ARIZONA
TRANSPORTATION
RESEARCH
CENTER

ATMOSPHERIC EFFECTS ASSOCIATED WITH HIGHWAY NOISE PROPAGATION

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We want to recognize the contributions of all the individuals and firms who contributed to this project. They are:

Hugh Saurenman, ATS Consulting, LLC: Principal Investigator.

Estomih (Tom) Kombe: ATRC Project Manager.

Technical Advisory Committee: Fred Garcia, Arizona Department of Transportation, Environmental Planning Group; Kelly McMullen, Maricopa County Department of Transportation; Robert Pikora, City of Phoenix; Steve Thomas, Federal Highway Administration, Arizona Division; Jerri Horst, S. R. Beard & Associates.

Jim Chambers, University of Mississippi, National Center for Physical Acoustics: Jim performed all of the computer modeling, contributed to the field studies, and prepared the modeling sections of the final report.

Hans Forschner, Navcon Engineering Network: Hans was responsible for analysis of the large quantity of short-interval measurement data from the Phase 1 tests. His work included generating 1-minute and 15-minute averages from the 1-second data, producing spectrograms like the ones in Appendix B.4, and preparing the initial plots of the A-weighted noise, frequency spectrum, and weather results. He also processed the WAV files to generate 15-second 1/3 octave band spectra.

Lou Sutherland, Consultant in Acoustics: Lou's vast experience with previous sound propagation studies gave us an enormous leg up in the initial phases of the project. He did most of the work on the literature review and prepared the first draft of the background sections of the final report. His insights were a valuable resource throughout the project.

Robert Bronsdon, Consultant in Acoustics: Bob's role in the project was as a technical advisor, something he is very qualified for through his work on sound propagation for Disney Imagineering. His experience and insights on how atmospheric conditions affect sound propagation and his untiring energy in identifying interesting events in the data were valuable assets to the project.

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EXECUTIVE SUMMARY

BACKGROUND

This report presents the final results of Arizona Transportation Research Center project SPR 555, “Evaluate the Atmospheric Effects Associated with Highway Noise Propagation.” The prime motivator for this project was the observation that traffic noise from freeways in the Phoenix area was sometimes substantially higher than expected at distances of 1/4 mile or farther from the roadway. It is evident that these higher than normal sound levels are caused by atmospheric conditions. The primary questions investigated in this project were: What are the atmospheric conditions in the Phoenix valley that contribute to higher than normal sound levels? Are the conditions unique to the Phoenix valley? Can the atmospheric effects be anticipated?

The main components of the project are:

- A review of the literature relevant to how atmospheric conditions affect sound propagation.
- Detailed noise measurements in a Scottsdale neighborhood along the East Loop 101 Freeway (Pima Freeway) where there had been complaints about freeway noise from residents living more than 400 m (1/4 mile) west of the freeway. Measurements were performed over a two-week period in March 2004 and a one-week period in October 2004 out to distances of approximately 800 m (1/2 mile) west and 400 m (1/4 mile) east of the freeway.
- Computer modeling of sound propagation under various measured and inferred atmospheric conditions.
- Noise measurements before and after installation of an asphalt rubber friction course (ARFC) on the Pima Freeway. The ARFC installation was part of the ADOT Quiet Pavement Pilot Program. The scope of this project was adjusted to coincide with the Quiet Pavement Program and to collect valuable information on the benefits of ARFC pavements in residential areas that are more than 400 m from the freeway.
- A pilot study investigating parametric models of tire/pavement noise.

The results of each of these tasks are summarized here and discussed in detail in the body of the report.

