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---PROPAGATION OF TRAFFIC NOISE---

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ABSTRACT

The effects of various traffic, ground cover, and geometric conditions on traffic noise propagation were evaluated in this study. There were two general methods of data collection. The first used as many as four sound-level meters and graphic-level recorders to take simultaneous recordings of the traffic stream; the second method involved a constant noise source using a random noise generator.

The $L_{10}$ noise level reduction per doubling of distance increased substantially when the traffic volume was less than 1,000 vehicles per hour. Wind speed and direction had a large effect on noise propagation. Ground cover also had a definite effect. Data were taken on short grass, tall weeds, tall grass, average grass, pavement, gravel, smooth dirt, snow, and plowed field. The drop-off per doubling of distance decreased from about 4.5 dBA for receiver heights of 10 feet (3 m) or below to 3.0 dBA for heights above 10 feet (3 m). At heights above 10 feet (3 m), the type of ground cover did not have a significant influence on the propagation loss. Noise attenuation per doubling of distance remained constant to about 400 feet (122 m) where the drop-offs were influenced by the ambient noise level. Individual noise readings indicated that noise propagation was influenced by vehicle type and speed. Noise drop-off was larger for smaller percentage levels, but the differences decreased as volumes increased. Source height also had an effect on noise propagation.
INTRODUCTION

The propagation of traffic noise is a concept hard to quantify in the prediction of highway noise levels. To some degree, noise propagation depends on traffic conditions, type of ground cover, and the geometry of the highway and nearby terrain. The effect of these variables on noise levels, combined with the difficulty of predicting noise levels on low-volume roads, make accurate noise prediction difficult. As a general rule, sound from a point source, such as a single vehicle, spreads uniformly (spherical spreading) and the sound level drops off at the rate of 6 dB for each doubling of distance. This is referred to in acoustics as the "inverse square law" (1). This drop-off rate does not apply to highway situations because an observer seldom hears just a single vehicle. In the limiting case, a continuous line of vehicles becomes a line source and the rate of sound level drop-off with distance approaches "cylindrical spreading," which produces a 3-dB drop-off rate for each doubling of distance. The effects of various traffic, ground cover, and geometric conditions on traffic noise propagation are evaluated in this paper.

PROCEDURE

TYPES OF DATA

Data were collected to determine the effects of the following variables on traffic noise propagation:

(1) traffic volume,
(2) wind,
(3) ground cover,
(4) receiver height,
(5) source height,
(6) source-to-receiver distance,
(7) traffic speed,
(8) percentage level, and
(9) type of vehicle.

DATA COLLECTION

There were two general methods of data collection. The first used as many as four sound-level meters and graphic-level recorders to take simultaneous recordings of the traffic stream. These data were taken at different distances and heights from the roadway. Source-to-receiver distances were measured from
the centerline of the near traffic lane. Ten-minute recordings were obtained using the A-weighting scale.

The data were generally analyzed in terms of $L_{10}$ (noise level exceeded 10 percent of the time) or $L_{eq}$ (equivalent noise level). A description of the sites at which measurements were taken is given in Table 1. The numbers of recordings are summarized. For any given 10-minute period, several measurements were recorded simultaneously. The summary in Table 1 shows that an average of three measurements were taken during each recording period. Noise levels of individual vehicles were also obtained using the sound-level meter.

The second method involved a constant noise source using a random noise generator. The output noise was input into a sound-level meter equipped with an octave band analyzer, amplified, and broadcast through a speaker. The random noise generator was stationary, and therefore, the noise was propagated as a point source. The resulting noise level was analyzed at different distances and heights from the speaker using a sound-level meter equipped with an octave band analyzer. Octave band analysis was set for center frequencies from 63 through 8,000 hertz. Pink noise (constant energy per octave bandwidth) was used for the octave band analysis while white noise (flat spectrum with constant energy per hertz bandwidth) was used for unweighted (linear) and A-weighted noise analysis.

