without significant attenuation, the potential for highway noise to mask bittern calls will extend to a greater distance from the highway than will the potential to mask either the Black-necked Stilt of Brewer's Sparrow calls. Inversely, Black-necked Stilts and Brewer's Sparrows can effectively communicate closer to the highway than can bitterns, given the same level of traffic noise.

When one examines the sets of three parallel signal profile curves for each species and compares their position relative to the masking profile lines, it becomes evident that as individuals move apart, the amplitude of their signals attenuates proportionally to the distance between them. The greater the distance, the softer the signal will be at the receiver. Accordingly, if the birds move apart parallel to the highway, the traffic noise level will remain constant, but because the vocal signal attenuates with the distance between the birds, the masking effect will increase. For example, the Black-necked Stilt signal, represented by the secondary peak at 1,250 Hz, could be heard at 152.4 m (500 ft) from the highway when the birds are 15.2 m (50 ft) apart, but would be masked by traffic noise if the birds were to move 30.5 m (100 ft) apart.

This differential masking effect with communication distance is perhaps more clearly illustrated in Figures E-10 and E-11, which show the natural attenuation of vocal signals for each species and the distances the birds can move apart at different distances from the highway before traffic noise will mask their signals. In Figure E-10, the differences in the heights of the attenuation lines of the Black-necked Stilt and the Brewer’s Sparrow is a function of the source amplitude of the signals: Black-necked Stilt calls are louder than Brewer’s Sparrow vocal signals (elements in a song). The lower Brewer’s Sparrow line indicates the attenuation of the softer element in the song (see discussion below). This figure shows that due to the strength of the Black-necked Stilt call, individuals can communicate effectively at inter-individual distances of 76.2 m (250 ft) or more without masking from traffic noise. Brewer’s Sparrows, however, would be restricted to communication distances of 15.2 m (50 ft) when both are 15.2 m (50 ft) feet from the highway, 45.7 m (150 ft) at 38.1 m (125 ft) from the highway, and 76.2 m (250 ft) feet at 76.2 m (250 ft) feet from the highway

These results illustrate several important aspects of the species-specific nature of traffic noise impacts, which can only be properly interpreted relative to the biology of each species. Black-necked Stilts are very gregarious, with nonbreeding inter-individual distances typically averaging only 0.03 m (0.1 ft) and breeding distances averaging 0.5 m (1.6 ft). The amplitude of their call (99 dB) is easily high enough to offset interference from highway noise (75 dB) at these distances, and even to allow inter-individual communication with other individuals that are 76 m (250 ft) or more away (Figure E-10). This longer-range communication may be critical for individuals to warn other birds of predators and/or to solicit a mobbing response from others when a nest is being preyed upon (Robinson et al.1999). Because of this vocal pattern, Black-necked Stilts are not likely to be affected by traffic noise from the Legacy Parkway project.

By comparison, Brewer’s Sparrows maintain territories with center-to-center distances ranging between 35.4 m and 178.6 m (116 ft and 586 ft) (calculated from territory size data in Rottenberry et al. 1999). Figure E-10 (top curve) shows that in order to communicate at these distances using the loudest song elements (86 dB), the territories would need to be approximately 30.5–152.4 m (100–500 ft) from the highway, respectively, to avoid masking. For complete transmission of the song, including the softest notes (66 dB at the source) (Figure E-10 bottom curve), the territories would need to be approximately 300–610 m (1,000–2,000 ft) from the highway. These distances define the noise impact zone for this species.

Finally, Figure E-11 shows the same masking potential relationship for American Bittern. As described above, because of the lower dominant frequency (200 Hz) in this species’ principal vocal signal and the predominant low-frequency characteristics of the highway noise, the traffic noise masking effects are greater despite a high source amplitude (104 dB). However, this species requires this high intensity, low frequency sound to communicate effectively through the dense vegetation of its emergent marsh habitat. No information is available on territorial behavior or spacing of nests in American Bitterns (Gibbs et al. 1992), but males within range of about 500 meters (0.31 mi) are known to respond to each other’s calls. Figure E-11 shows that in order to communicate effectively at this distance without masking from traffic noise, the birds would have to be more than 4,800 m (16,000 ft or 3.03 mi) from the highway. For this species, this distance defines the potential noise impact zone within the project study area.

One aspect of these distance predictions not included in the calculations is the effect of the sound of wind on the hearing capacity and communicating ability of these species. Wind and air turbulence can affect communication in two ways: disruption of signals and creation of additional noise. Wind blowing over irregular surfaces can generate local vortices in the air within which the speed of sound and the density of the air differ from the surrounding medium (Bradbury and Vehrencamp 1998). These vortices can scatter sound—acoustic signals from birds as well as highway noise. Such disruptive turbulence is more likely to be found in open areas where the sun can heat the ground to create thermal currents and/or where strong winds blow over irregular surfaces such as rocks and clumps of vegetation. The presence of wind turbulence can significantly increase the rate of signal attenuation over distance (Wiley and Richards 1982). Without wind, sound naturally attenuates at approximately 1-12 db/100m (328 ft) for frequencies of 1–10 kHz. With wind and turbulence attenuation, rates can increase from two to several hundred dB/100 m (328 ft). Such conditions can result in significant reduction in the distances sound, including highway noise, can be heard. Gibbs and Melvin (1993) noted that calling activity in American Bitterns in response to playback surveys was dampened by winds > 5 kmh (3.1 mph). This is likely due to a reduced ability of the birds to hear the signals, to which, under quiet conditions, they can respond at 500 m (1,640 ft or 0.31 mi.) Similarly, the transmission distance (masking effect) of highway noise is likely to be reduced by wind-generated air turbulence in direct proportion to wind velocity.

Wind passing over vegetation, substrate edges, and the head and body of the receiver also creates background noise that can potentially mask some vocal signals (Bradbury and Vehrencamp 1998). Regardless of habitat, the wind-generated noise is greatest at low frequencies. Wind contributes little to background noise at frequencies above 2 kHz. Typical levels for frequencies under 100 Hz range from 20–30 dB (SPL) for winds about 1 m/sec (2.2 mph) to 60–70 dB (SPL) for winds of 8 m/sec (18 mph). Figure E-4 shows the daily wind pattern in the proposed project study area (min. 1.1 m/sec [2.5 mph]; max. 10.7 m/sec [24 mph]). This observation indicates that even low-level winds could have a masking effect on communication in American Bitterns.

Using a moderately high wind noise level (52 dB[A]), Figure E-12 shows the relationship between wind-generated noise and highway noise with distance from the highway. Close to the highway, the highway noise exceeds wind noise. With increasing distance from the highway, the highway noise attenuates but the wind noise stays relatively constant. Fundamental principals of acoustics indicate that two noise sources will not influence each other if they are more than 10 dB apart; that is, if the two noise sources are more than 10 dB apart, the louder noise will predominate. When the noise sources are within 10 dB, the lower noise levels begin to influence the overall noise effect (i.e., combined noise level). When the two sources are equal (at the intersection of the highway noise and wind noise lines in Figure E-12), the combined sound level is 3 dB higher than each source. Figure E-12 illustrates that highway noise is not affected by wind noise until the highway noise attenuates to approximately 62 dB (10 dB above the wind noise). This occurs at approximately 152 m (500 ft or 0.09 mi) from the highway. The noise levels are equal at about 580 m (1,900 ft or 0.36 mi) from the highway. The highway noise attenuates to 42 dB (10 dB below the wind noise) at approximately 4,877 m (16,000 ft or 3.03 mi) from the highway, where it effectively no longer contributes to the overall background noise level. This chart shows that wind noise at 52 dB it will contribute to the combined noise effect within this range (152 – 4877 m [500–16,000 ft or 0.09–3.03 mi]). While the combined noise remains higher than the wind noise across this distance, it is evident that the highway noise becomes proportionally less important from 580 m (1,900 ft or 0.36 mi) outward. By the same analysis, wind noise of approximately 30 dB would not effectively contribute to road noise nearer than 5,486 m (18,000 ft or 3.4 mi) from the highway.

While it is not possible to determine precisely where wind noise would effectively become the primary masking source in the environment for birds, humans can detect 3-dB differences between noise levels and can clearly discern 5-dB differences. In this context, the road noise attenuates to 3 dB below the wind noise (52 dB in Figure E-12) at approximately 914 m (3,000 ft or 0.57 mi) from the highway; it attenuates to 5 dB below the wind noise at approximately 1,524 m (5,000 ft or 0.95 mi). For wind noise at 45 dB, these distances would increase to approximately 4,877 and 5,486 m (16,000 and 18,000 ft or 3.03 and 3.4

mi), respectively. This analysis shows that moderate to high wind velocities can potentially produce sufficient noise (52 db and above) to dominate the potential masking effects of road noise at 966 m (3,168 ft or 0.6 mile); this distance decreases as higher wind velocity increases. With decreasing wind velocity, the distance from the highway at which wind noise would dominate road noise increases rapidly, effectively becoming inconsequential for wind speeds that would generate noise levels of 40 dB or less (approximately 19 k/hr [12 mph]).

Figure E-4 shows that for the period of measurement in the vicinity of the project study area, wind noise can exceed 52 db, but for a large part of the day does not. This pattern indicates that wind-generated noise would only potentially dominate road noise during the night and short periods during the day. For effective communication during windy conditions, birds must either communicate more loudly, move closer to their intended receivers, or avoid calling except during lulls in wind or during periods of the day when the wind is minimal. Gibbs et al. (1992) indicate that American Bitterns reduce their calling frequency during high winds.

Predator/Prey Detection

The ability to detect and locate sounds of prey is critical to the survival of many predatory birds and mammals. Barn Owls are the quintessential acoustic predators in the project study area; cats have comparable auditory sensitivity. Figure E-1 shows both species' exceptional hearing capacity. Owls tested with pure tones and artificial noise can optimally localize frequencies between 5 and 9 kHz (Konishi 1993; Volman 1994; Wagner 1995); they can locate broad-band signals more easily than narrow-band signals. This hearing optimization is consistent with the general broad-band vocalizations of many mice (fundamental frequency approximately 2.5 kHz with harmonics to 8 kHz) and the sounds from rustling leaves caused by the mice (broad-band noise 1–9 kHz [Swanson and Sanderson 1999]). Figure E-1 shows that under very quiet conditions, road noise could potentially interfere with the ability of the owls to detect low-amplitude (4–8 kHz) prey sounds out to 4,000 feet. However, natural background noise, (moving vegetation, wind), can reach up to 70 dB (SPL) for winds 8 m/sec (18 mph); such conditions would require owls to move much closer to the prey to hear it. The inherent ability of owls to hunt close to the ground allows them to behaviorally reduce the masking threshold and effective acoustic impact area of the highway noise (see discussion below). Similarly, cats, by virtue of their mobility and stealth, would be able to approach relatively close to potential prey, minimizing the long-range masking effects of highway noise.

