2. BACKGROUND ON SOUND PROPAGATION

The primary purpose of this study was to increase the understanding of how atmospheric conditions in the Phoenix valley affect propagation of highway noise. Our focus has been on propagation at distances of 400 m (1/4 mile) or more where, under neutral atmospheric conditions, highway noise is almost always well below the FHWA Noise Abatement Criterion (NAC). The FHWA guidelines are that noise abatement should be considered when the maximum hourly Leq from traffic approaches or exceeds 67 dBA. ADOT defines an Leq of 64 dBA as the point where Leq “approaches” 67 dBA.

This section discusses the different mechanisms by which traffic noise changes as it propagates away from the highway. Section 2.1 discusses the primary factors that cause traffic noise to be attenuated under neutral atmospheric conditions. This includes geometric spreading, ground effects, diffraction by barriers, and atmospheric absorption. Note that TNM incorporates algorithms to account for all of these effects.

Section 2.2 discusses atmospheric conditions that affect sound propagation including refraction and air turbulence. Refraction is discussed in Section 2.2.1, turbulence in Section 2.2.2, and Section 2.2.3 is an introduction to computer models that are used to predict refraction effects. In this study, we have used the Parabolic Equation (PE) Method to predict how refraction caused by different temperature and wind gradients will affect sound levels.

2.1 NEUTRAL ATMOSPHERIC CONDITIONS

2.1.1 Geometric Spreading

Recalling the sketch earlier in Section 1.1 (page 10), as a sound wave travels out from a source with an ever-increasing radius of the wave front, the sound intensity decays as the surface of this wave front increases. A point sound source creates a spherical wave with geometric spreading loss that obeys an “inverse square” law. This causes the sound level to decay by 6 dB for every doubling of the distance from the source in the absence of any other propagation effects. This is the pattern for the decay of sound from a single, stationary vehicle.

However, highway noise analysis is typically based on Leq, the energy average or equivalent sound level over a period of time. This means that we are really concerned with the integrated time average of sound as vehicles move along the highway. Thus, the time average level from a line of traffic decreases with distance (in a loss-less, neutral atmosphere) as if the sound source is an infinite cylinder, not a single point. In terms of Leq, even a single moving vehicle acts like a line source. For a very long, straight roadway, traffic noise can thus be modeled as a cylindrical source and the area of the expanding cylindrical wave front increases with just the radius, not the square of the radius as for spherical spreading. In this case, the spreading loss causes a 3 dB reduction in sound level for every doubling of the distance from the source.

The idealized attenuations for point and line sources are shown in Figure 6. The three lines in Figure 6 are all based on a sound level of approximately 80 dB at 50 feet from the source. As can be seen, the difference between line and point sources at a distance of 1,000 feet is 13 dB. Also shown in Figure 6 is the commonly assumed attenuation curve for highway noise propagation over soft ground, an attenuation rate of 4.5 dB per distance doubling. At 1,000 ft, the difference between propagation over very hard ground and over soft ground is 6.5 dB.

For a finite segment, the road will act like a line source when the distance to the receiver is much less than the length of the segment. Conversely, it will act as a point source when the distance to the receiver is much greater than the length of the roadway. The general approach used by TNM to accurately model geometric spreading is to divide all roadways in to relatively small segments and consider the propagation from each segment independently. The contributions from all the segments are combined to get the projected sound level at each receiver.

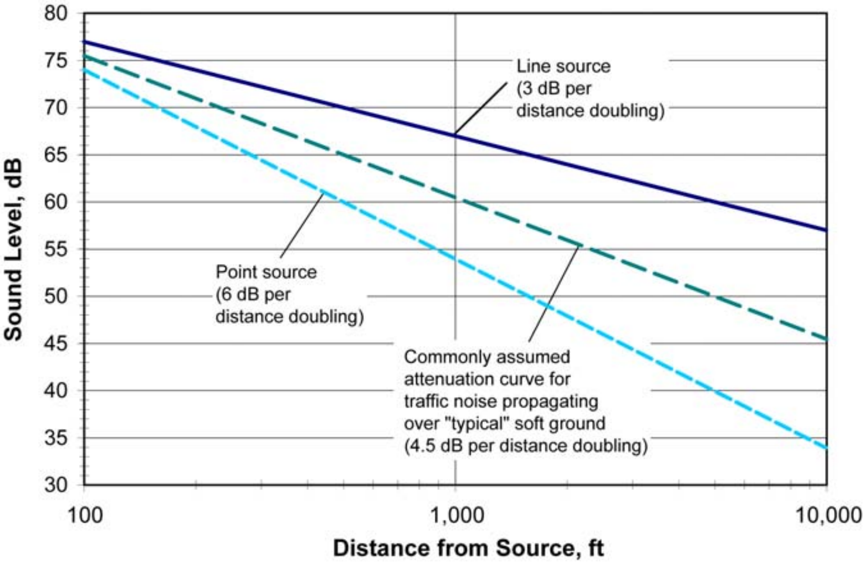

Figure 6. Attenuation Curves for Line and Point Sources

2.1.2 Atmospheric Absorption

Spreading losses do not represent a loss of sound power from a noise source, only a reduction in the sound power per unit area as the radius of an expanding wave front increases. However, there is a true loss in the total sound power as the sound propagates through the atmosphere. This loss occurs as a result of small amounts of heating and viscous losses and energy exchange between air molecules as a sound wave passes. This is called ***atmospheric absorption*****.** Atmospheric absorption varies strongly with the frequency of the sound wave and the temperature, humidity, and, to a minor extent, the atmospheric pressure in the air. This loss is greatest at high frequencies and in hot, dry air.