### Table 1. Traffic Stream Measurement Sites.

<table>
<thead>
<tr>
<th>Site Number</th>
<th>Route</th>
<th>Location (City)</th>
<th>Highway Name</th>
<th>Type of Location</th>
<th>Speed Limit (MPH)</th>
<th>Average Speed (MPH)</th>
<th>Typical Hourly Volume</th>
<th>10-Minute Measurements</th>
<th>Total Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>US 27</td>
<td>Lexington</td>
<td>South</td>
<td>Urban</td>
<td>40 (18)</td>
<td>37 (17)</td>
<td>2150</td>
<td>244</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>US 68</td>
<td>Lexington</td>
<td>Limestone Street</td>
<td>Rural</td>
<td>55 (25)</td>
<td>54 (24)</td>
<td>570</td>
<td>102</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>1 75</td>
<td>Lexington</td>
<td>Harrodsburg Road</td>
<td>Rural</td>
<td>55 (25)</td>
<td>62 (28)</td>
<td>1800</td>
<td>203</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>I 264</td>
<td>Lexington</td>
<td>Interstate 75</td>
<td>Urban</td>
<td>55 (25)</td>
<td>48 (21)</td>
<td>3880</td>
<td>102</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>US 60</td>
<td>Lexington</td>
<td>Winchester Expressway</td>
<td>Rural</td>
<td>55 (25)</td>
<td>53 (24)</td>
<td>420</td>
<td>58</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>US 31W</td>
<td>Louisville</td>
<td>Dixie Highway</td>
<td>Urban</td>
<td>40 (18)</td>
<td>36 (16)</td>
<td>2500</td>
<td>51</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>US 60</td>
<td>Versailles</td>
<td>Versailles Road</td>
<td>Rural</td>
<td>50 (22)</td>
<td>56 (25)</td>
<td>820</td>
<td>90</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>US 68</td>
<td>Lexington</td>
<td>Harrodsburg Road</td>
<td>Urban</td>
<td>45 (20)</td>
<td>37 (17)</td>
<td>660</td>
<td>36</td>
<td>12</td>
</tr>
<tr>
<td>9</td>
<td>US 60</td>
<td>Lexington</td>
<td>Winchester Road</td>
<td>Urban</td>
<td>45 (20)</td>
<td>34 (15)</td>
<td>2130</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>299</td>
</tr>
</tbody>
</table>
RESULTS

TRAFFIC VOLUME

A primary objective of the study was to determine the effect of traffic volume on traffic noise propagation. Theory states that noise propagation will vary from 3 to 6 dB for a line or point source, respectively. The current design guide uses a 4.5-dBA drop-off for all traffic volumes (2). This is termed a modified line source. A past study concluded that traffic volume did not influence noise propagation when the volume was over 2,000 vph (3). However, it was noted that noise propagation might be significantly influenced by volumes lower than 2,000 vph. Since a large percentage of Kentucky highways have volumes less than 2,000 vph, data were taken in an attempt to resolve this question.

Data collection involved taking simultaneous recordings of the traffic stream at different source-to-receiver distances, the distances were measured to the centerline of the near lane. All data were taken at a 5-foot (1.5-m) height over short grass. Sites were chosen at locations with zero grade, with the observer level with the roadway, and with no shielding to reduce the number of variables that would alter the noise drop-off. Sites were chosen so a large range in traffic volumes could be obtained. The wind speed and direction were obtained and data were not used in the analysis if the wind vector either toward or away from the roadway was over 10 knots (11.5 mph (5 m/s)).

The reduction in the L_{10} noise level per doubling of distance increased substantially when the volume was less than 1,000 vph. The reduction in the L_{eq} noise level also increased for volumes less than 1,000 vph; however, the increase was not quite as dramatic as for the L_{10} level. For both the L_{10} and L_{eq} noise levels, the average reduction for the various traffic volumes was very close to the 4.5-dBA drop-off per doubling of distance currently used in traffic noise prediction for all traffic volumes. This assumption is very good, except for traffic volumes less than 1,000 vph where the drop-off increased to over 5 dBA. It should be noted that this is an average value for volumes less than 1,000 vph. In some cases, the drop-off was less than 5 dBA. However, considering all data, it is recommended that the reduction per doubling of distance used to predict L_{10} noise levels be increased to 5.0 dBA for volumes less than 1,000 vph.

The equivalent distance, which is basically the distance to the centerline of the roadway, is used rather than the distance to the near lane in the prediction procedure (2). An analysis was performed using the equivalent distance. As before, there was an increase in the noise reduction per doubling of distance for
low-volume conditions, particularly using the $L_{10}$ values. Based on an analysis excluding data where the reduction per doubling of distance was greater than 6.5 dBA or less than 2.5 dBA, the reduction in $L_{10}$ varied from 4.5 dBA for volumes of 2,001 to 3,000 vph to 4.8 dBA for volumes between 1,000 and 2,000 to 5.1 dBA for volumes less than 1,000 vph. For $L_{eq}$, the reduction per doubling of distance varied from 4.5 dBA for volumes of 2,001 to 3,000 vph to 4.7 dBA for volumes between 1,000 and 2,000 to 4.9 dBA for volumes less than 1,000 vph.