E.5 Discussion

The results of this acoustics study indicate that the potential effects distances for noise masking of wildlife communication within the project study area are potentially greater than those determined from the bird demographic studies described in the *Introduction*. For grassland birds, declines in species diversity and abundance have been documented out to 3,500 m (11,581 ft or 2.17 mi) from highways with traffic volumes of 50,000 vehicles per day (Reijnen et al. 1995; Reijnen et al. 1996). Figure E-11 illustrates that highway noise (with traffic volumes of 72,000 vehicles per day for the Legacy Parkway project) could potentially affect American Bittern communications at 4,877 m (16,000 ft or 3.03 mi) and beyond. However, wind and heat-generated turbulence in the open fields of the project study area are likely to reduce this distance, at least during some periods of the day.

The results of this study also indicate that the effects distances are species-specific and therefore highly variable. The communication requirements of American Bitterns differ significantly from those of Black-necked Stilts and Brewer's Sparrows. Presumably, each species responds differently to traffic noise, seeking areas away from the highway at distances that are optimal for communication. By physically avoiding areas where masking can occur, each species behaviorally adapts to the existing noise environment. Ongoing research in avian bioacoustics has shown that there are a variety of adaptations by which species can reduce the masking threshold, and hence the distance from the highway at which they can communicate. Some of these adaptations are discussed in the following paragraphs.

The source amplitude of the signal is not the only determinant of effective communication distance. Characteristics of the receiver's signal detection capabilities, including temporal summation, amplitude co-modulation, and directional hearing sensitivity, can potentially reduce the effects of masking and increase the effective distance at which birds can detect signals in background noise.

Temporal summation is an acoustic response in the listener wherein the detectability of signals in noise improves with increasing signal duration (Dooling 1979; Dooling and Searcy 1985; Klump and Maier 1990; Klump 1996). In some birds this effect can result in a lowering of the detection threshold up to 3 dB per doubling of the signal duration (Klump 1996).

Amplitude co-modulation (co-modulation masking release) is an adaptive response to predictable amplitude fluctuations in the noise that allows the listener to improve the detection of signals by using correlated amplitude fluctuations in different frequency channels of the auditory system (Hall et al.1984; Schooneveldt and Moore 1987; Moore 1990, 1992). The detection of a signal added to one of the channels (e.g., a bird call) may be enhanced by a cross-spectral comparison of the time course of the signal amplitude in the different analysis channels. If, for example, highway noise shows correlated amplitude fluctuations in different frequency channels, the addition of a signal (e.g., a bird call) will reduce the correlation between the amplitude fluctuations in the different channels, which is then detected by the listener. Alternatively, a low-amplitude noise level in one frequency channel could predict a good time for the listener to detect vocal signals embedded in the noise in other frequency channels. Furthermore, amplitude constancy in a signal, sharp frequency modulations, or redundant predictable signal patterns that contrast against the regular amplitude fluctuations of the background noise offer additional acoustic opportunities for enhanced signal detection in noise (Fastl 1993; Klump 1996). The amount of masking release under these conditions may be as great as 15 dB (Richards and Wiley 1980; Schooneveldt and Moore 1987; Klump and Langemann 1995; Klump 1996).

Finally, signals of interest to wildlife and highway noise often originate from different locations. Most wildlife species can therefore make use of innate *directional hearing sensitivity* to improve their detection of important signals in noise. This spatial release from masking is frequency dependent, with maximum threshold detection changes of up to 12 dB at optimal sensitivity frequencies for some birds (Klump and Larsen 1992; Klump 1996). Use of any or all of the masking release mechanisms described here can potentially allow wildlife species to detect signals in background noise at much greater distances than those predicted by simple critical ratio detectability determinations.

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Species	Vocalization Frequency Data (kHz)				Frequency Range (kHz units)										Reference
	Low	High	Range	Median	1	2	3	4	5	6	7	8	9	10	
Belted Kingfisher	0.1	8.5	8.4	4.3											Hamas 1994
Trumpeter Swan	0.1	6	5.9	3.05											Mitchell 1994
Black Tern	0.1	6	5.9	3.05											Dunn and Agro 1995
Sandhill Crane	0.2	6	5.8	3.1											Tacha, Nesbitt, and Vohs 1992
Short-eared Owl	0.2	8	7.8	4.1											Holt and Leasure 1993
Mourning Dove	0.2	0.3	0.1	0.25											Mirarchi and Baskett 1994
Double-crested Cormorant	0.2	1.2	1	0.7											Hatch and Weseloh 1999
Great Horned Owl	0.25	0.39	0.14	0.32											Houston, Smith, and Rohner 1998
Brown-headed Cowbird	0.3	12	11.7	6.15											Lowther 1993
Long-eared Owl	0.3	10	9.7	5.15											Marks, Evans, and Holt 1994
Pectoral Sandpiper	0.3	5	4.7	2.65											Holmes and Pitelka 1998
Hooded Merganser	0.4	1.25	0.85	0.825											Dugger, Dugger, and Fredrickson 1994
White-faced Ibis	0.4	5	4.6	2.7											Ryder and Manry 1994
Greater White-fronted Goose	0.4	5	4.6	2.7											Ely and Dzubin 1994
Black-crowned Night-heron	0.5	6	5.5	3.25											Gauthier 1993
Wilson’s Phalarope	0.5	3.6	3.1	2.05											Colwell and Jehl, Jr. 1994
Herring Gull	0.5	7	6.5	3.75											Pierotti and Good 1994
Northern Flicker	0.5	8	7.5	4.25											Moore 1995
Gray Catbird	0.5	10	9.5	5.25											Cimprich and Moore 1995
Virginia Rail	0.5	4.5	4	2.5											Conway 1995
Black-bellied Plover	0.5	1	0.5	0.75											Paulson 1995
Green-winged Teal	0.5	7.5	7	4											Johnson 1995
Northern Harrier	0.5	6.2	5.7	3.35											MacWhirter and Bildstein 1996
American Wigeon	0.5	3.8	3.3	2.15											Mowbray 1999
Pied-billed Grebe	0.5	5	4.5	2.75											Muller and Storer 1999
Black-necked Stilt	0.5	6	5.5	3.25											Robinson, Reed, Skorupa, and Oring 1999
California Quail	0.5	6	5.5	3.25											Calkins, Hagelin, and Lott 1999
Snow Goose	0.5	7	6.5	3.75											Mowbray, Cooke, and Ganter 2000
Forster’s Tern	0.5	7.5	7	4											McNicholl, Lowther, and Hall 2001
Wood Duck	0.7	9	8.3	4.85											Hepp and Bellrose 1995
Green-tailed Towhee	0.7	8.2	7.5	4.45											Dobbs, Martin, and Martin 1998
Ring-billed Gull	0.75	7	6.25	3.875											Ryder 1993
Burrowing Owl	0.8	7.5	6.7	4.15											Haug, Millsap, and Martell 1993
Red-winged Blackbird	0.8	5.8	5	3.3											Yasukawa and Searcy 1995
Spotted Sandpiper	0.8	4	3.2	2.4											Oring, Gray, and Reed 1997
Lesser Goldfinch	0.8	5.5	4.7	3.15											Watt and Willoughby 1999
Red-necked Phalarope	0.8	5	4.2	2.9											Rubega, Schamel, and Tracy 2000
Barn Owl	1	2	1	1.5											Mari 1992
Tree Swallow	1	7	6	4											Robertson, Stutchbury and Cohen 1992
House Sparrow	1	8	7	4.5											Lowther and Cink 1992
American Bittern	1	3	2	2											Gibbs, Melvin, and Reid 1992
Great Blue Heron	1	2.5	1.5	1.75											Butler 1992
Western Grebe	1	3.5	2.5	2.25											Storer and Nuechterlein 1992
Clark’s Grebe	1	3.5	2.5	2.25											Storer and Nuechterlein 1992
Glaucous-winged Gull	1	4	3	2.5											Verbeek 1993
Tundra Swan	1	8	7	4.5											Limpert and Earnst 1994
Western Sandpiper	1	5.8	4.8	3.4											Wilson 1994
Ruby-crowned Kinglet	1	10	9	5.5											Ingold and Wallace 1994
Green Heron	1	5.5	4.5	3.25											Davis, Jr and Kushlan 1994
Dunlin	1	3	2	2											Warnock and Gill 1996
Whimbrel	1	9	8	5											Skeel and Mallory 1996
Loggerhead Shrike	1	9	8	5											Yosef 1996
Gadwall	1	5	4	3											LeShack, McKnight, and Hepp 1997
Purple Martin	1	4.2	3.2	2.6											Brown 1997
Stilt Sandpiper	1	5	4	3											Reed, Ward, Derksen, and Sedinger 1998
Eared grebe	1	4	3	2.5											Cullen, Jehl Jr., and Nuechterlein 1999
Parasitic Jaeger	1	7	6	4											Wiley and Lee 1999
Barn Swallow	1	14	13	7.5											Brown and Brown 1999
Lark Bunting	1	6	5	3.5											Shane 2000
Mountain Chickadee	1	10	9	5.5											McCallum, Grundel, and Dahlsten 1999
Red-breasted Nuthatch	1	9	8	5											Ghalambor and Martin 1999
Sage Thrasher	1	7	6	4											Reynolds, Rick, and Stephens 1999
Common Raven	1	4	3	2.5											Boarman and Heinrich 1999
Snowy Egret	1	4	3	2.5											Parsons and Master 2000
Marbled Godwit	1	8	7	4.5											Gratto-Trevor 2000
Long-billed Dowitcher	1	9	8	5											Takekawa and Warnock 2000
Black-chinned Hummingbird	1	9	8	5											Baltosser and Russell 2000
Horned Grebe	1	3.8	2.8	2.4											Stedman 2000