Figure 7 shows atmospheric absorption as a function of frequency over a distance of 500 m (1640 ft) for the early morning and mid-day conditions of one day in March 2004. The atmospheric absorption at 1000 Hz is about 2 dB in the early morning and about 3 dB mid-day. However, by 5000 Hz, the attenuation for both times of day is over 20 dB. This is the reason that sounds lose their high-frequency content as they propagate over long distances. In fact, we judge how close a noise source is not only by the loudness but also by the high frequency content of the sound. The less high frequency, the farther away a source seems to be.

Figure 8 shows the difference between the two curves shown in Figure 7. Although there is a substantial difference at the higher frequencies, referring back to Figure 7, it is seen that these frequencies are severely attenuated in both cases so that the difference in A-weighted sound level is small.

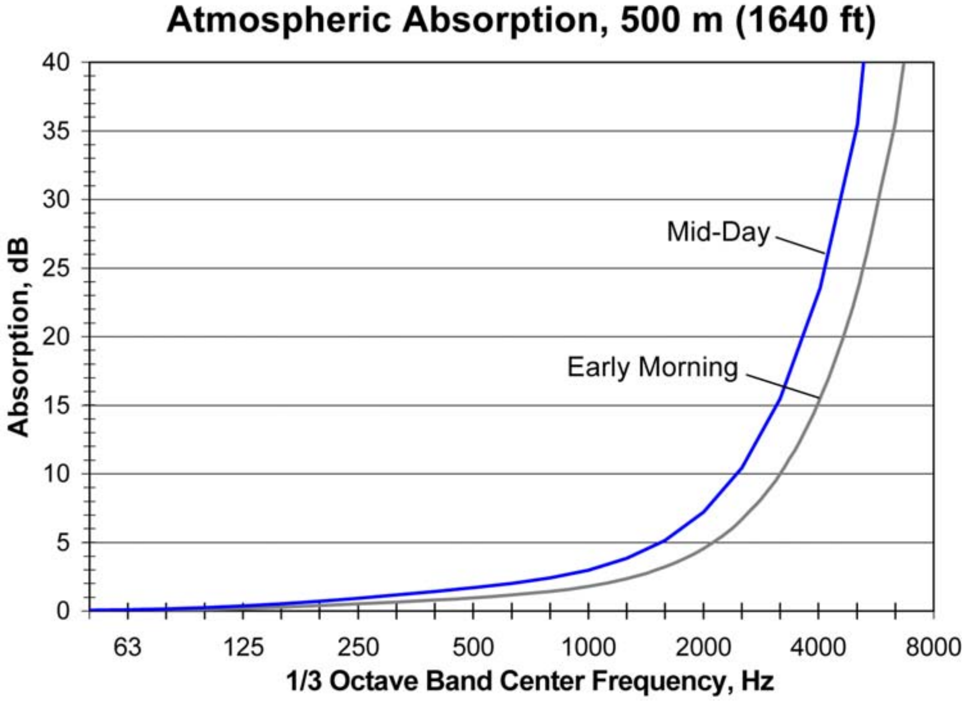

Figure 7. Atmospheric Absorption Early Morning and Mid-Day for a Representative Day in March 2004

Early morning conditions:	50°F,	75% Relative Humidity
Mid-day conditions:	86°F,	20% Relative Humidity

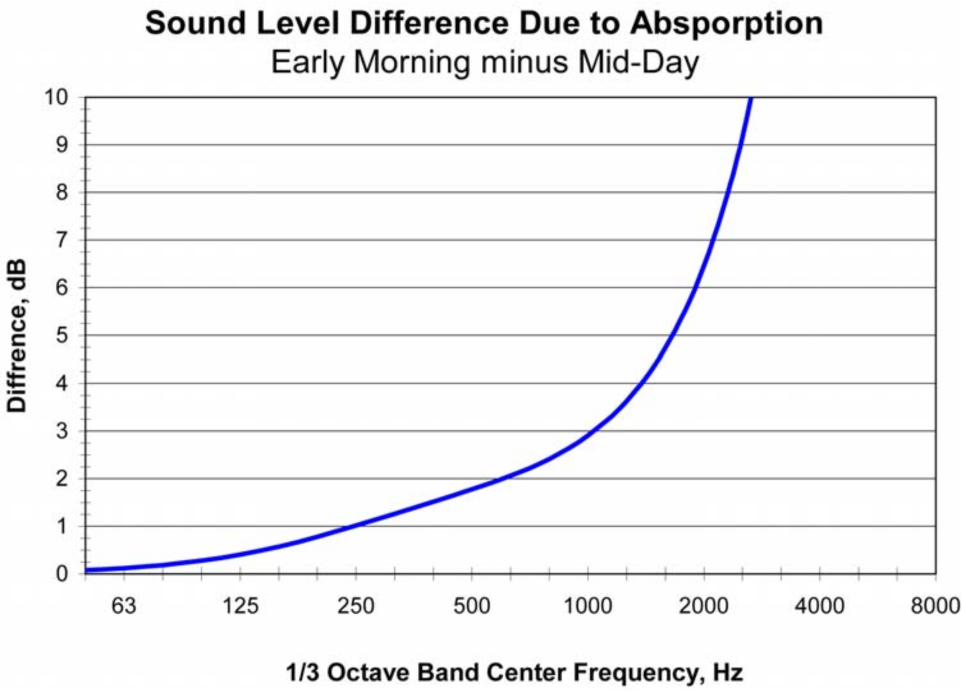

Figure 8. Difference in Atmospheric Absorption in Figure 7

2.1.3 Ground Effects

Sound propagation primarily parallel to the ground is affected by the complex interaction of the sound waves and the ground surface, which can both increase and decrease the propagation loss in excess of that provided by geometrical spreading and atmospheric absorption. The amount of ground attenuation depends on the nature of the ground, the frequency of the sound, the distance over the ground, and the source and receiver heights. TNM includes an algorithm to approximate the ground effect attenuation based on the acoustic impedance of the ground. This is illustrated in Figure 9. TNM Version 2.5 characterizes the ground impedance in terms of cgs Rayls* and allows default values ranging from 20,000 cgs Rayls (pavement) to 10 cgs Rayls (powder snow). The difference in predicted A-weighted Leq values between pavement and lower impedance ground types at several distances are tabulated in Table 1. At 305 m (1,000 ft), the difference between very high impedance (pavement) and high impedance (hard soil) results in about a 3 dB difference in the A-weighted sound level. Going from hard soil to loose soil results in an additional 8 dB difference. However, going from loose soil to the lowest default impedance in TNM (powder snow, an uncommon occurrence in Phoenix) results in an additional attenuation of only 4 dB.