When the $L_{eq}$ noise level is considered, traffic volume should not have the influence reflected in the $L_{10}$ value. However, the $L_{eq}$ drop-off also increased for volumes less than 1,000 vph but not as much as that found for $L_{10}$. A different situation was found when the $L_{50}$ was considered. The $L_{50}$ experienced a lower drop-off compared to both $L_{10}$ and $L_{eq}$. Also, the $L_{50}$ drop-off was not significantly affected by traffic volume. The $L_{50}$ reduction actually decreased slightly for lower traffic volumes.

In addition to using the actual volume count, a separate analysis was made using what was termed the "equivalent volume". This was a weighted volume based on the number of automobiles and medium and heavy trucks in the traffic stream. The medium and heavy truck volume were multiplied by factors of two and four, respectively, to obtain the equivalent volume. Medium trucks generally refer to gasoline-powered, two-axle, six-wheel vehicles. Heavy trucks refer generally to diesel-powered, three-or-more-axle truck combinations. There is a large difference in the noise levels emitted by these types of vehicles. Multiplying factors were applied to medium and heavy trucks to determine if this would alter the previous findings concerning the relationship between noise-level reduction per doubling of distance and traffic volume. However, when the data were summarized using equivalent volume, very similar results were found.

WIND

Large fluctuations in noise drop-off were sometimes observed at a site even when the traffic volumes were similar. These variations were partially explained by the effect of wind. Wind speed and direction for each measurement were observed. These data were used to determine the component either directly toward or away from the roadway. These components were then grouped according to wind speed. Data taken when the traffic volume was less than 1,000 vph were not used in this analysis, since the low traffic volume influenced the data. The measurement height was 5 feet (1.5 m) and the ground cover was short grass.
When the component speed was over 10 knots (11.5 mph (5 m/s)), the noise drop-off was influenced significantly. When the wind was blowing away from the roadway, the noise was spread by the wind, and the noise drop-off was small. Conversely, when the wind was blowing toward the roadway, spreading of the noise was inhibited and the drop-off was increased. Results showed that reliable data cannot be taken when the speed of the wind component either toward or away from the roadway is greater than 10 knots (11.5 mph (5 m/s)). Even at speeds less than 10 knots (11.5 mph (5 m/s)), the wind speed and direction should be considered. The reduction of traffic noise levels per doubling of distance for various wind vectors is given in Table 2.

GROUND COVER

The effect of ground cover on noise propagation was investigated using both types of data sources -- noise generated by the traffic stream and a random noise generator. Traffic-stream data were collected at a low-volume location and a high-volume location. The random noise generator was used at numerous sites such as parking lots, grass fields, and agricultural areas isolated from highways. Reference noise levels, at a distance of 3 feet (0.9 m) from the random noise generator, was 95 dB for all measurements except linear noise where a 90 dB reference was used.

The analysis of traffic stream data involved the calculation of drop-off in $L_{10}$ and $L_{eq}$ per doubling of distance for various ground covers. On short grass at the high-volume site, the $L_{10}$ dropped off 5.0 dBA compared to 4.7 dBA for $L_{eq}$. The $L_{10}$ reduction per doubling of distance was 5.8 dBA over tall grass (5.4 dBA).

<table>
<thead>
<tr>
<th>DIRECTION</th>
<th>WIND VELOCITY (KNOTS)</th>
<th>$L_{10}$</th>
<th>$L_{eq}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toward Roadway</td>
<td>Greater than 10</td>
<td>8.6</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Less than 5</td>
<td>5.0</td>
<td>4.9</td>
</tr>
<tr>
<td>Away from Roadway</td>
<td>Less than 5</td>
<td>4.2</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>3.8</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>Greater than 10</td>
<td>2.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>
dBA for Leq) compared to a drop-off of only 2.9 dBA over pavement (2.8 dBA for Leq). For the low-volume site, the L10 noise level dropped off 5.9 dBA over short grass and a plowed field compared to 3.1 dBA over pavement. The effect of a reflective surface (pavement) on noise attenuation was clearly demonstrated.

The random noise generator was utilized for determining noise attenuation (A-weighted noise levels) for various ground covers (Table 3). The noise attenuations were compared to that for short grass. A plowed field produced the same attenuation as short grass. Attenuations per doubling of distance for medium and high grass, snow, and smooth dirt ground covers were within 1 dBA of that for short grass. Pavement, followed by gravel, provided the least attenuation. High weeds provided much more attenuation than any other ground cover. The attenuation provided by pavement compared to high weeds showed that ground cover can have a significant effect on noise propagation. However, comparison of various heights of grass showed that typical right-of-way ground covers do not show a large range in attenuation.