Species	Vocalization Frequency Data (kHz)				Frequency Range (kHz units)										Reference
	Low	High	Range	Median	1	2	3	4	5	6	7	8	9	10	
Short-billed Dowitcher	1	6	5	3.5											Jehl Jr., Klima, and Harris 2001
Ring-necked Pheasant	1	6	5	3.5											Giudice and Ratti 2001
American Golden-plover	1	4	3	2.5											Johnson and Connors 1996
Cliff Swallow	1.1	7	5.9	4.05											Brown and Brown 1995
Greater Yellowlegs	1.2	6	4.8	3.6											Elphick and Tibbitts 1998
Northern Mockingbird	1.5	8	6.5	4.75											Derrickson and Breitwisch 1992
White-throated Sparrow	1.5	6.6	5.1	4.05											Falls and Kopachena 1994
Black-headed Grosbeak	1.5	12	10.5	6.75											Hill 1995
Lincoln’s Sparrow	1.5	7.3	5.8	4.4											Ammon 1995
Common Nighthawk	1.5	4	2.5	2.75											Poulin, Grindal, and Brigham 1996
House Wren	1.5	9	7.5	5.25											Johnson 1998
Semipalmated Plover	1.5	3.4	1.9	2.45											Nol and Blanken 1999
Common Yellowthroat	1.5	6.5	5	4											Guzy and Ritchison 1999
Killdeer	1.5	7	5.5	4.25											Jackson and Jackson 2000
American Pipit	1.6	5.5	3.9	3.55											Verbeek and Hendricks 1994
Mountain Bluebird	1.6	4	2.4	2.8											Power and Lombardo 1996
Western Meadowlark	1.7	4.8	3.1	3.25											Lanyon 1994
Snowy Plover	1.7	6.5	4.8	4.1											Page, Warriner, Warriner, and Paton 1995
Ross’ Goose	1.7	4.4	2.7	3.05											Ryder and Alisauskas 1995
House Finch	1.8	6	4.2	3.9											Hill 1993
Cooper’s Hawk	1.8	7.5	5.7	4.65											Rosenfield and Bielefeldt 1993
Yellow-headed Blackbird	1.8	8	6.2	4.9											Twedt and Crawford 1995
Western Kingbird	1.8	8	6.2	4.9											Gamble and Bergin 1996
American Avocet	1.8	6.5	4.7	4.15											Robinson, Oring, Skorupa, and Boettcher 1997
Swamp Sparrow	1.8	8	6.2	4.9											Mowbray 1997
Chestnut-collared Longspur	1.8	6.5	4.7	4.15											Hill and Gould 1997
Plumbeous Vireo	1.8	7.5	5.7	4.65											Curson and Goguen 1998
Black-billed Magpie	1.8	8	6.2	4.9											Trost 1999
Willet	1.9	3	1.1	2.45											Lowther, Dougls, III, and Gratto-Trevor 2001
Violet-green Swallow	2	7	5	4.5											Brown, Knott, and Damrose 1992
Blue-gray Gnatcatcher	2	10	8	6											Ellison 1992
European Starling	2	9	7	5.5											Cabe 1993
Red-tailed Hawk	2	6	4	4											Preston and Beane 1993
Harris’ Sparrow	2	7	5	4.5											Norment and Shackleton 1993
American Goldfinch	2	8.2	6.2	5.1											Middleton 1993
Solitary Sandpiper	2	5.8	3.8	3.9											Moskoff 1995
Cassin’s Finch	2	6	4	4											Hahn 1996
Swainson’s Hawk	2	2.8	0.8	2.4											England, Bechard, and Houston 1997
Pine Siskin	2	9	7	5.5											Dawson 1997
Say’s Phoebe	2	3.8	1.8	2.9											Schukman and Wolf 1998
Lesser Yellowlegs	2	8	6	5											Tibbitts and Moskoff 1999
Western Wood-Pewee	2	6.5	4.5	4.25											Bemis and Rising 1999
American Robin	2	4	2	3											Sallabanks and James 1999
Rock Wren	2	6	4	4											Lowther, Kroodsma, and Farley 2000
Lark Sparrow	2	7	5	4.5											Martin and Parrish 2000
Olive-sided Flycatcher	2	4.1	2.1	3.05											Altman and Sallabanks 2000
Warbling Vireo	2	7	5	4.5											Gardali and Ballard 2000
Ferruginous Hawk	2.2	3	0.8	2.6											Bechard and Schmutz 1995
Marsh Wren	2.3	9.4	7.1	5.85											Kroodsma and Verner 1997
Broad-tailed Hummingbird	2.5	7.5	5	5											Calder and Calder 1992
Black-capped Chickadee	2.5	10.2	7.7	6.35											Smith 1993
Least Sandpiper	2.5	3.9	1.4	3.2											Cooper 1994
Evening Grosbeak 599	2.5	5.1	2.6	3.8											Gillahan and Byers 2001
Northern Waterthrush	2.8	7	4.2	4.9											Eaton 1995
Horned Lark	2.8	6	3.2	4.4											Beason 1995
Bank Swallow	2.8	7.5	4.7	5.15											Garrison 1999
MacGillvray’s Warbler	3	8.2	5.2	5.6											Pitocchelli 1995
White-crowned Sparrow	3	6	3	4.5											Chilton, Baker, Barrentine, and Cunningham 1995
Lazuli Bunting	3	10	7	6.5											Greene, Muehter, and Davison 1996
Northern Rough-winged Swallow	3	6	3	4.5											DeJong 1996
Spotted Towhee	3	8	5	5.5											Greenlaw 1996
American Redstart	3	8	5	5.5											Sherry and Holmes 1997
Brewer’s Sparrow	3	6.5	3.5	4.75											Rotenberry, Patten, and Preston 1999
Common Redpoll	3	12	9	7.5											Knox and Lowther 2000
Yellow Warbler	3	7	4	5											Lowther, Celada, Klein, Rimmer, and Spector 1999
Virginia’s Warbler	3	7	4	5											Olson and Martin 1999
Sharp-shinned Hawk	3	12	9	7.5											Bildstein and Meyer 2000
Red Knot	3	6	3	4.5											Harrington 2001

Species	Vocalization Frequency Data (kHz)				Frequency Range (kHz units)										Reference
	Low	High	Range	Median	1	2	3	4	5	6	7	8	9	10	
American Tree Sparrow	3.2	7.2	4	5.2											Naugler 1993
Yellow-rumped Warbler	3.2	5.8	2.6	4.5											Hunt and Flaspohler 1998
Chipping Sparrow	3.5	8.1	4.6	5.8											Middleton 1998
Merlin	3.6	4.3	0.7	3.95											Sodhi, Oliphant, James, and Warkentin 1993
Savannah Sparrow	3.7	10	6.3	6.85											Wheelwright and Rising 1993
Nashville Warbler	3.7	10.5	6.8	7.1											Williams 1996
Townsend's Warbler	3.7	8	4.3	5.85											Wright, Hayward, Matsouka, and Hayward 1998
Cedar Waxwing	3.8	8.5	4.7	6.15											Witmer, Mountjoy, and Elliot 1997
Wilson's Warbler	3.8	9	5.2	6.4											Ammon and Gilbert 1999
Orange-crowned Warbler	4	8.5	4.5	6.25											Sogge, Gilbert, and van Riper III 1994
Eastern Kingbird	4	8.2	4.2	6.1											Murphy 1996
Caspian Tern	4	9	5	6.5											Cuthbert and Wires 1999
Western Tanager	4	9	5	6.5											Hudon 1999
Bald Eagle	5	9.5	4.5	7.25											Buehler 2000
Barrow's Goldeneye			0	0											Eadie, Savard, and Mallory 2000

Table E-2. Sound-Masking Thresholds (10 bird average)

Frequency	63 Hz	125 Hz	250 Hz	500 Hz	1K Hz	2K Hz	4K Hz	8 K Hz
Masking Threshold	13 dB*	16 dB*	19 dB	22 dB	24 dB	26 dB	30 dB	38 dB

* Extrapolated based on 3 dB per octave slope, as suggested by Dooling 2002.

Table E-3. Short-Term Sound Level Measurements

Recording Location	Date	Start Time	Duration (min)	Average Wind Speed (mph)	Leq[1]	Lmin[2]	L90[3]	L50[3]	L10[3]	Lmax[4]	Distinct Noise Sources
5	1 Jul	12:43	16:00	8.4	52.2	41.8	43.9	47.1	53.5	67.3	Vehicle passages, crickets, wind in vegetation
6	1 Jul	13:50	16:00	11.6	52.3	40.2	44.8	49.3	56.3	62.6	Aircraft, wind in vegetation
7	1 Jul	14:48	10:00	14.8	52.3	45	47.1	51.3	55.1	66.6	Wind in vegetation, no audible human sound
8	1 Jul	15:36	15:00	8.6	59.5	39.2	42.3	48	60.5	79.1	Vehicle passages, distant traffic, aircraft, wind in vegetation
9	1 Jul	18:40	18:00	11.1	48.3	32.2	39.7	44.7	52.4	60.9	Wind in vegetation, aircraft
10	1 Jul	19:20	15:00	2.7	59.9	33.2	36.2	45	62	76.5	Aircraft, birds
11	1 Jul	19:59	15:00	4.4	51.9	33.1	40.2	45.4	51.5	71.4	Aircraft, birds
12	2 Jul	7:02	19:00	2.2	43.9	32	33.7	36.1	44	61.6	Aircraft, birds
13	2 Jul	7:57	14:00	2.8	46.8	39.8	41.8	43.4	46.6	61	Aircraft, distant birds
1	2 Jul	9:36	17:00	1.2	42.6	33.4	36.5	40.6	45.8		Aircraft, birds
2	2 Jul	10:33	18:00	2.9	45.1	31.2	33.8	40.8	49.2	57.1	Aircraft, crickets
6	2 Jul	12:33	15:00	4.1	40.8	31.7	33.8	36.7	42.1	57.6	Wind in vegetation, birds, aircraft
14	2 Jul	13:29	16:00	4.5	47.2	31.8	33.7	36.6	52.3	61.2	Wind in vegetation, birds, aircraft
4	2 Jul	14:53	15:00	4.8	37.1	30.8	31.6	33.6	38.4	53.1	Distant construction activity, aircraft
				Mean	48.6	35.4	38.5	42.8	50.7	64.3	
				STDEV	6.6	4.7	5.0	5.5	6.8	7.6	
				Min	37.1	30.8	31.6	33.6	38.4	53.1	
				Max	59.9	45	47.1	51.3	62	79.1	
				Range	22.8	14.2	15.5	17.7	23.6	26.0	

[1] **Leq.** Equivalent Sound Level. The equivalent steady-state sound level that, in a stated period of time, would contain the same acoustical energy.
[2] **Lmin.** Minimum Sound Level. The minimum sound level measured during the measurement period.
[3] **Lxx.** Percentile-Exceeded Sound Level. The sound level exceeded "x" percent of a specific time period. L10 is the sound level exceeded 10 percent of the time.
[4] **Lmax.** Maximum Sound Level. The maximum sound level measured during the measurement period.