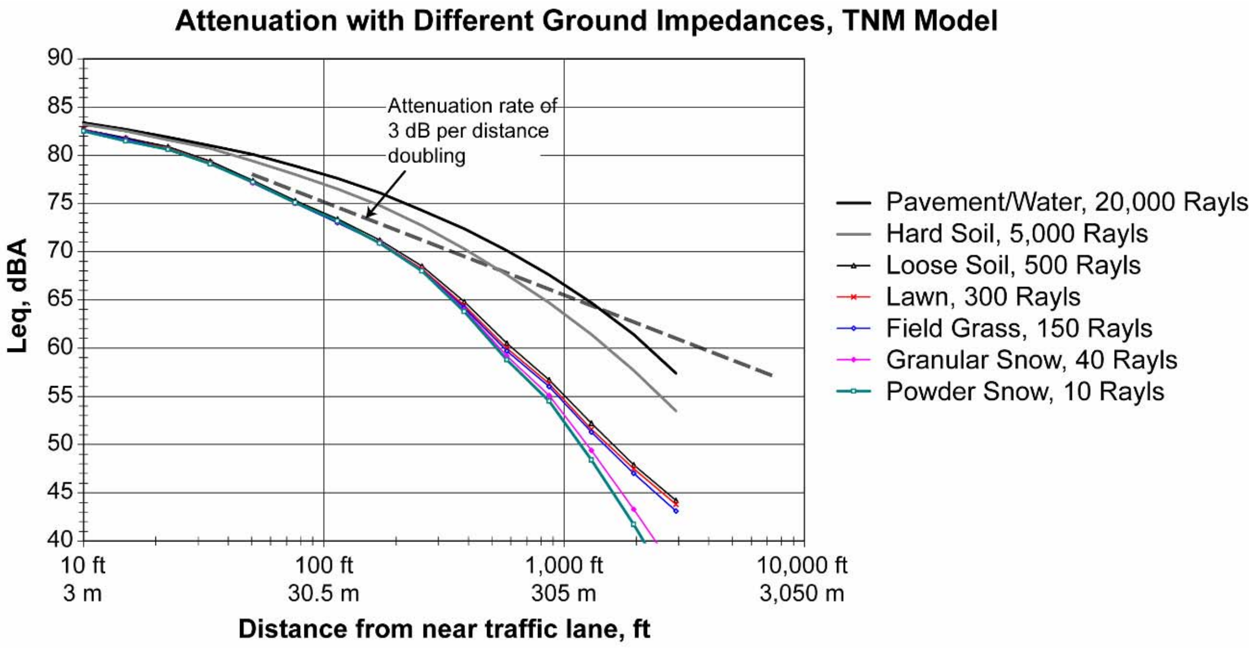

Figure 9. Combined Geometric Attenuation and Excess Ground Attenuation, Automobile Traffic on Pima Freeway

(Ground impedance in terms of cgs Rayls, receiver height = 5 ft, 1.5 m)

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* Acoustic impedance is the complex ratio of the dynamic pressure to acoustic particle velocity, 1 cgs Rayl = 1 dyne·sec/cm^3.

Table 1. Effects of Ground Impedance on Leq as a Function of Distance from Highway
(calculations performed using TNM version 2.5)

Distance	Difference in Average A-weighted Sound Levels Compared to Pavement[a], dB					
	Hard Soil (5000 Rayls)	Loose Soil (500 Rayls)	Lawn (300 Rayls)	Field Grass (150 Rayls)	Granular Snow (40 Rayls)	Powder Snow (10 Rayls)
152 m (500 ft)	-2	-8	-9	-9	-10	-10
305 m (1000 ft)	-3	-11	-11	-12	-14	-15
610 m (2000 ft)	-4	-13	-14	-14	-18	-20
914 m (3000 ft)	-4	-14	-15	-16	-21	-23

Notes:
(a) Ground impedance is in terms of cgs Rayls. Pavement is assumed to have an impedance of 20,000 cgs Rayls.

2.1.4 Diffraction by Barriers and Other Obstructions

Barriers have been extensively employed along highways to help reduce the impact of highway noise at nearby residences. They are most effective at relatively short distances, typically within the first block or two from a highway. At larger distances from sound barriers, downward refraction of sound initially headed skyward can short-circuit the sound attenuation by a barrier.

In the absence of these atmospheric effects, the attenuation of barriers can be accurately predicted by well-known methods already incorporated into highway noise prediction models. For example, TNM includes provisions for evaluating attenuation from single or dual parallel noise barriers and attenuation over/through rows of buildings and dense vegetation.

The basic design and performance parameters for highway noise barriers can be summarized in a simplified form as follows:

- The barrier must block the straight-line direct path from the noise source to the receiver.
- Barrier attenuation increases as the barrier height increases.
- For structural reasons, barrier heights are generally limited to heights of no more than 30 feet.
- Barrier attenuation is greater when the distance between the barrier and the noise source or between the barrier and the listener is relatively small. That is, to be effective a barrier should be close to the noise source or close to the receiver; the farther the receiver is from the barrier, the less benefit there will be from the barrier.