The noise drop-offs per doubling of distance for the various ground covers were also analyzed for octave-band center frequencies of 62.5 to 8,000 Hz (Table 3). The difference in propagation for the ground

<p>| TABLE 3. NOISE LEVEL REDUCTION PER DOUBLING OF DISTANCE FOR VARIOUS GROUND COVERSa. |
|--------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|</p>
<table>
<thead>
<tr>
<th>GROUND COVER</th>
<th>A-WEIGHTED NOISE</th>
<th>OCTAVE - BAND CENTER FREQUENCY (HZ)</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>4,000</th>
<th>8,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement</td>
<td>6.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>3.0</td>
<td>6.5</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>6.5</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>7.5</td>
<td>7.0</td>
<td>6.5</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Smooth ground</td>
<td>7.0</td>
<td>6.0</td>
<td>6.5</td>
<td>6.5</td>
<td>8.5</td>
<td>8.0</td>
<td>9.0</td>
<td>8.0</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>(No grass)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow</td>
<td>7.5</td>
<td>6.0</td>
<td>8.0</td>
<td>9.5</td>
<td>10.0</td>
<td>9.5</td>
<td>9.0</td>
<td>8.5</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Plowed field</td>
<td>8.0</td>
<td>6.5</td>
<td>7.0</td>
<td>8.0</td>
<td>9.5</td>
<td>9.0</td>
<td>8.5</td>
<td>8.5</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>Short grassb</td>
<td>8.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>9.0</td>
<td>10.0</td>
<td>9.0</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>Medium grassc</td>
<td>8.5</td>
<td>6.0</td>
<td>6.0</td>
<td>7.0</td>
<td>8.0</td>
<td>8.0</td>
<td>10.5</td>
<td>10.0</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>High grassd</td>
<td>9.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>8.0</td>
<td>9.5</td>
<td>10.5</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>High weeds e</td>
<td>11.5</td>
<td>6.5</td>
<td>6.0</td>
<td>7.0</td>
<td>9.5</td>
<td>10.0</td>
<td>12.0</td>
<td>13.5</td>
<td>15.0</td>
<td></td>
</tr>
</tbody>
</table>

a Reference noise level of 95 dB at distance of 3 feet (0.9 m) from speaker for each test. Microphone height of 4 feet (1.2 m). Distances of 25 (7.6 m), 50 (15 m), 75 (2.3 m), and 100 feet (30 m) from reference point were used. White random noise used for A-weighted. Pink random noise used for various frequencies.
b About 1 inch (2.5 cm) high.
c About 3 (7.6) to 5 (13) inches (cm) high.
d About 9 (23) to 12 (30) inches (cm) high.
e About 3 (0.8) to 4 (1.0) feet (m) high.
covers varied in different octave-band center frequencies. For example, a plowed field or smooth soil provided higher attenuation than short grass at 500 Hz but less at 2,000 Hz. The higher attenuation over high weeds compared to short grass varied from 1 dB at 250 Hz to 6 dB at 8,000 Hz. The noise drop-off over snow was greater than over short grass at 125 through 1,000 Hz but was lower at the higher frequencies. The lower attenuation over gravel and pavement was due primarily to a low attenuation of the higher frequencies. Attenuation over high grass was higher than over short grass at 4,000 and 8,000 Hz.

A comparison of noise level reduction for short grass, pavement, and high weeds by octave-band center frequency was conducted. Noise attenuations over the three ground covers were less for low frequencies (centered on 63, 125, and 250 Hz octave bands) than for high frequencies; low-frequency noise was affected very little by ground cover. Ground covers had a greater effect on noise levels in the higher frequencies.

RECEIVER HEIGHT

Both traffic stream noise data and data from the random noise generator were measured to determine the relationship between noise propagation and measurement (receiver) height. The major objective was to determine the height above the ground where the effect of ground cover becomes negligible. Measurements were made at receiver heights of 5 to 30 feet (1.5 to 9.1 m) above the ground. Distance from the roadway (measured from the centerline of the near lane) ranged from 25 to 600 feet (7.6 to 183 m). For an urban location, both the $L_{10}$ and $L_{eq}$ noise levels showed a reduction in drop-off per doubling of distance for 20-foot (6.1 m) and 30-foot (9.1 m) heights compared to 5-foot (1.5 m) and 10-foot (3.0 m) measurement heights. This relationship was also observed for a high-speed interstate location that had a high volume of heavy trucks. The data support the present procedure of using a different noise reduction per doubling of distance depending on receiver height. Also, the current level of 10 feet (3.0 m) appears to be the point at which the drop-off changes.