Table E-4. Mean, Standard Deviation, Minimum, and Maximum Noise Levels

SPL[1] (dBA)[2]	Leq[3]				L10[4]				L50[4]				L90[4]			
	L1	L2	L3	L1–L3	L1	L2	L3	L1–L3	L1	L2	L3	L1–L3	L1	L2	L3	L1–L3
Mean	53	45	52	50	55	48	54	51	47	41	46	45	43	36	41	40
SDEV	11	8	8	10	11	8	9	11	8	7	8	8	7	5	6	7
Minimum	41	36	40	36	42	37	41	35	37	34	36	34	36	32	35	32
Maximum	78	69	71	78	81	73	75	81	71	67	69	71	65	58	64	65

[1] SPL. Sound Pressure Level.
[2] dB(A). A-Weighted Decibel. An overall frequency-weighted sound level in decibels that approximates the frequency response of the human ear.
[3] Leq. Equivalent Sound Level. The equivalent steady-state sound level that, in a stated period of time, would contain the same acoustical energy.
[4] Lxx. Percentile-Exceeded Sound Level. The sound level exceeded "x" percent of a specific time period. L10 is the sound level exceeded 10 percent of the time.

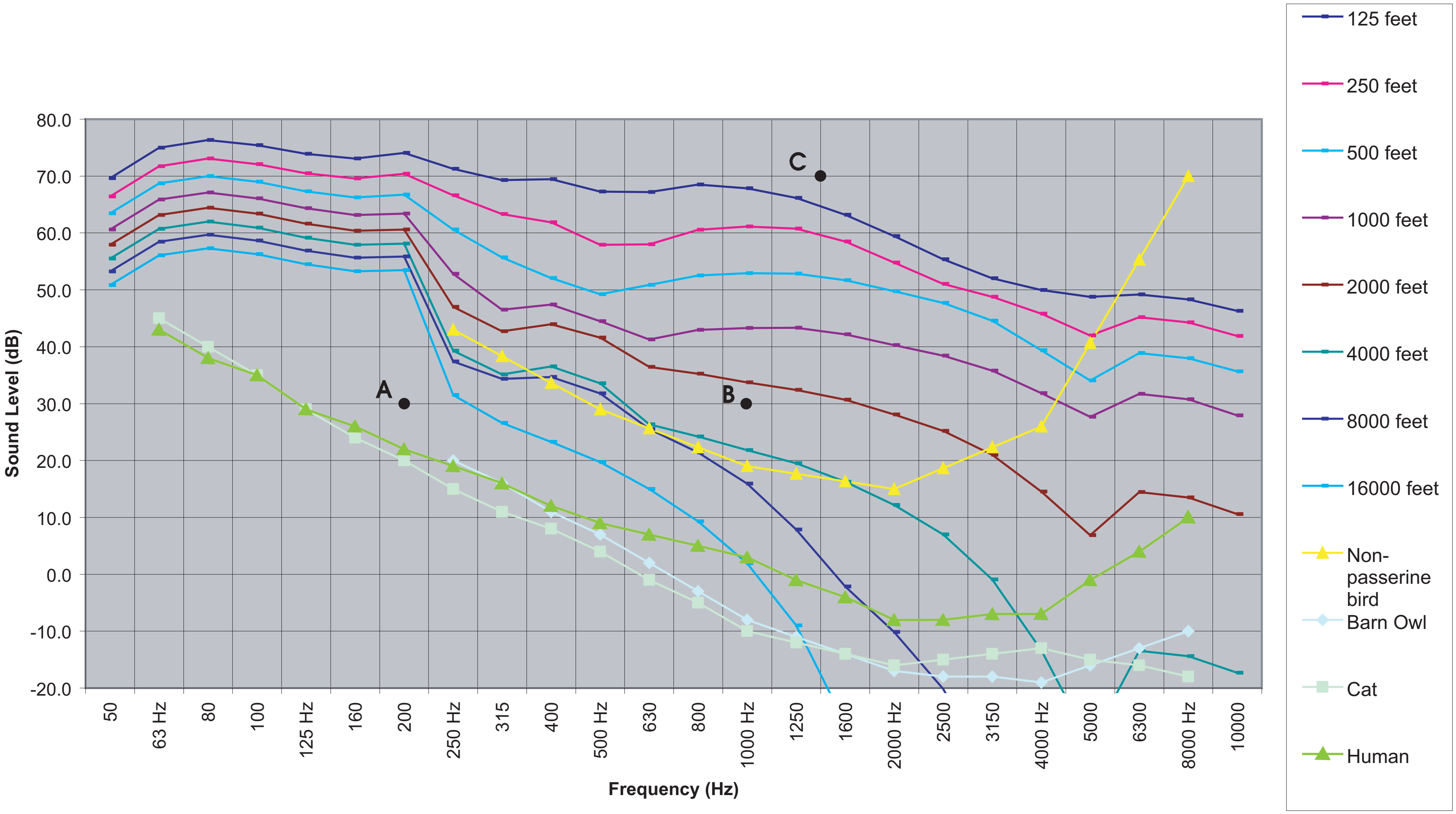

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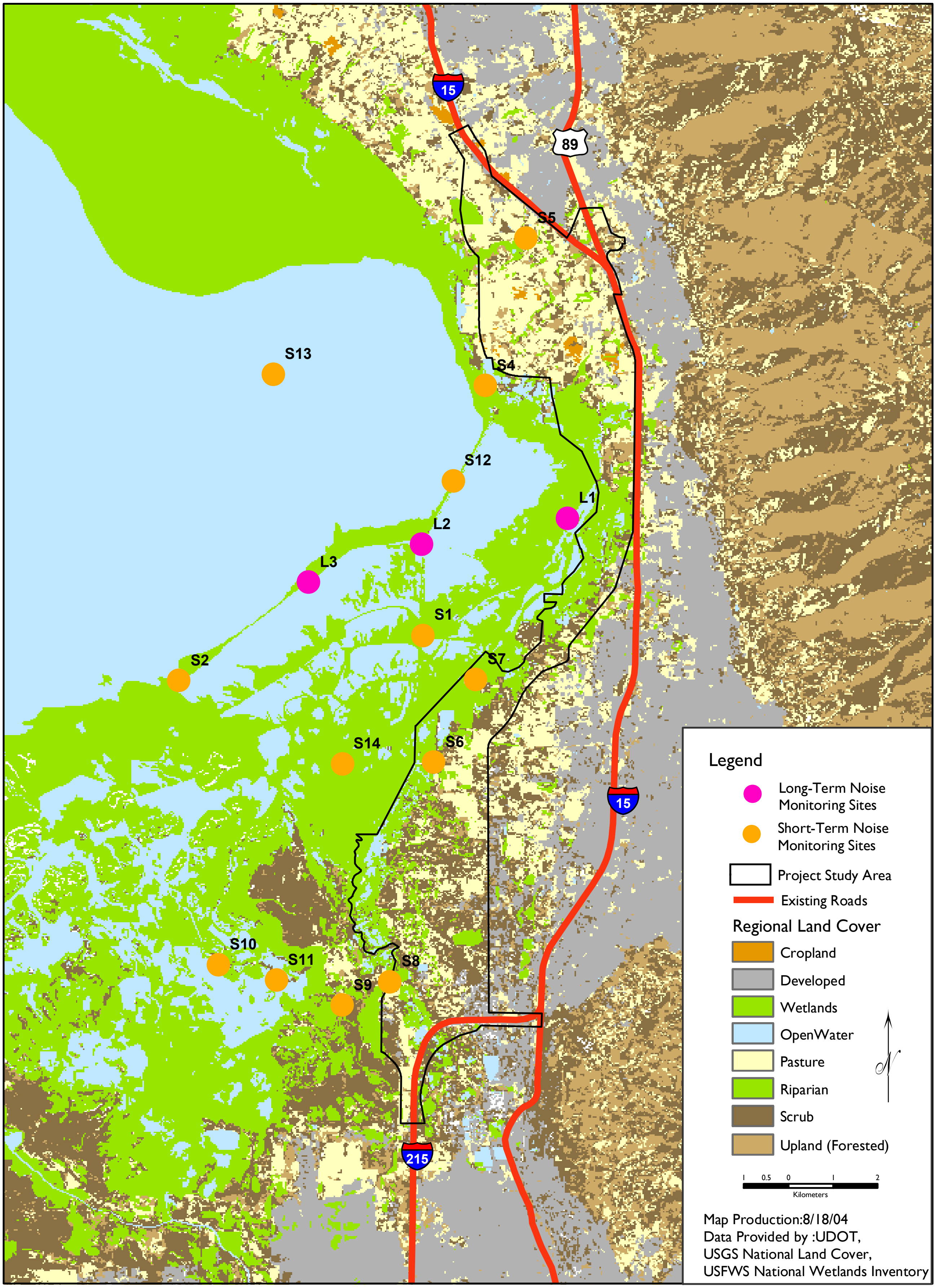
Figure E-1
Traffic Noise Masking Thresholds and Auditory Curves for Birds and Mammals



H:\GIS\Projects\udot\037076.03\arcmap\E2_noise.mxd

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Figure E-2
Noise Monitoring Sites in the Legacy Parkway Project Study Area