ATMOSPHERIC PARAMETERS

The atmospheric parameters that affect sound propagation are:

- **Atmospheric absorption**: As sound propagates through a uniform atmosphere, some of the sound energy is absorbed by temperature and humidity-dependent processes. The sound energy absorbed increases dramatically at frequencies greater than 1,000 Hz. As a result, high frequencies tend to disappear at distances greater than 400 m from the source. Atmospheric absorption is greatest under high temperature, low humidity conditions. However, for highway noise, changes in temperature and humidity generally result in relatively small changes (1 to 3 dB) in the overall A-weighted sound level.
- **Thermal and wind gradients**: The effective speed of sound in air is a function of air temperature and wind speed. Similar to the way that light is bent at an air/water interface because of the different speeds of light in the two media, sound waves are refracted, or bent, when sound speed varies because of wind and thermal gradients.
- **Turbulence**: Turbulence causes scattering of sound and will result in short-term temporal variations in sound levels. This means that when sound propagates through turbulent air,

sound levels will fluctuate by several decibels even when there is no change in the noise source and other atmospheric conditions are stable. Since atmospheric conditions are never completely stable, the combination of turbulence and wind fluctuations causes highway sound levels at distances of 400 m or greater from a sound source to constantly fluctuate, the greater the distance, the greater the fluctuation. The maximum fluctuation is about ± 6 dB, although with the relatively stable conditions and low wind speeds typical in the Phoenix area, we believe the typical fluctuations from turbulence in the study area are closer to ±2 dB.

CONDITIONS IN THE PHOENIX VALLEY

The Phoenix valley is characterized by light winds, clear skies, and, for approximately 70% of the time, relatively weak synoptic flow* conditions. On a typical clear sunny day, solar radiation heats the ground, which in turn heats the air in contact with the ground. The result is that the warmest air is at ground level and air temperature tends to decrease with elevation. This is referred to as a temperature ***lapse***. After sunset, the ground cools faster than the air causing air temperature to increase with elevation. Air temperature increasing with elevation is referred to as a temperature ***inversion***. Temperature lapse during the daytime and inversion at night is the typical pattern for the Phoenix valley. As illustrated in Figure 1B and Figure 1C, a temperature lapse causes sound waves to bend up creating a sound shadow and a temperature inversion causes sound waves to bend down and increase the sound at the ground level.

The other effect of the clear skies and weak synoptic flow conditions is that warming of the air during the daytime causes air to flow up the slopes of the local mountain ranges and cooling at night causes air to flow back down the slopes. Figure 1D illustrates the effects on sound waves when wind speed monotonically increases with elevation. There is a shadow zone upwind from the noise source and amplified sound levels downwind. During the nighttime inversion conditions, down-slope winds in the Phoenix valley tend to be characterized by calm, or nearly calm, conditions at the ground surface and low-speed jets (3 to 5 m/sec, 6 to 10 mph) at elevations of 15 to 100 m (50 to 330 ft). Thus, the wind speed profile can be quite complex with wind speed increasing and decreasing with elevation and wind direction changing with elevation. The wind conditions are apt to be particularly complex and unstable around sunrise as the inversion conditions start to break up and wind directions start to change.

Based on our literature review and discussions with meteorologists at the Arizona Department of Environmental Quality, we understand that the down-slope flow tends to be east to west in the Scottsdale area where we performed the noise measurements. Figure 1E illustrates the sound focusing and de-focusing that can be created with combination of the down-slope winds and the temperature inversions.

We can generalize the sound fields that are created by atmospheric conditions into five categories:

1. **Neutral Conditions** (Figure 1A): Sound propagates equally in all directions. Completely neutral conditions almost never exist although it is a reasonable assumption within several hundred feet of a noise source.
2. **Temperature Lapse Shadow Zone** (Figure 1B): The normal mid-day temperature lapse on clear, sunny days in the Phoenix valley creates a shadow zone around noise sources.
3. **Temperature Inversion** (Figure 1C): The temperature inversion conditions that form in the Phoenix valley on most clear nights cause sound waves to curve downward and increase sound levels. The result is that sound levels near Phoenix area freeways tend to be relatively high between sunset and about one hour after sunrise.