Results obtained with the random noise generator confirmed findings obtained from measurements of the traffic stream. The reduction per doubling of distance for short grass and pavement were compared at different heights. Data were taken with the noise source at ground level to represent car noise (Table 4) and at an 8-foot (2.4-m) height to represent truck noise (Table 5). With the noise source at ground level, the difference in propagation over grass compared to pavement almost dissipated at a 9-foot (2.7-m) meas-
TABLE 4. NOISE LEVEL REDUCTION PER DOUBLING OF DISTANCE FOR GRASS COMPARED TO PAVEMENT (NOISE SOURCE AT GROUND LEVEL).a

<table>
<thead>
<tr>
<th>MEASUREMENT HEIGHT (FEET) (M)</th>
<th>A-WEIGHTED NOISE</th>
<th>OCTAVE-BAND CENTER FREQUENCY (HZ)</th>
<th>MEASUREMENT NOISE</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>4,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GRASS</td>
<td>PAVEMENT</td>
<td>GRASS</td>
<td>PAVEMENT</td>
<td>GRASS</td>
<td>PAVEMENT</td>
<td>GRASS</td>
<td>PAVEMENT</td>
<td>GRASS</td>
</tr>
<tr>
<td>5 (1.5)</td>
<td>8.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>6.5</td>
<td>6.5</td>
<td>7</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>9 (2.7)</td>
<td>6</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>6</td>
<td>7.5</td>
<td>4.5</td>
<td>4</td>
<td>6.5</td>
</tr>
<tr>
<td>15 (4.6)</td>
<td>4.5</td>
<td>4.5</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1.5</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>20 (6.1)</td>
<td>3.5</td>
<td>3.5</td>
<td>4.5</td>
<td>5</td>
<td>3.5</td>
<td>2.5</td>
<td>0</td>
<td>5.5</td>
<td>3</td>
</tr>
</tbody>
</table>

a Reference noise level taken at distance of 3 feet (0.9 m) from speaker for each test. Reference levels varied slightly for different frequencies. Distances of 25 (7.6), 50 (15), 75 (23), and 100 feet (30 m) from the reference point were used. White random noise was used for A-weighted measurements, and pink random noise was used for the various frequencies.

TABLE 5. NOISE LEVEL REDUCTION PER DOUBLING OF DISTANCE FOR GRASS COMPARED TO PAVEMENT (NOISE SOURCE AT 8-FOOT (2.4m) HEIGHT).

<table>
<thead>
<tr>
<th>MEASUREMENT HEIGHT (FEET) (M)</th>
<th>A-WEIGHTED NOISE</th>
<th>OCTAVE-BAND CENTER FREQUENCY (HZ)</th>
<th>MEASUREMENT NOISE</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>4,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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a Reference noise level taken at distance of 3 feet (0.9 m) from speaker for each test. Reference levels varied slightly for different frequencies. Distances of 25 (7.6), 50 (15), 75 (23), and 100 feet (30 m) from the reference point were used. White random noise was used for A-weighted measurements, and pink random noise was used for the various frequencies.
urement height and completely dissipated at the 15-foot (4.6-m) height. This agreed with data from the traffic stream, which showed that a change in the propagation loss occurs above a measurement height of 10 feet (3.0 m). At this height above the ground, the ground cover no longer had a significant influence on noise propagation.

Data on noise reduction in various octave bands are also given in Table 4. The major differences in noise reduction between grass and pavement surfaces occurred in the octave bands centered on 500 and 1,000 Hz. The results given in Table 5 show no difference in noise reduction per doubling of distance at any measurement height when the noise source was put at a height of 8 feet (2.4 m). This was observed for A-weighted noise and all octave bands.

Also considered was the change in noise level at any given measurement distance as a function of measurement height. Except at locations close to the roadway or noise source, noise increases as measurement height increases. Simultaneous recording of the traffic stream showed that noise levels keep increasing to the highest point of measurement (30 feet (9.1 m)).

An analysis of the L10 noise levels as a function of receiver height and distance from the roadway was done for an urban location (Figure 1). At 50 feet (15.2 m) from the roadway, the increase in noise level with increased height above the ground ceased at the 20-foot (6.1-m) height. At 25 feet (7.6 m) from the roadway, the noise level was the same at all measurement heights. At 100 feet (30.5 m) from the roadway, the noise level increased very little above the 20-foot (6.1-m) height. However, as the distance from the roadway increased, the noise level increased more with height. Also, the height at which the increase ceased kept increasing as the distance from the roadway increased. At 200 feet (61 m), the noise level appeared to be leveling at the 30-foot (9.1-m) height. Also, at 400 feet (122 m), the increase in noise level from the 20-foot (6.1-m) to 30-foot (9.1-m) heights was less than from the 10-foot (3.0-m) to 20-feet (6.1-m) heights.