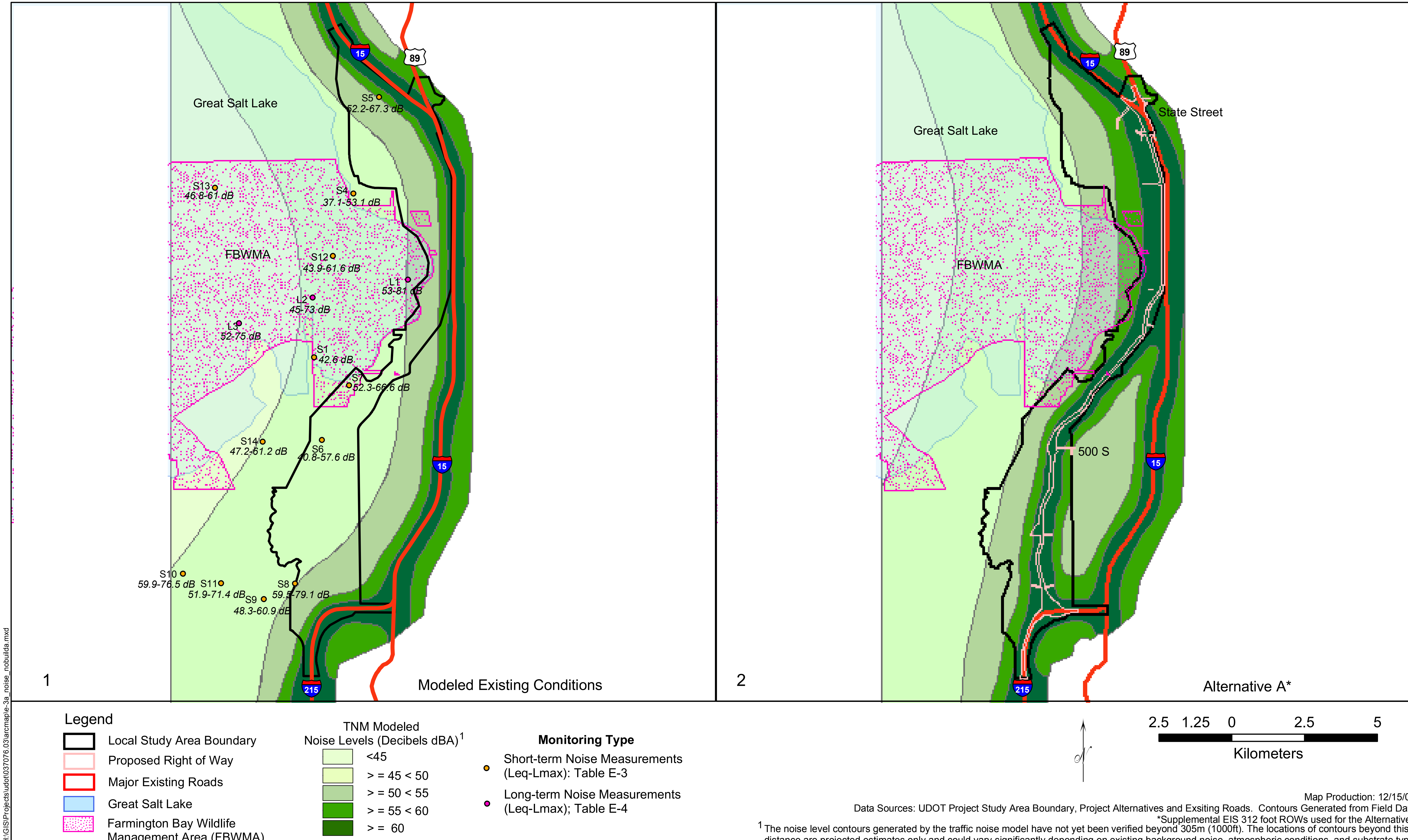

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Figure E-3a
Highway Noise Level for the Legacy Parkway

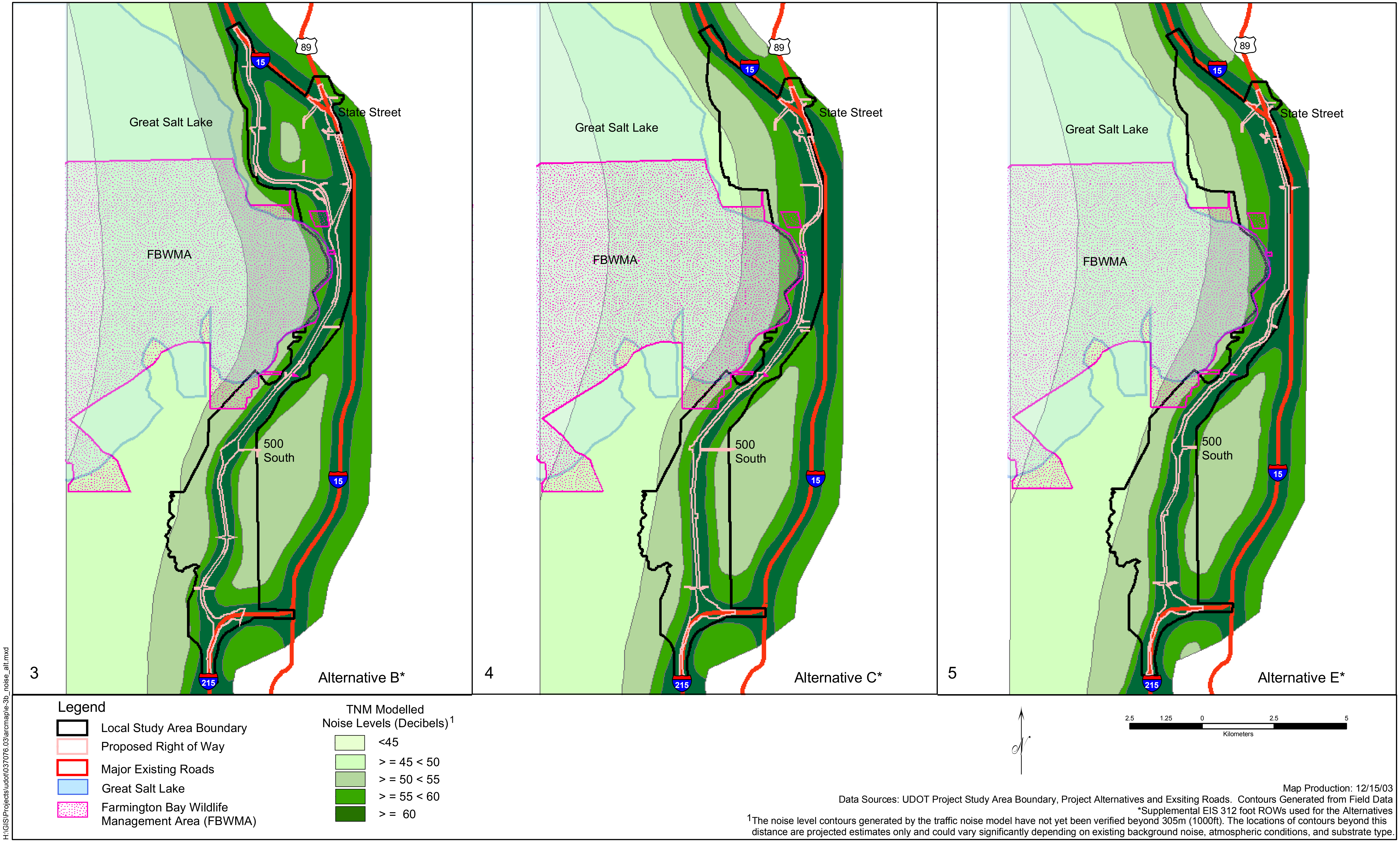

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Figure E-3b
Highway Noise Level for the Legacy Parkway

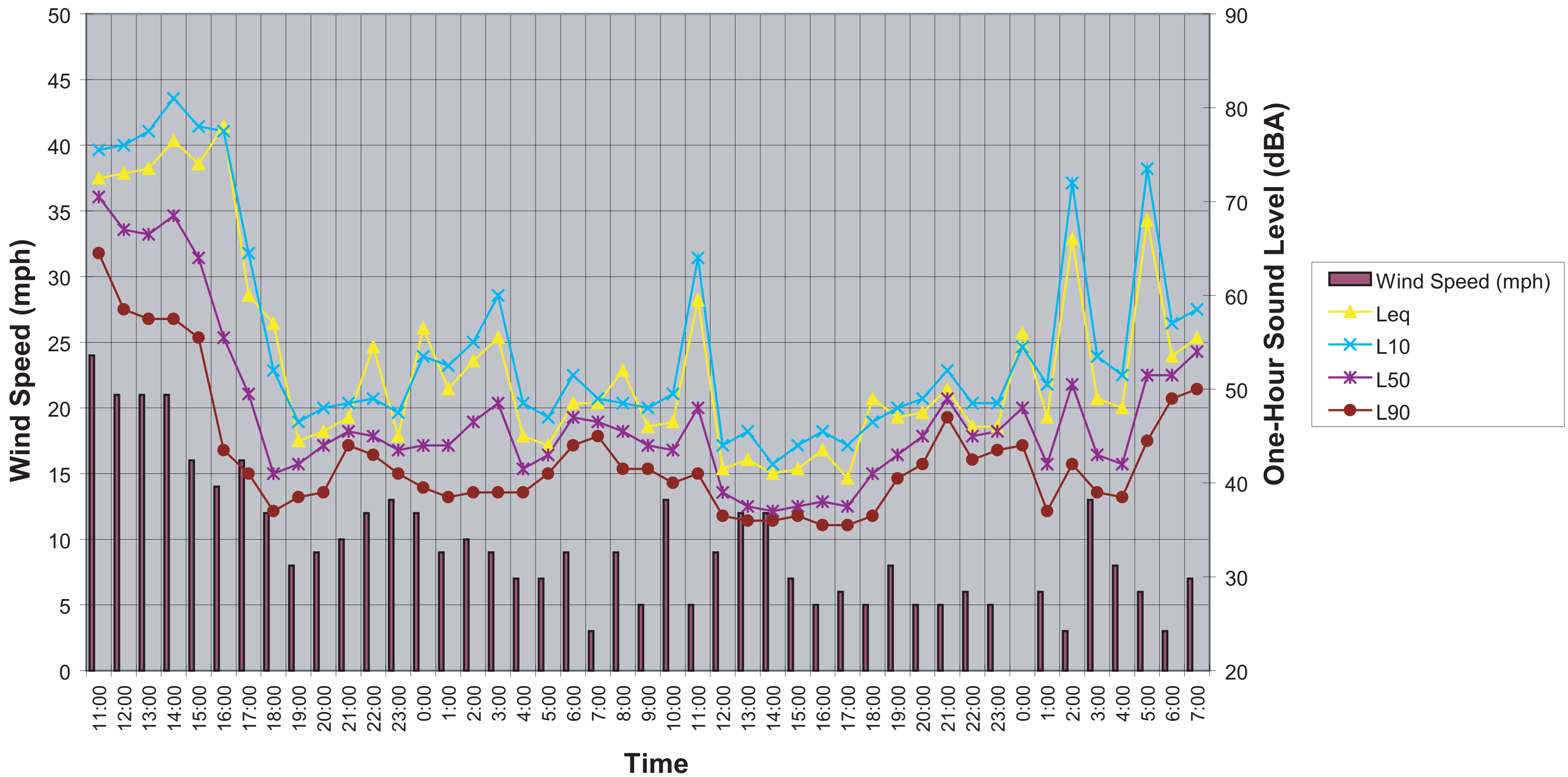

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Figure E-4
Background Sound and Wind Levels at Long-Term Position