A few of the trends in barrier insertion loss as a function of barrier height and distance from the source are shown in Figure 10. This example is based on the geometry at the Scottsdale test site along the Pima Freeway with a 2.4 to 8.5 m (8 to 28 ft) high sound wall located parallel to the west side of the freeway, 4.6 m (15 ft) from the edge of the pavement. The model used a default ground impedance of 500 cgs Rayls (loose soil). Figure 10 illustrates how barrier effectiveness increases with barrier height and decreases with distance from the noise source. The noise source heights are as assumed in TNM and the receiver height is 1.5 m (5 ft).

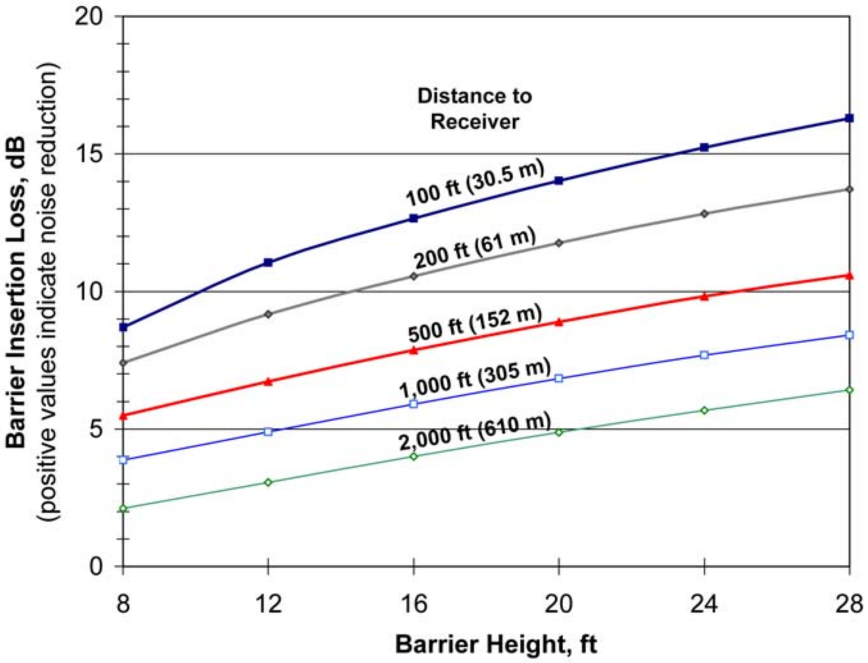


Figure 10. Representative Values for the Barrier Insertion Loss as a Function of Barrier Height and Distance to Receiver

Atmospheric effects on the propagation of sound over buildings acting as barriers in urban areas can be expected to have some similarities to those for thin barriers discussed above. However, the buildings can partially obstruct the flow of air causing the viscous and thermal boundary layer to approach the height of buildings. Thus, weather-induced refraction effects could be more limited in areas with buildings. The same influence on the surface boundary layer is also true for propagation through forests.

The ground attenuation effect in urban areas is generally much smaller than in suburban or rural areas because of more paving. The interference or sound reflection pattern of buildings is much different from that encountered over flat terrain. Prediction of sound propagation of noise from highways in suburban areas is based largely on empirical methods.[17, 19]

2.2 ATMOSPHERIC EFFECTS

2.2.1 Refraction

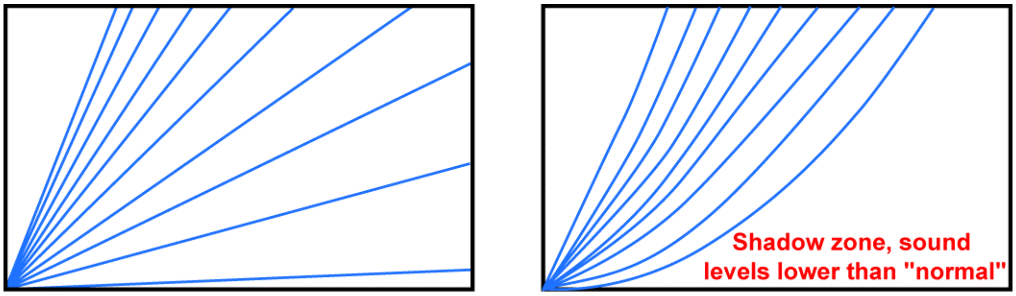
Refraction of highway noise is the key factor for this study. As sound travels through still air with a uniform temperature at all altitudes, sound rays emanating in all directions from a source on the ground will travel in straight lines as illustrated in Figure 11A below. During the day, solar radiation heats the earth surface resulting in warmer air near the ground. This condition, called a temperature lapse (Figure 11B), is pronounced on sunny days but can also exist under overcast skies. A temperature lapse is the common daytime condition during most of the year and causes ray paths to curve upward. After sunset, there is often radiation cooling of the ground, which produces cooler air near the ground surface and forms a temperature inversion. Within the temperature inversion, the temperature increases with height and ray paths curve downward. (Figure 11C). Finally, when the temperature change with elevation is initially negative, close to the ground (like in Figure 11A), and then begins to increase at higher altitudes, and/or the wind is initially opposite to the propagation direction close to the ground and then reverses direction at a higher altitude, a more complex pattern such as in Figure 11D can occur. These four patterns may be categorized by their sound propagation character as:

(A) Uniform geometric spreading without any excess attenuation or amplification from refraction effects.

(B) Upward refraction creating an acoustic shadow zone with lower than normal sound levels. Sound levels with this condition will often be about 5 dB lower than for condition (A).