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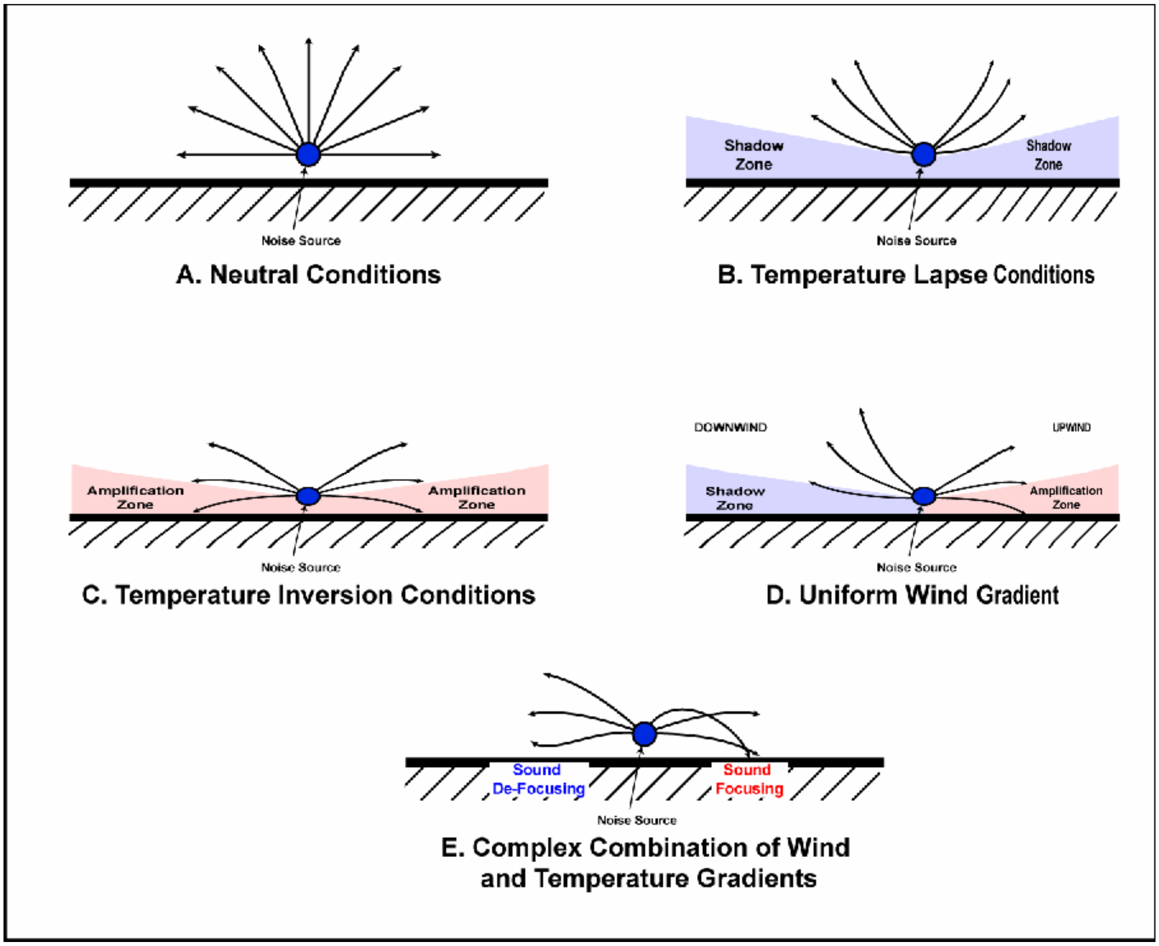
* ***Synoptic*** flow is defined as large scale meteorological patterns on a scale of 1000 km or greater.

4. **Uniform Wind Gradient** (Figure 1D): The Phoenix valley is characterized by light winds except for a few events per year. As such, sound levels are rarely controlled by upwind shadow zones and downwind sound amplification.