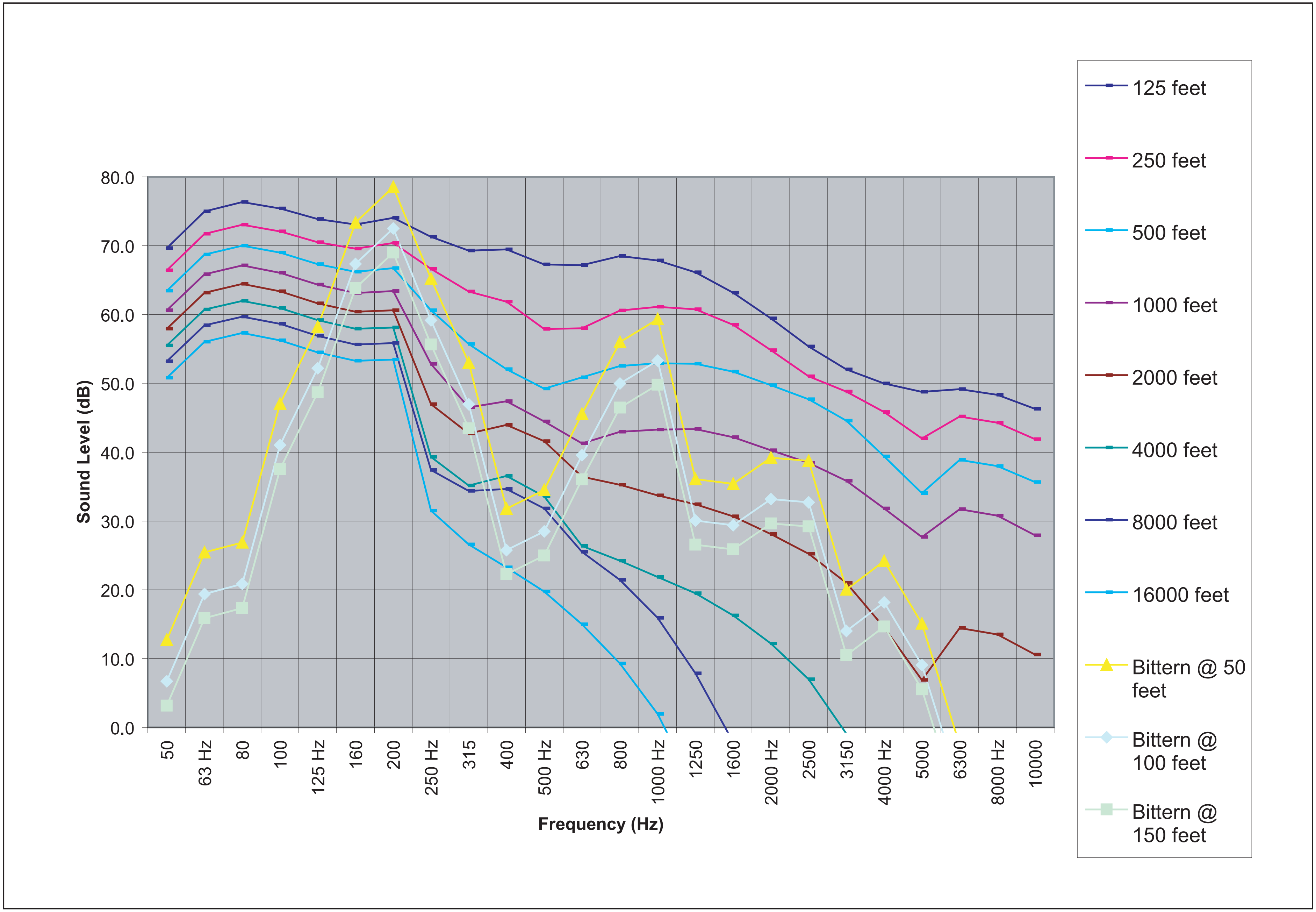

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Figure E-5
Traffic Noise Masking Thresholds and American Bittern Vocal Signal Profile

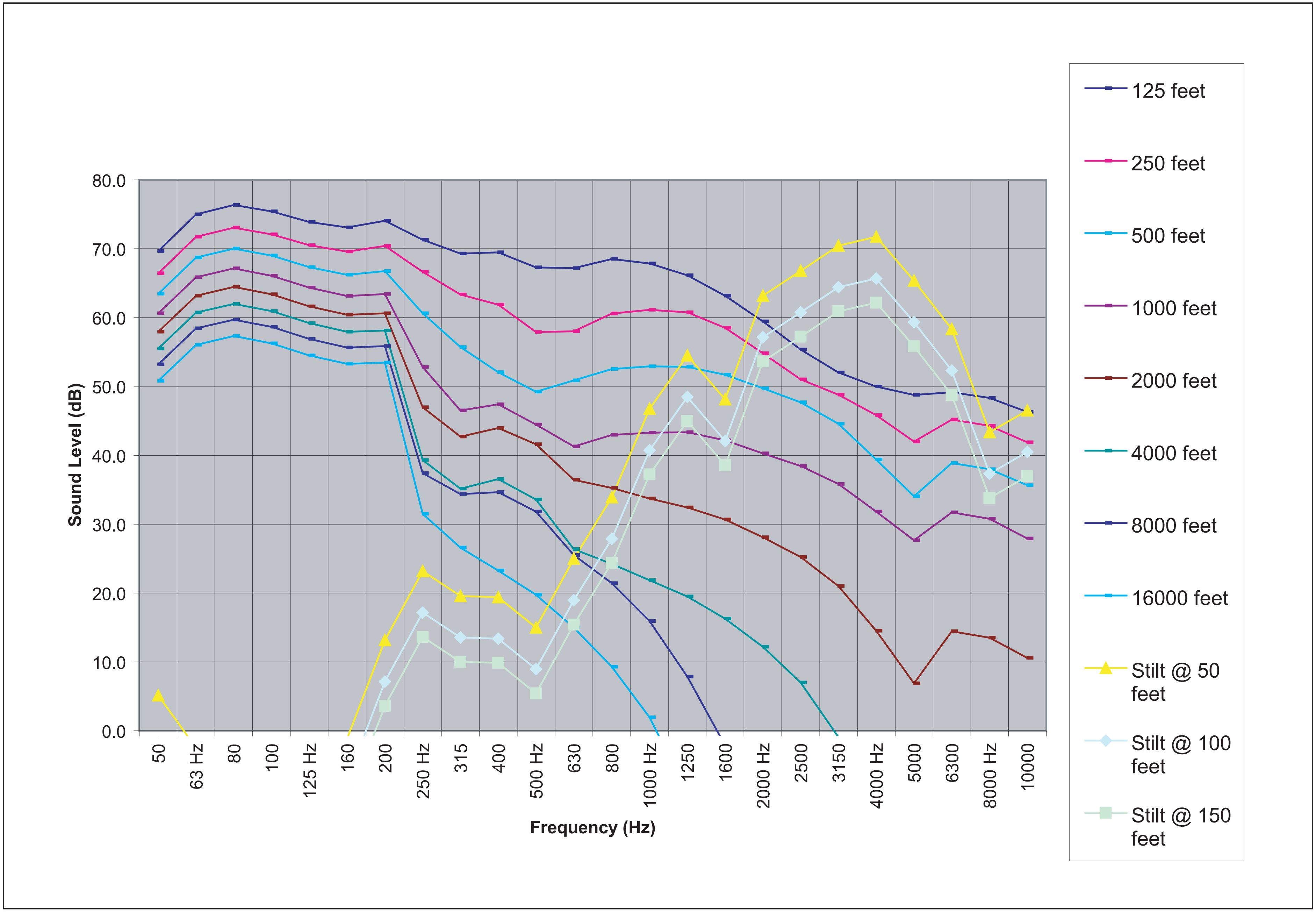

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Figure E-6
Traffic Noise Masking Thresholds and Black-Necked Stilt Vocal Signal Profile