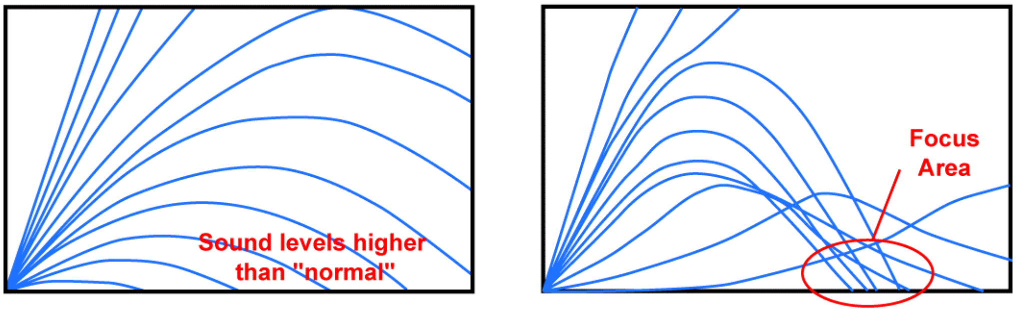
(C) Downward refraction creating an enhanced sound fields and higher than normal sound levels. Sound levels with this condition can be 5 to 10 dB higher than for condition (A).

(D) Sound focusing in localized regions. Depending on the amount of focusing, sound levels for this condition could be 15 to 20 dB higher than for condition (A) and more than 20 dB higher than for condition (B).



(**A**) Straight ray paths under neutral atmospheric conditions

(**B**) Upward refraction when vertical velocity gradient is negative



(**C**) Downward refraction when vertical velocity gradient is positive

(**D**) Focusing with complex vertical velocity gradient

Figure 11. Sound Ray Paths for Different Patterns for Sound Velocity Gradients
(Figure after reference 20)

Representative temperature profiles measured during the Phase 1 measurements in March 2004 are shown in Figure 12. Shown are the vertical temperature profiles on the hour for 4 days. The first curve on the left is the temperature profile at midnight and the last curve on the right is the temperature profile the following night at 23:00 (11 PM). As can be seen, the vertical profile varies significantly through the day. Starting at midnight, the profile was slightly positive on March 8 and strongly positive on the other 3 days. Around 8:00, the transition from inversion to lapse starts and by 9:00 the profile is almost straight on all 4 days. This represents neutral atmospheric conditions as is assumed by the highway noise prediction programs. At around 18:00 (6 PM), the profiles are once again vertical. This means that between 9:00 and 18:00 we would expect levels of freeway noise to be equal to or lower than projected by TNM and between about 18:00 and 8:00 the following day, we would expect freeway noise to be higher than projected by TNM.

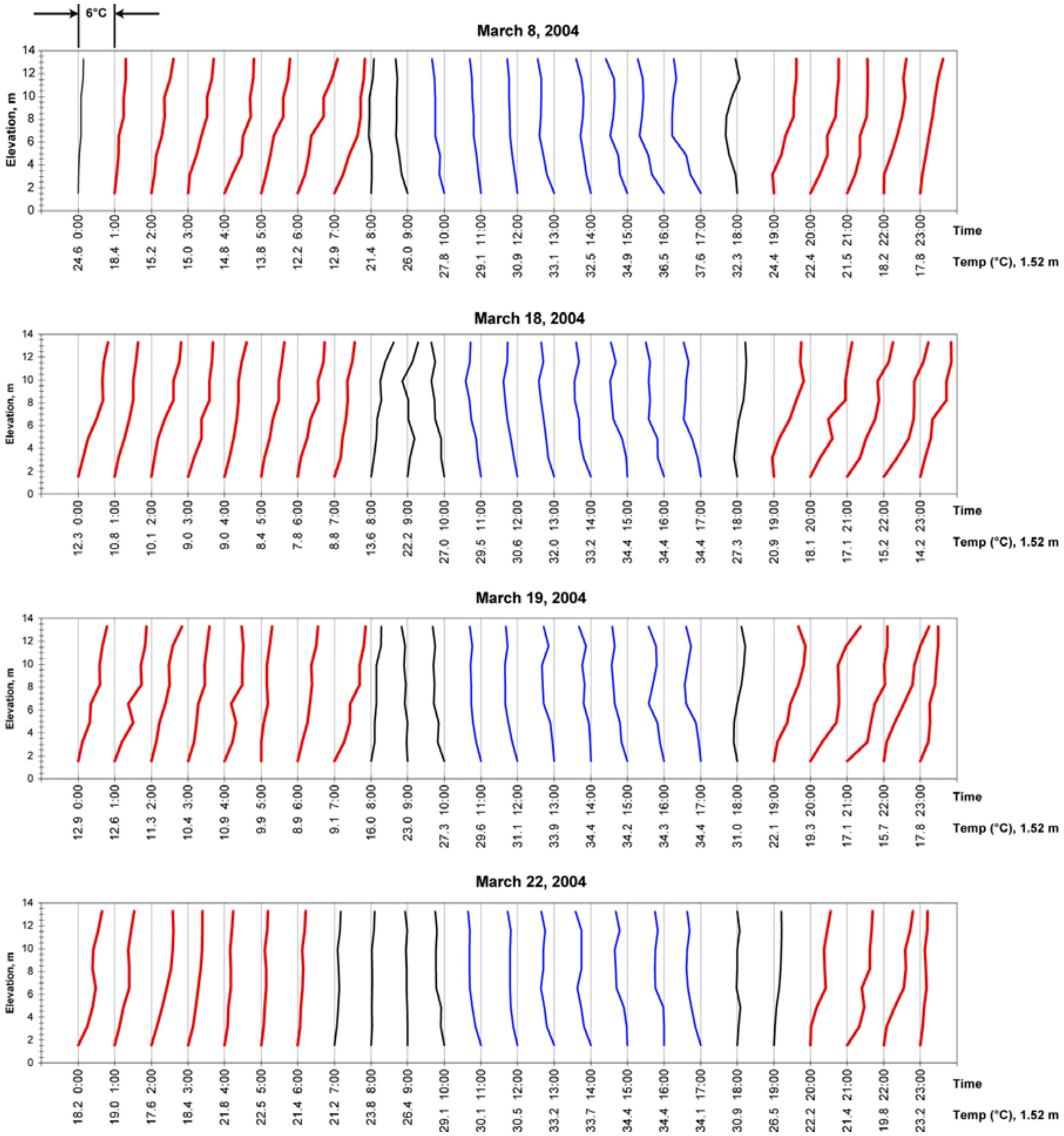


Figure 12. Vertical Temperature Profiles for 4 Days During Phase 1 Measurements
Slope to the left indicates a temperature lapse and slope to the right indicates an inversion (temperature increases with elevation)