SOURCE HEIGHT

The random noise generator was used to determine the effect of source height on noise propagation. The speaker was set at ground level and then at 8 feet (2.4 m). The ground-level source represented automobile noise. The 8-foot (2.4 m) height represented the noise height for trucks. Microphone heights of 2.5 to 25 feet (0.8 to 7.6 m) were obtained by connecting the microphone to a surveying level rod and adjust-
Figure 1. L_{10} Noise Levels as a Function of Receiver Height and Distance from Roadway (Site 1).
ing the measurement heights. Distances of 25 to 300 feet (7.6 to 91 m) from the speaker were used.

The first series of measurements were taken with a zero height above grass and pavement. For a microphone height of 2.5 feet (0.8 m), noise levels over grass were reduced by 11 dBA per doubling of distance compared to only 6 dBA over pavement. As height increased to 10 feet (3 m), the drop-off per doubling of distance over grass decreased sharply to about 5 dBA and then was very similar to pavement for measurement heights up to 25 feet (9 m). The drop-offs for grass and pavement both approached about 3.0 to 3.5 dBA. The curves in Figure 2 show that the noise drop-off per doubling of distance decrease for both ground covers as measurement height increased. This drop-off is greater for grass than pavement at measurement heights up to 10 feet (3.0 m). Drop-offs per doubling of distance ranged from about 11 dBA to 3 dBA, depending on measurement height.

The other source height used was 8 feet (2.4 m), obtained by mounting the speaker on a platform in the bed of a pickup truck. Data were collected over grass and pavement at measurement heights of 2.5 to 25 feet (0.8 to 7.6 m). For both ground covers, the noise reduction per doubling of distance remained at
5.5 dBA for measurement heights up to 15 feet (4.6 m). Above 15 feet (4.6 m), reductions dropped to 3.5 dBA over pavement and 4.0 dBA over grass. Thus, ground cover had little, if any, effect on noise propagation for 8-foot (2.4 m) source heights. Also, the drop-off per doubling of distance is nearly constant at around 5.5 dBA for an 8-foot (2.4 m) source height at measurement heights up to 15 feet (4.6 m).

In summary, ground cover had very little influence on noise propagation when the source height was 8 feet (2.4 m). When the noise source was at ground level, ground cover influenced noise propagation up to a receiver height of about 10 feet (3 m).

**SOURCE-TO-RECEIVER DISTANCE**

Measurements were made to determine how noise drops off as the source-to-receiver distance increases for a microphone height of 5 feet (1.5 m). Distances were measured from the center of the near-lane and ranged from 25 to 400 feet (7.6 to 122 m) for most measurements. Three or four distances were monitored simultaneously to determine noise drop-off per doubling of distance.

On a low-speed urban road, data for \( L_{10} \), \( L_{50} \), \( L_{90} \), and \( L_{eq} \) were obtained. Measurements were made at 25, 50, 100, 200, and 400 feet (7.6, 15, 30, 61, and 122 m) over short grass. The data were used to calculate the drop-off in noise per doubling of distances for \( L_{10} \) and \( L_{eq} \). The average drop-off per doubling of distance was 3.3 dBA for \( L_{10} \) and 3.1 dBA for \( L_{eq} \). Noise drop-offs remained relatively constant per doubling of distance, but dropped slightly between 200 and 400 feet (61 and 122 m). This was probably caused by the low noise levels at 400 feet (122 m) (approached ambient (background) noise). Plots of \( L_{10} \), \( L_{eq} \), \( L_{50} \), and \( L_{90} \) were made for various distances. A linear relationship was found using a log scale of distance. All \( L_{eq} \) levels were about halfway between \( L_{50} \) and \( L_{10} \) values at each distance.

Similar data were collected and summarized on a high-speed rural road. Distances of 25, 50, 100, and 200 feet (7.6, 15, 30, and 61 m) were used over short grass. Values of \( L_{10} \) ranged from 71.9 dBA at 25 feet (7.6 m) to 54.8 dBA at 200 feet (61 m). Drop-offs per doubling of distance averaged 5.7 dBA (\( L_{10} \)) and 5.5 dBA (\( L_{eq} \)). These average drop-offs were higher than at the urban site, probably because of lower volumes and higher speeds.

The equivalent distance also was used to verify these results. When the equivalent distance was used, the noise drop-off increased at distances close to the roadway (less than 50 feet (15 m) from the centerline of the near lane). Using the equivalent distance also increased the noise drop-offs at each distance.
The dual effect of distance and measurement height on noise propagation was then analyzed. Noise data were collected at Site I at heights of 5, 10, 20, and 30 feet (1.5, 3.0, 6.1, and 9.1 m) and distances of 25 to 400 feet (7.6 to 122 m). At a distance of 25 feet (7.6 m), L10 noise levels were about the same regardless of height. As distance increased, noise levels were definitely higher as measurement heights increased. At 400 feet (122 m), noise levels at the 30-foot (9-m) height were about 62 dBA compared to 60 dBA at 20 feet (6.1 m), 56 dBA at 10 feet (3.0 m), and 55 dBA at 5 feet (1.5 m). A plot of these data for the L10 level is shown in Figure 3. Values of r^2 ranged between 0.96 to 0.99 for all relationships. Similar findings were found using Leq values.