5. **Complex Sound Fields** (Figure 1E): The combination of nighttime temperature inversions and the down-slope drainage air flow creates complex sound fields. The average sound levels are caused by the temperature inversion conditions. Layered on top of the increased sound levels from the inversion will be both hot spots from sound focusing and cool spots from sound de-focusing. The hot spots tend to be in the downwind direction from the noise source and the cool spots in the upwind direction. Focusing/de-focusing effects can occur intermittently over 30- to 60-minute periods or can be a fairly consistent occurrence over several days. An example of consistent focusing was observed at one of the noise measurements locations during the second week of the March 2004 measurements. A dramatic example of de-focusing was observed in October 2004 at a site east of the Pima Freeway. Sound levels dropped about 10 dB from about 7:45 AM to 8:00 AM and then returned close to the original levels by 8:15 AM. At the lowest point, the traffic noise had almost completely disappeared into the background noise even though traffic volumes and speeds were relatively constant.



A. Neutral Conditions

B. Temperature Lapse Conditions

C. Temperature Inversion Conditions

D. Uniform Wind Gradient

E. Complex Combination of Wind and Temperature Gradients

Figure 1. Sketch of Sound Refraction Effects

DIURNAL SOUND LEVEL PATTERNS IN THE PHOENIX VALLEY

In Figure 2 we have consolidated the factors that contribute to diurnal variations of traffic noise in the Phoenix valley into idealized curves. These idealized curves apply to locations more than about 300 m (1000 ft) from major freeways and are based on the measurements and modeling performed for this project. Figure 2A shows the effects for sites that are downwind relative to the early morning down-slope air flows and Figure 2B shows the effects for sites that are upwind. The plots on the left show the approximate effects of the thermal and wind gradients and the plots on the right show both the sound levels that would exist under neutral atmospheric conditions and the range of sound levels expected when atmospheric effects are included.

The hourly Leqs for the neutral atmospheric case are based on average hourly traffic counts at the Scottsdale test site in October 2004. The neutral case sound levels are lowest between 3 and 4 AM when traffic volumes are lowest. By 6 AM traffic volumes have reached their typical daytime levels and sound levels are relatively constant until 8 PM. The exceptions are a small dip at 8 AM, and a larger dip between 4 to 7 PM when traffic speeds drop because of rush hour congestion. After 8 PM traffic volumes and sound levels drop each hour until 4 AM when the morning commute period starts again.

Next the effects of refraction by temperature and wind gradients are added in. The effects of temperature inversion at night and temperature lapse during the day are an approximately 8 dB increase in sound levels between sunset and sunrise relative to neutral atmospheric conditions and an approximately 6 dB reduction in sound levels during the daytime. The transitions from inversion to lapse in the morning and lapse to inversion in the evening take two to three hours. The more rapidly the temperature increases at sunrise and decreases at sunset, the shorter the transition periods.

The final effect is the wind gradient, which, under inversion conditions, often consists of low speed jets at elevations of 15 to 100 m (50 to 330 ft). We expect that although there is a complex pattern for the inversion condition wind gradients over the Phoenix valley, the pattern is fairly consistent. This means that there may be locations that are consistently acoustic “hot spots” and others that may be only a few blocks away that are consistently acoustic “cool spots.” Without the ability to characterize the wind gradients at specific locations it does not appear that it will be feasible to predict where acoustic hot spots will occur without extensive noise measurements.

The sound level variation for different wind gradient conditions shown in Figure 2 are:

- Inversion, downwind (Figure 2A, nighttime and early morning): In this case the wind tends to strengthen the downward refraction of the inversion conditions. The result is a small increase in the sound levels shown as 2±3 dB in Figure 2A. This 2±3 dB is added to the approximately 8 dB caused by the inversion giving a range of 7 to 13 dB.
- Lapse, upwind (Figure 2A, daytime): Wind directions in the Phoenix valley tend to shift 180° between inversion and lapse conditions, which means that where nighttime conditions are an inversion and downwind, the daytime condition will tend to be a lapse and upwind. Because both the wind and the temperature gradient tend to create a sound shadow, we expect the wind gradient to slightly reduce sound levels. This is shown as 1±2 dB in Figure 2A added to the -6 dB due to the lapse conditions giving a range of -9 to -5 dB.
- Inversion upwind (Figure 2B, nighttime and early morning): Now the wind gradient tends to counteract the temperature gradient. The result appears to be that sound levels fluctuate over a wider range than for the downwind case. Sometimes the wind will act to increase sound levels and other times it will act to decrease sound levels to be approximately equal to the neutral atmospheric condition case. The wind-effect range