As discussed above, downwind sound refraction can cause the initially skyward-bound sound to be refracted over buildings, trees, and other obstructions, and thus negate any benefits from obstructions partially blocking the direct path. This concept is included in ISO Standard 9613-2 where it is assumed that the refracted path, such as illustrated in Figure 5 (page 14), has a radius of 5 km (3.1 mi). However, based on a brief analysis, it appears that use of the ISO model to evaluate sound propagation from Phoenix area freeways is impractical.

2.2.2 Turbulence

Sound from a directive sound source loses energy from the primary beam of radiation by scattering or diffraction from atmospheric turbulence in addition to spreading loss, atmospheric absorption, and refraction. Theoretical predictions by Brown and Clifford[4] indicate that this scattering attenuation should vary substantially with the elevation of the source, the scattering attenuation decreases as the source elevation increases. This mechanism for sound attenuation is generally not included in engineering prediction models for outdoor sound propagation.

Another, more important effect of scattering by turbulence is to limit the maximum attenuation achieved in a sound shadow zone created by a negative sound speed gradient (see Figure 11B) or behind a solid body or barrier. The ray theory of sound propagation predicts that this shadow zone has sharply defined boundaries. Thus, in principle, on one side of the boundary there is a finite sound field and close by on the other side of the boundary there would be no sound. This does not really happen in practice. As sound waves propagate along the boundary of a shadow, sound is scattered (diffracted or “leaked”) by turbulence across this sharp boundary into the shadow zone. A more complete discussion of diffraction of sound can be found in Reference 23. For engineering prediction models of attenuation into a shadow zone, it is reasonable to limit the maximum attenuation to somewhere between 15 to 30 dB depending on the intensity of the turbulence in the air.[12,24]

One final detail about the effect of turbulence on sound propagation deserves mentioning: the temporal fluctuation in sound levels caused by passage of a sound wave through the turbulent structure of the atmosphere.[5,8] These fluctuations are normally averaged-out, even in measurements conducted over relatively short time intervals. However, the presence of these fluctuations should be recognized when acquiring any valid outdoor noise measurements and in presenting a story about outdoor sounds to the public. Their rate of fluctuation can vary from seconds to many minutes reflecting the wide range scale of turbulent patches in the air, often called “turbules.” These fluctuations of sound, when rapid, can be considered as acoustic “twinkle” like the optical twinkle in starlight or, when very slow, as like the slowly changing brightness of the moon as a patch of clouds passes though its image.

Although scattering by turbulence must be recognized as one of reasons that sound level fluctuate, turbulence will not typically cause sound levels to increase significantly compared to the non-turbulence condition. As such, turbulence is unlikely to have an important role in the relatively high noise levels observed at distances greater than 400 m (1/4 mi) from Phoenix area freeways.

2.2.3 Computer Modeling of Refraction Effects

For years, theoretical methods that used ray-tracing of sound propagation paths in the atmosphere, such as those illustrated in Figure 11, have been capable of predicting sound refraction effects. See References 18 and 20 for an introduction to these methods and Reference 21 for an updated treatment of the subject. At low frequencies, due to diffraction by turbulence, ray tracing leads to unreliable predictions of long-range sound propagation. When the effects of terrain and scattering by turbulence are included, numerical solutions to the wave equation become necessary. Until recently, the costly computation time tended to make this approach impractical. Recent advances in computers and new computer codes have made it possible to efficiently and quickly evaluate actual sound propagation under realistic weather conditions. Nevertheless, it should be made clear that earlier, but slower, computational techniques (e.g., in the days of punch cards and mainframes) were successfully employed in many situations to evaluate the risk of sound focus conditions.

The following three basic numerical programs, some with variations, have been found to be valuable tools in studying refraction effects:

- Gaussian Beam Model
- Fast Field Program (FFP) Model
- Parabolic Equation (PE) Model

An extended benchmark evaluation of these models is reported by 16 authors in Reference 2. The paper compares results for each of the models using one ground impedance model with a flow resistivity about 50% more than for grass turf and four sound speed gradient conditions (zero, negative, positive, and mixed). For the cases studied, it was found that the FFP and PE algorithms agreed to within numerical accuracy and agreed with analytical closed-form solutions for the constant gradient cases for which solutions were available. The Gaussian beam model, which is effectively a more accurate ray tracing model, apparently agreed with the more accurate FFP and PE models for the cases not involving upward refraction. No attempt was made to validate the calculations with any measurements. Each of these models is discussed below.

Gaussian Beam Model

The Gaussian Beam method calculates the path of a Gaussian cross section sound beam, as opposed to a single ray, for an arbitrary set of temperature and wind conditions and an arbitrary source above an absorptive ground plane.[7]

The Gaussian beam approach solves the wave equation in the neighborhood of the conventional rays. The solution associates with each ray a beam having a Gaussian amplitude profile normal to the ray. The approximate overall solution for a given source is then constructed by a superposition of Gaussian beams along nearby rays. The solution removes ray-tracing artifacts such as perfect shadows and infinite energy at caustics without the computational difficulties of numerical solutions to the wave equation. The method results suggest that the augmented beam tracing can be applied to complex atmospheric sound propagation problems with advantages over conventional ray tracing and full-wave solutions.