The very high correlation between noise level and distance from the roadway indicated the validity of the assumption that traffic noise attenuation is constant per doubling of distance. Results show this assumption, which was questioned in a past report (3), is also valid at low-volume locations.

![Figure 3. L10 Noise Levels for Various Distances and Receiver Heights (Site 1).](image-url)
SPEED

To determine if vehicle speed is related to noise propagation, measurements were taken using a test car. Simultaneous measurements were made as the car was driven by at a constant speed. Data were taken at 25 feet (7.6 m) and 50 feet (15.2 m) from the centerline of the driving lane. Noise from other vehicles caused problems when distances greater than 50 feet (15.2 m) were used. The speeds used were 30, 40, and 50 miles per hour (13.4, 17.9, and 22.4 m/s). Also, data were collected on various ground covers including pavement and short and tall grasses.

The average reduction for all speeds for a doubling of distance varied from 5.2 dBA for pavement to 8.2 dBA for tall grass. Noise propagation varied with the speed of the test car for short and tall grass ground covers; the noise drop-off increased as vehicle speed increased. The drop-off remained relatively constant over pavement. As speeds increase, tire-pavement noise increases rapidly and becomes the controlling factor in automobile noise. The tire-pavement noise that predominates at higher speeds has a higher frequency than engine noise. Thus, the noise at higher speeds consists of higher frequencies, which were found to have a high drop-off with distance compared to low frequencies.

PERCENTAGE LEVEL

Noise reduction per doubling of distance was determined for $L_{10}$, $L_{50}$, $L_{90}$, and $L_{eq}$ at three locations. The locations included a low-volume location (hourly volume below 1,000), a medium-volume location (hourly volume around 2,000), and a high-volume location (hourly volumes above 3,000). Data at all locations were collected over grass.

The average drop-off per doubling of distance for all sites was 4.5 dBA for $L_{10}$ and 4.4 dBA for $L_{eq}$. At the low-volume location, drop-offs were 5.7 and 5.5 dBA for $L_{10}$ and $L_{eq}$. At the high-volume site, drop-offs of 4.6 dBA were observed for both $L_{10}$ and $L_{eq}$. At the medium-volume site, lower drop-offs in $L_{10}$ (3.3 dBA) and $L_{eq}$ (3.1 dBA) were found. These could have resulted from the lower speeds and low truck volumes.

The drop-offs in $L_{50}$ averaged 3.3 dBA for all sites. The $L_{90}$ drop-offs averaged only 2.1 dBA, since these levels often approach ambient levels, especially at low-volume sites. The $L_{90}$ drop-offs were lowest (0.9 dBA) at the low-volume site and highest (3.5 dBA) at the high-volume location. Drop-offs in $L_{50}$ at the sites varied between 2.8 and 4.1 dBA.
Noise drop-off varies with the percentage level used to describe the noise. In general, as the percentage level becomes smaller, the noise drop-off increased. However, the difference in drop-off between the various percentage levels decreased as the traffic volume increased. At volumes over 4,000 vph, the difference in the noise drop-off disappeared.

**TYPE OF VEHICLE**

Measurements were made of individual automobile and truck noise levels with a sound-level meter employing the A-weighting network. Measurements were taken at 50 feet (15 m) and 100 feet (30 m) from the center of the traffic lane and approximately 4 feet (1.2 m) above ground. The vehicle type and noise level were recorded manually as a vehicle passed. Measurements were taken only when the noise emitted by a single vehicle could be clearly isolated or distinguished from the noise of the traffic stream.

The data were taken at several locations classified as urban, interstate, and rural non-interstate roads. These categories were based primarily on traffic speeds. Average automobile speeds ranged from 40 mph (18 m/s) on the urban roads to 54 mph (24 m/s) at the rural non-interstate roads and 62 mph (28 m/s) on the interstate roads. Three different vehicle types were used to represent the various types on the highway. These categories corresponded to those types listed in the noise prediction design guide (2). Single-unit, two-axle, six-tire trucks were used to represent the medium truck category, and combination, five-axle tractor trailers were used to represent the heavy truck category. Noise readings were obtained for over 8,000 vehicles, which included approximately 6,000 automobiles, 1,000 medium trucks, and 1,000 heavy trucks.