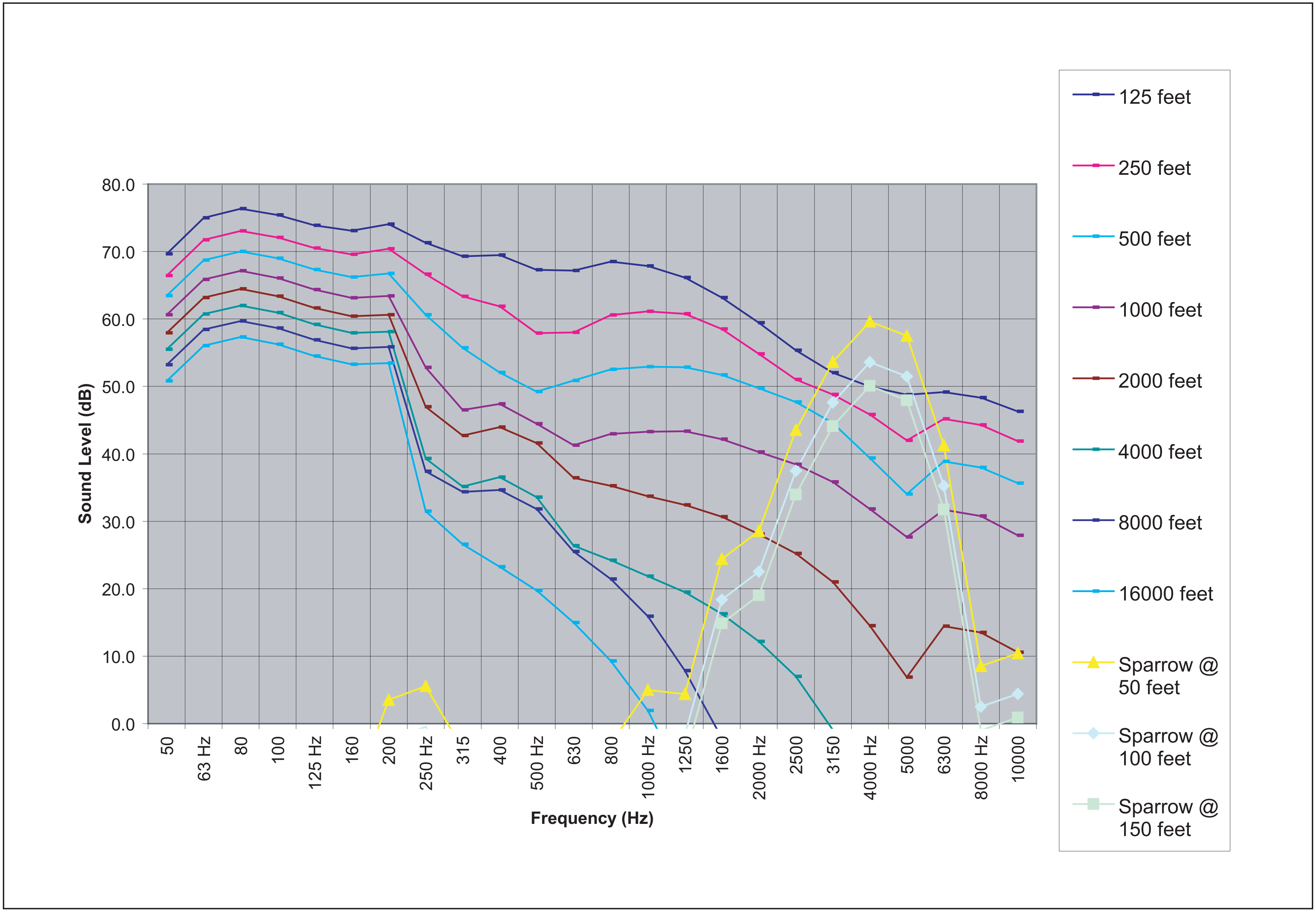

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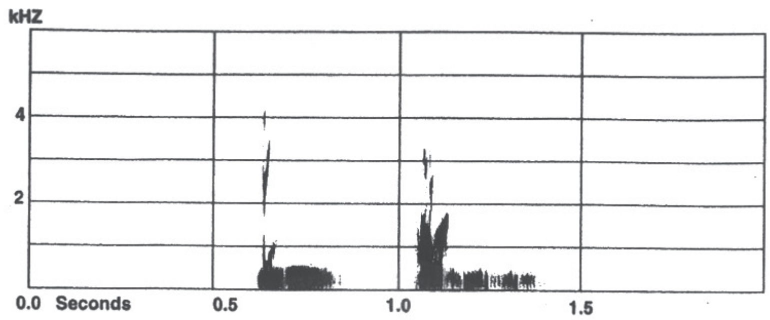
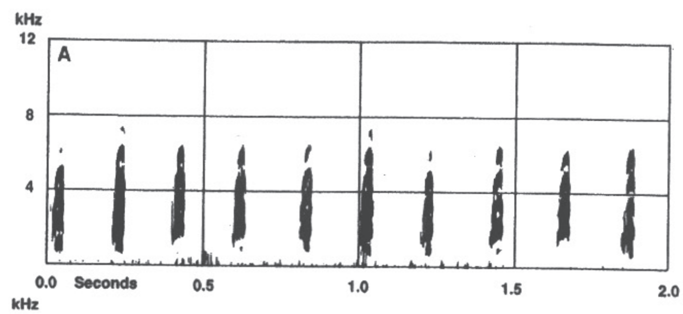
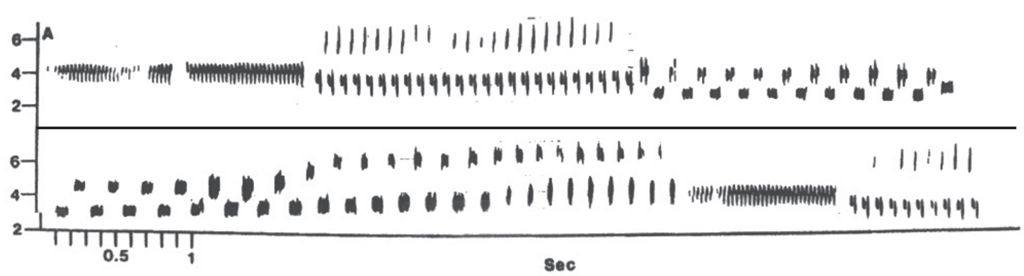
Figure E-7
Traffic Noise Masking Thresholds and Brewer's Sparrow Vocal Signal Profile



American Bittern



Black-necked Stilt



Brewer's Sparrow

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Figure E-8
Sonograms of Representative Bird Vocalizations

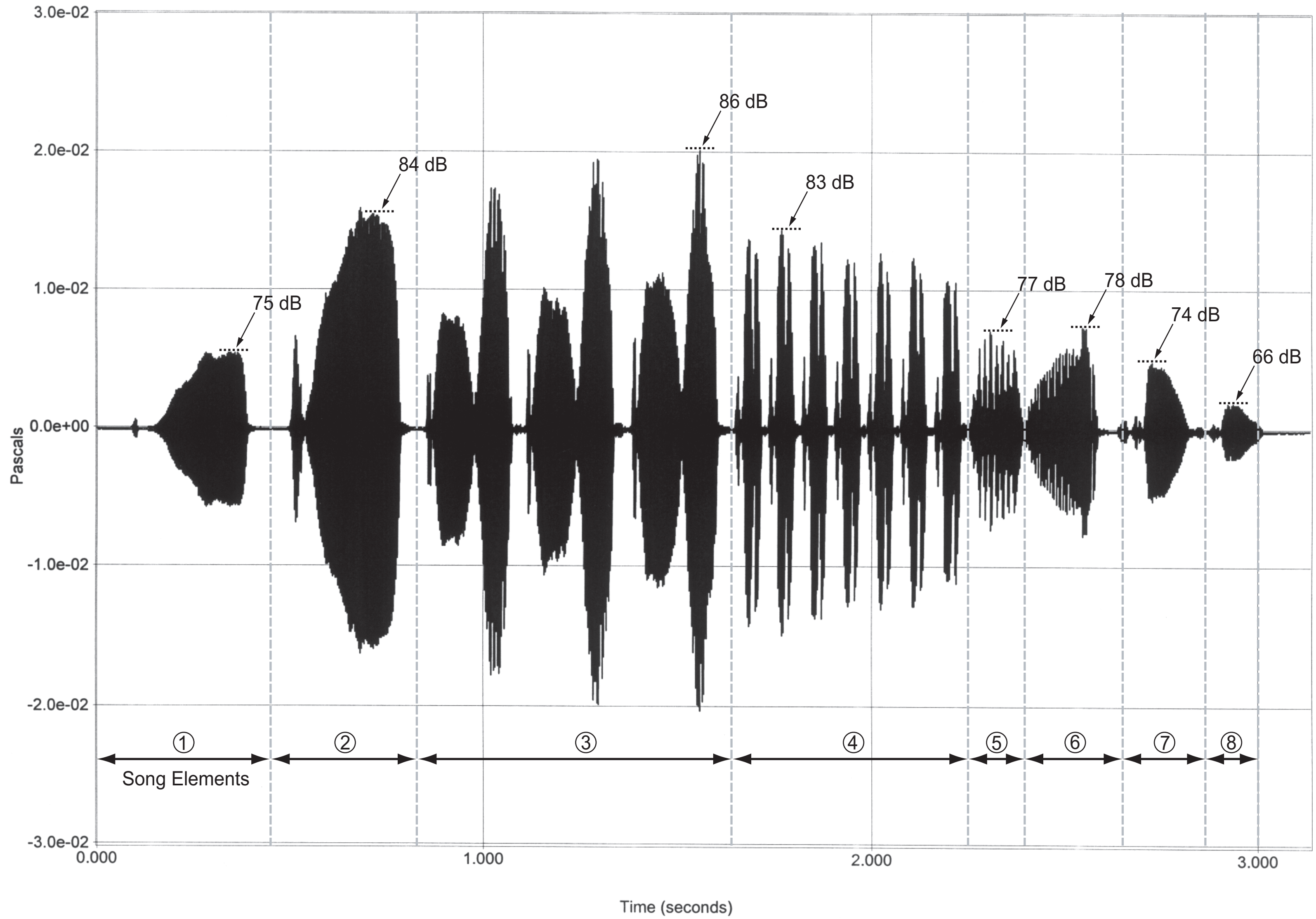

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Figure E-9
Brewer's Sparrow Song Waveform