In one application written for SoundPLAN (a commercial computer program for environmental noise mapping), the sound path transmission data from the Gaussian beam program is handed off to SoundPLAN, and SoundPLAN then computes the far-field sound contours.[3] This approach, called Gausbeam, was developed by acousticians at the Applied Research Laboratory at Pennsylvania State University. Gausbeam calculates the beam paths for a given set of temperature and wind conditions for a full 180° around an arbitrary sound source of known height above an absorptive plane. This model has the benefit of preserving the concept of propagation path while enabling a path computation based on actual propagation conditions. After path and propagation loss are handed over to SoundPLAN, SoundPLAN calculates barrier insertion losses based on the Gausbeam curved paths.

Gausbeam applies the concept of similarity in meteorology to either two or three temperature and two wind data points to estimate what the average sound speed profile will be for each azimuth angle relative to the direction of the wind. Ray paths are constructed using these vertical profiles. SoundPLAN then employs these path calculations to generate noise estimates and noise contours.

Fast Field Program (FFP) Model

Fast field programs permit the prediction of sound pressure in a layered (horizontally-homogeneous) refracting atmosphere at an arbitrary receiver on or above a flat continuous ground from a point source above the ground. The sound speed can be computed from known temperature and wind profiles or specified as an arbitrary function of height above the ground. The FFP method works numerically from exact integral representations of the sound field within the layered atmosphere in terms of coefficients that may be determined from the ground impedance.[14,15] The method gets its name from the discrete Fourier transform used to evaluate these integrals. Several variants of the FFP model (CERL FFP, CFFP, FFLAG FFP, and SAFARI FFP) were included in the benchmark evaluation.[2]

The solution for the integral equation is found and the total field at the desired frequency calculated at any range by carrying out an inverse transform. The mathematically-indefinite integral is replaced by a numerically-finite sum using discrete Fourier transforms.

At very long ranges, the FFP has an advantage in run time but can still be time consuming. The method has the ability to provide useful predictions for any arbitrary layered atmospheric profile that is the same at all points along the propagation path.

The FFP is capable of handling realistically complicated atmospheric profiles through the altitude dependant sound speed but it is limited to either flat topography or a single large-scale topographical feature, such as a large hill. As such, it is difficult to envision adopting the FFP for analysis of realistic topography and highway barrier effects without significant additional development.

Parabolic Equation (PE) Model

In contrast to the FFP model, the PE model is a marching solution that begins at the source and sequentially solves the governing wave equation, step by step, to the receiver position. As such, it is be capable of being "perturbed" along its route to account for range-dependent changes in the atmospheric profile and for modifications to account for topography and barriers. Thus, it should be superior to the FFP for real-world predictions. This is the model that we have used to analyze the effects of atmospheric conditions on sound propagation in this study.

The PE has the capability of including the largest number of atmospheric effects. It assumes that the sound wave from a source is always directed outwards and solves a two-dimensional Helmholtz wave equation with this constraint. Two variants of the PE model (Finite-PE and Fast PE) were included in the benchmark evaluation.[2]

The current state-of-the-art in propagation modeling is the Parabolic Equation with Greens Functions, identified as the GE-PE[10,16] This technique makes a stepwise calculation of the sound field as it propagates outward from the source. It can use specific sound speed profiles at each range step. However, a sound speed profile is normally measured for average conditions at one location, and generally not within the sound propagation field. This average condition is then used for each range step.

It is not practical to evaluate the real propagation path between the source and the receiver without an accurate knowledge of the atmospheric conditions that exist at each range step between the two. It is, however, possible to infer complex propagation conditions in a sound field if the atmospheric conditions are, while being complex, relatively stable. In other words, if the received sound pressure level indicates that a stable, complex propagation path has been established, then a wind and temperature profile measured near the propagation field can be applied to the entire sound field calculation.

Some examples of the PE calculations for representative weather conditions in the Phoenix valley are shown in Figure 13, Figure 14, and Figure 15. Figure 13 is for typical daytime conditions with no wind and air temperature decreasing with altitude (temperature lapse). This causes the sound rays to bend up and creates a strong shadow zone at distances greater than about 300 m (1,000 ft) from the roadway. For this situation, traffic noise even in quiet suburban areas would probably be inaudible beyond about 400 m (1/4 mile) of the roadway.

Figure 14 shows the much more complex situation that occurs under nighttime or downwind conditions. Even without air turbulence, the sound rays bend down with the result that the sound levels at distances as far as about 5 miles from the highway are attenuated by only 10 to 15 dB. These sound levels would be clearly audible in many suburban areas.

Figure 15 shows the same conditions from Figure 13 and Figure 14 except that turbulence is added. As can be seen, the results are similar in form but the turbulence increases the complexity of the sound field and tends to reduce the shadow effect and the focusing. As discussed above, including turbulence is necessary for a comprehensive accounting of atmospheric effects. At the time of this study, the available PE codes were not sufficiently sophisticated to deal with turbulence and detailed refraction effects. As such, the PE models presented in Section 5 do not account for turbulence and the results must be used with care. In general, the results tend to overstate the effects of sound shadows and have sharper peaks and dips than would be the case were some turbulence introduced into the models.