shown in Figure 2B is ±5 dB, which, again, is added to the approximately 8 dB caused by the inversion. The final range is 3 to 13 dB.

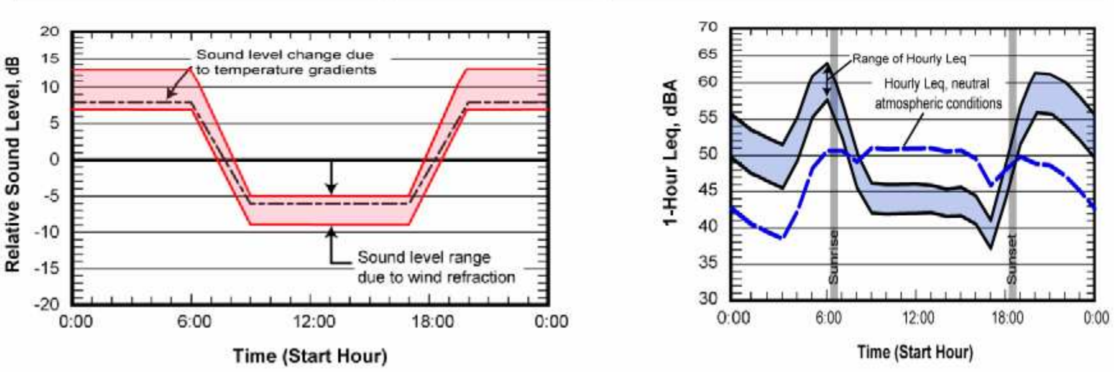
- Lapse, downwind (Figure 2B, daytime): Now the wind tends to counteract the sound shadow created by the lapse conditions. The result is expected to range from no effect to almost completely counteracting the effect of the temperature lapse. This is shown in Figure 2B as a 0 to 5 dB increase that is added to the -6 dB caused by the lapse conditions. The combined range is -6 to -1 dB.

The combined effect of traffic speed and volume variations, temperature gradients and wind gradients is shown in the graphs on the right in Figure 2. This figure illustrates that at locations where atmospheric effects are important, the actual levels can be expected to range approximately ±10 dB relative to neutral atmospheric conditions. Indeed, the only time the two coincide is when the lines cross during the morning and evening transition periods.

The curves in Figure 2 are based on sunset and sunrise times in March and October. In January when days are shorter, the higher noise levels will extend longer in the morning and will start earlier in the afternoon. Correspondingly, the longer days in the mid-summer will mean that inversion conditions generally will dissipate by the morning commute period and will not form until after the evening commute period. As a result, the noise increases due to inversions are probably most noticeable in cool months because the increased noise levels coincide with periods with high traffic volumes and when people tend to spend more time outside.

Another important factor is that since the range for the expected levels can be up to 20 dB, it is difficult to extrapolate from a limited number of noise measurements. However, the patterns of sound level variation observed in this project are believed to be reasonably representative of conditions in the Phoenix valley and in other locations in Arizona with similar topography and weather.