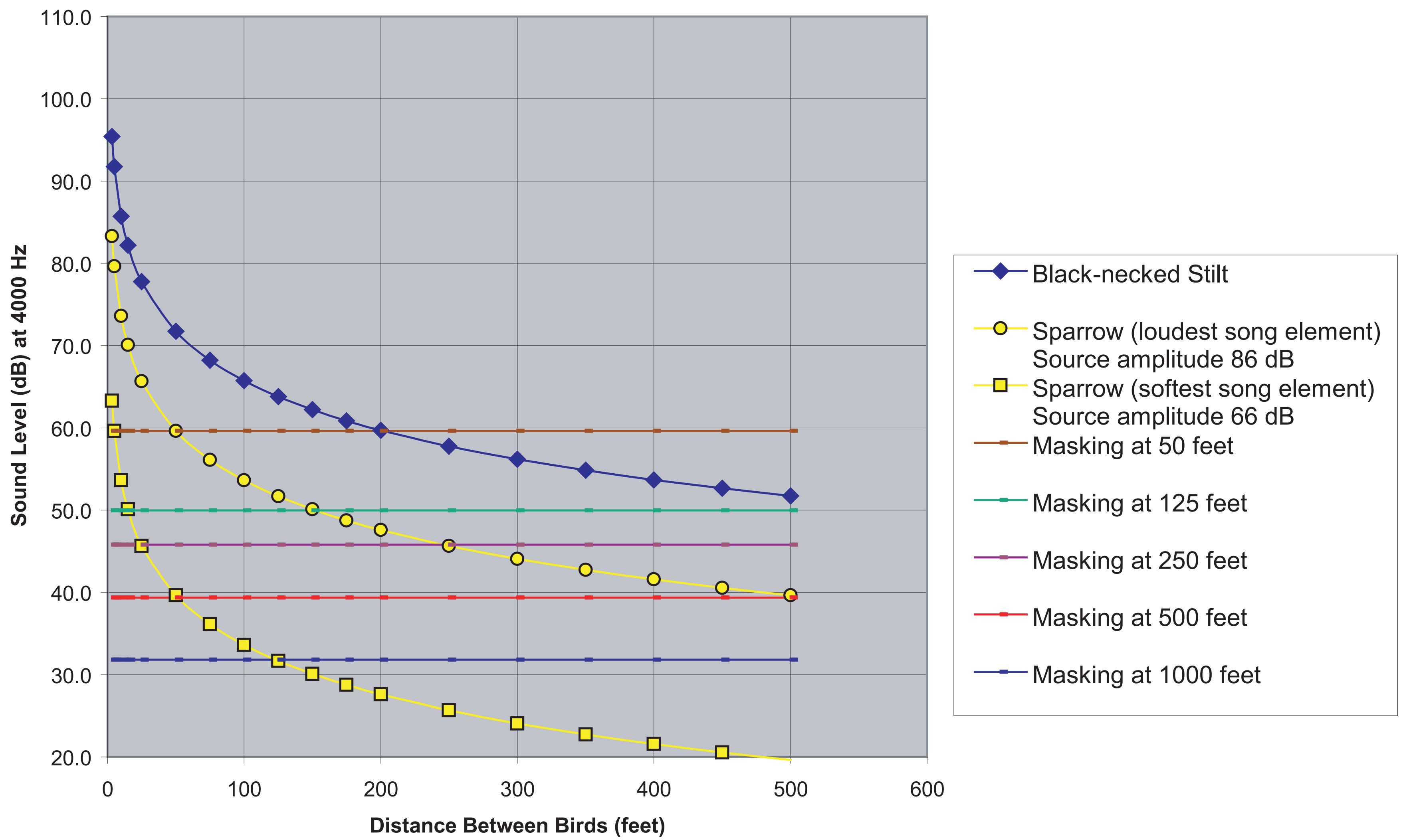

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Figure E-10
Black-Necked Stilt/Brewer's Sparrow Masking Distance

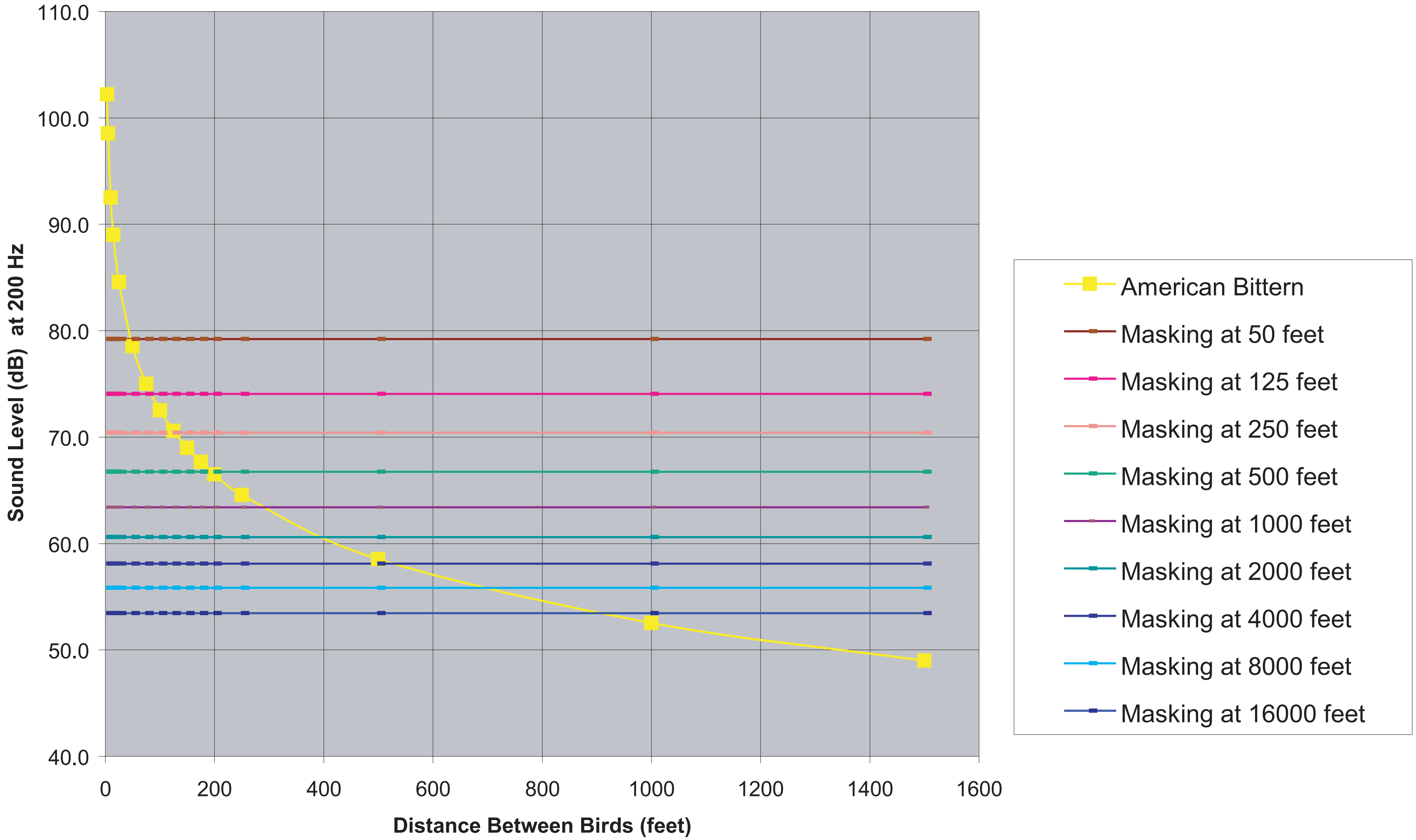

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Figure E-11
American Bittern Masking Distance

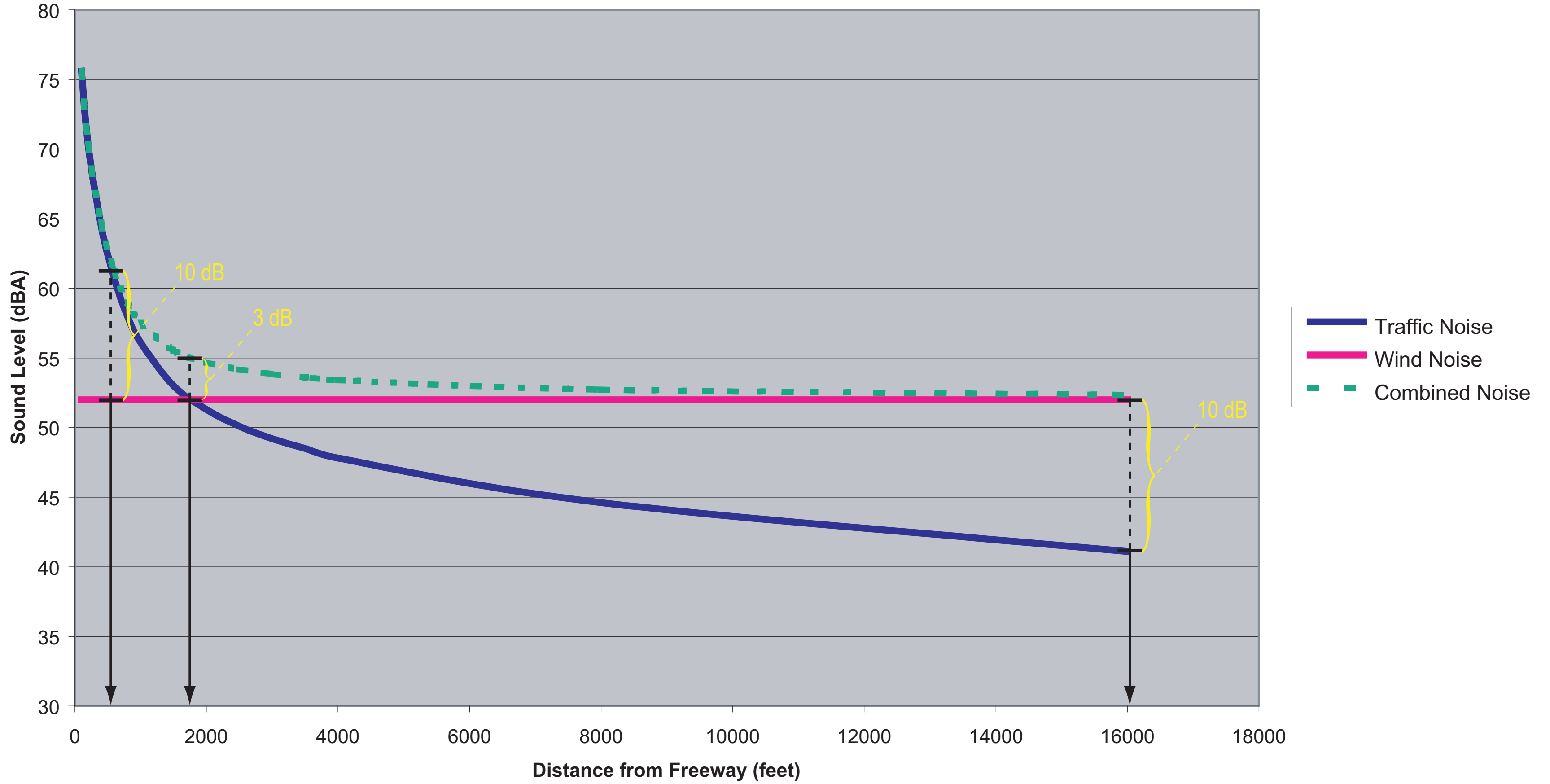

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Figure E-12
Combined Effects of Traffic Noise and Background Noise