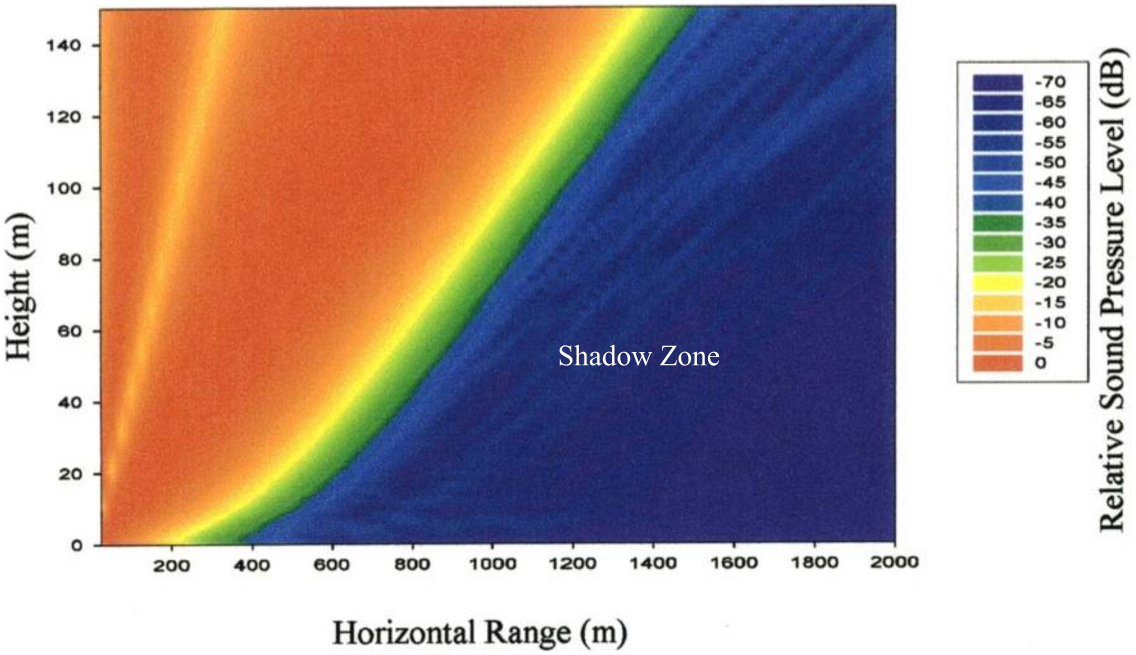


Figure 13. Example of Upward Refraction without Turbulence

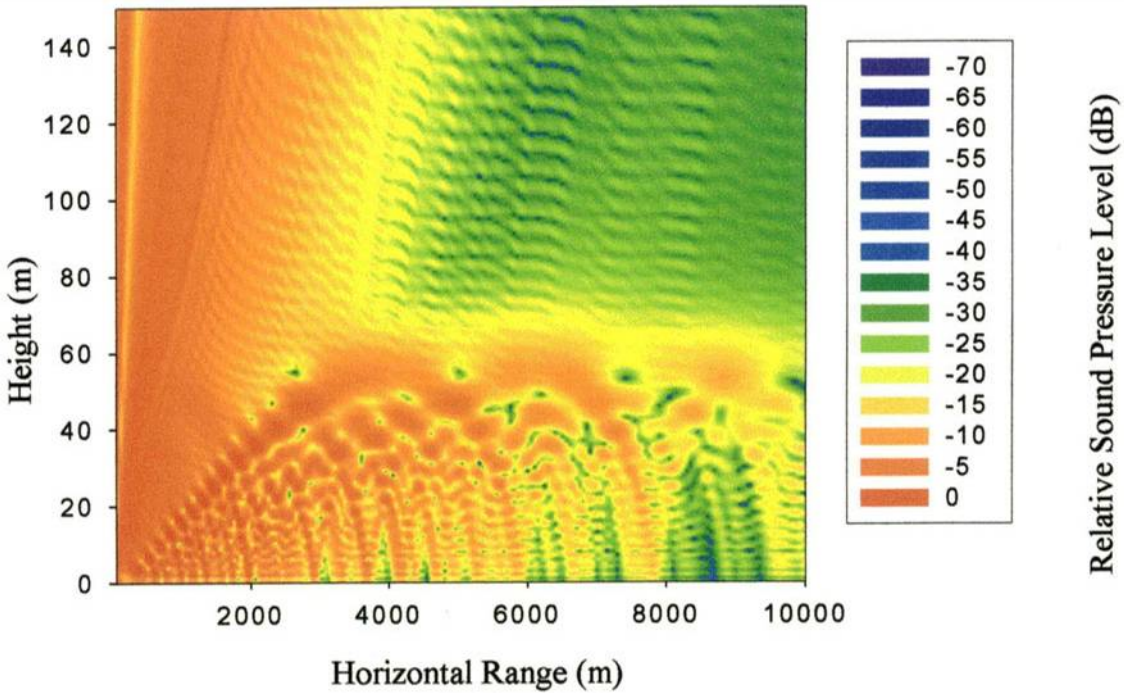
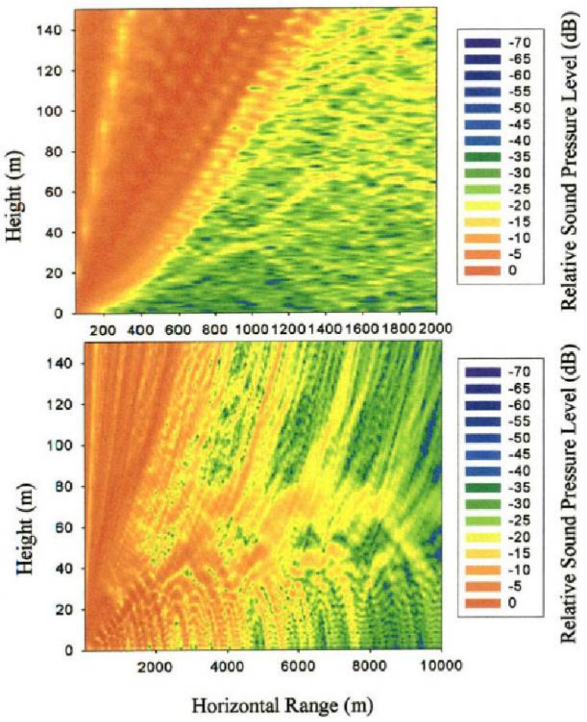


Figure 14. Nighttime or Downward Refraction without Turbulence



a. Upward refraction with no turbulence. Note reduced shadow zone.

b. Upward refraction with turbulence. Minimal global changes compared to turbulence.

Figure 15. PE Code Calculation of Sound Propagation with Turbulence