A. *Downwind* Location Under Late Night/Early Morning Down-Slope Flow, *Upwind* Under Daytime Up-Slope Flow



B. *Upwind* Location Under Late Night/Early Morning Down-Slope Flow, *Downwind* Under Daytime Up-Slope Flow

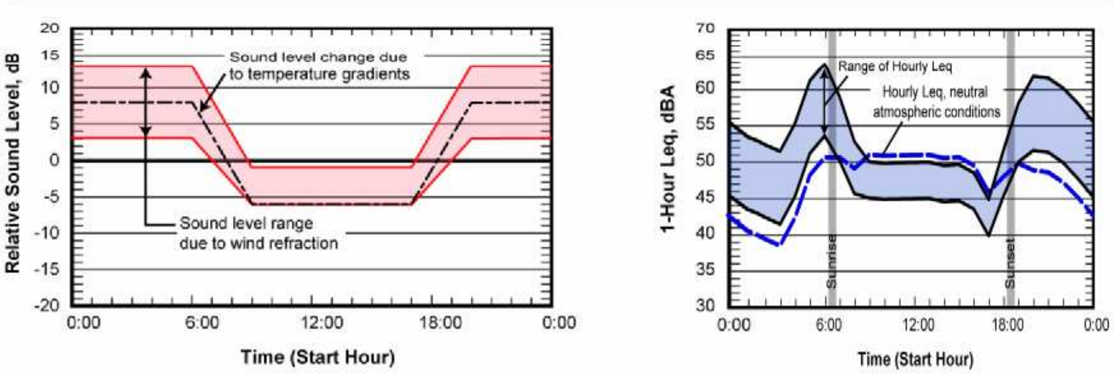


Figure 2. Illustration of Factors Driving Diurnal Variations in Sound Levels

STUDY CONCLUSIONS

The key overall conclusions of this study on how atmospheric conditions affect long distance sound propagation in the Phoenix valley are:

1. **Nighttime Inversion:** The nighttime inversion condition that is common from October through March results in sound level increases averaging from 5 to 8 dB at distances greater than 400 m (1/4 mile) from freeways. This is probably a year-round phenomenon since nighttime inversions occur in the warm weather months as well.
2. **Drainage Flow:** The nighttime down-slope drainage flows off the mountain ranges surrounding the Phoenix valley cause localized focusing and de-focusing of sound levels. These can be consistent patterns over several days or can be isolated events occurring over periods of 15 to 20 minutes. Focusing/de-focusing effects on the order of +4 to -10 dB were observed during the measurements. The Parabolic Equation computer model, a valuable tool for investigating refraction effects, could be used to investigate specific focusing effects if it were possible to obtain instantaneous wind speed and direction profiles up to elevations of 60 to 90 m (200 to 300 ft).
3. **Sound Level Variations:** Sound level variations under inversion conditions appear to be greatest at locations that are upwind relative to the down-slope flows.
4. **Seasonal Effects:** The highest sound levels during the October to March period will usually occur around sunrise when high traffic volumes coincide with strong inversion conditions.

The loudest hour during the March and October measurements was consistently 6 AM. The loudest hour is likely to shift with seasonal changes in sunrise and sunset.

5. **Onset of Refraction Effects:** The computer modeling indicates that there is a rapid onset of refraction effects between about 200 and 300 m (650 to 1000 ft) from Phoenix valley roadways. Closer than 150 to 200 m from a roadway the atmospheric refraction effects are generally less than ±5 dB. At greater than 300 m (1000 ft) the refraction effects are often on the order of ±10 dB. This is a tentative conclusion based on the computer modeling.
6. **Quiet Pavement Pilot Program:** The noise measurements before and after resurfacing the Pima Freeway with ARFC showed that sound levels were consistently reduced by 8 to 10 dB at the close-in and community measurement sites. The effects were almost entirely at frequencies of 500 Hz and higher. Before the ARFC, the sound level spectrum was dominated by sound in the 630 to 3000 Hz 1/3 octave bands. The spectrum was much more evenly balanced after the ARFC surfacing. The reduced sound levels were very evident at all of the measurement sites and a number of residents commented to us how pleased they were with the lower community sound levels. The more balanced spectrum also improved the sound "quality" and reduced the annoyance characteristic of the noise. This improved sound quality was evident at the freeway shoulder, but was less evident at the community sites because, with the reduced sound levels, the traffic noise often was no longer the dominant noise source.