Noise drop-off with distance for automobiles was slightly higher for the high-speed locations. The noise drop-off with distance for heavy trucks was also higher at the high-speed locations. The average speeds for the heavy-truck category ranged from 35 mph (16 m/s) on the urban to 51 mph (23 m/s) on the rural non-interstate roads and 61 mph (27 m/s) on the interstate roads. The reason for the increase in noise drop-off may be attributable to a change in the frequency distribution of the noise to a higher proportion of high-frequency noise at higher speeds. This change occurs for automobiles (7). The higher frequencies have a larger drop-off with distance. At higher speeds, tire noise may constitute a larger proportion of the noise; this would lower the overall source height, which also would lead to a larger drop-off. When all
locations were considered, the noise reduction was close to 6.0 dBA per doubling of distance for both automobiles and heavy trucks.

At urban locations where the speed is low, automobiles had a larger drop-off with distance compared to heavy trucks; however, on the high-speed interstate roads, heavy trucks had a larger drop-off than automobiles. The medium-truck category had the largest overall drop-off. Inconsistency in the data made generalized conclusions difficult.

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SUMMARY AND CONCLUSION

TRAFFIC VOLUME

1. The $L_{10}$ noise level reduction per doubling of distance increased substantially when traffic volume was less than 1,000 vph. For peak volumes experienced in Kentucky, noise reduction did not decrease significantly below 4.5 dBA per doubling of distance.

2. The $L_{eq}$ noise level reduction increased for traffic volumes less than 1,000 vph; however, the increase was not as dramatic as the $L_{10}$ level.

3. When $L_{50}$ levels were considered, the drop-off in noise was not significantly affected by traffic volume.

WIND

1. Large fluctuations in noise drop-off at a given site for similar traffic volumes were found to be partially explained by the effect of wind. Very good relationships were observed between noise drop-off and wind vector (component of the wind either directly toward or away from the roadway).

2. Reliable data could not be obtained when the wind vector speed toward or away from the roadway was greater than 10 knots (11.5 mph (5 m/s)).

GROUND COVER

1. Based on traffic stream data, drop-offs in $L_{10}$ noise per doubling of distance were 5.0 dBA over short grass, 2.9 dBA over pavement, and 5.8 dBA over tall grass for high-volume roads. Slightly larger drop-offs were found on low-volume roads.

2. Data obtained using a random noise generator showed that ground cover can have a significant effect on noise attenuation. Using short grass as a reference surface, higher noise attenuation per doub-
ling of distance was found for high weeds (3.5 dBA higher). Attenuations over high grass, medium grass, smooth dirt, snow, and plowed field were within 1.0 dBA of short grass. Attenuations per doubling of distance were lower on gravel (1.5 dBA) and pavement (2.0 dBA) compared to short grass.

3. Low-frequency noise (octave-bands centered at 63, 125, and 250 Hz) was affected very little by ground cover. Ground covers had a greater effect on noise levels in the higher frequencies.

4. A comparison of the attenuation provided by pavement and high weeds showed that ground cover can have a significant effect on noise propagation. However, various heights of grass showed that typical right-of-way ground covers did not significantly affect noise attenuation.

RECEIVER HEIGHT

1. Data from both the traffic stream and the random noise generator showed that changes in noise attenuation occurred at heights above 10 feet (3.0 m). The traffic stream data showed that the drop-off per doubling of distance decreased from about 4.5 dBA for receiver heights of 10 feet (3.0 m) or below to slightly over 3.0 dBA for heights above 10 feet (3.0 m).

2. For receiver heights above 10 feet (3.0 m), ground cover had no significant influence on attenuation.

3. Major differences in propagation loss between grass and pavement occurred in the octave bands with center frequencies of 500 and 1,000 Hz.

4. No differences in noise reduction per doubling of distance were observed at any measurement height when the noise source was at a height of 8 feet (2.4 m).

5. Except at locations close to the roadway (closer than about 50 feet (15 m)), noise increased as height of the receiver increased.

6. Up to 400 feet (122 m) from the roadway, the noise level increased with height of the receiver. Also, the height at which the increase in noise level ceased increased with distance from the roadway.

SOURCE HEIGHT

Ground cover had very little influence on noise propagation when the source height was 8 feet (2.4 m). When the noise source was at ground level, ground cover influenced noise propagation up to measurement heights of about 10 feet (3.0 m).
SOURCE-TO-_RECEIVER DISTANCE

1. Up to about 400 feet (122 m), noise drop-offs (dBA) remained constant per doubling of distance. When the equivalent distance was used, the noise drop-off increased at distances close to the roadway (less than 50 feet (15 m) from the centerline of the near lane).

2. The very high correlation between noise level and distance from the roadway validated the assumption that traffic noise attenuation is constant per doubling of distance.

SPEED

Using a test car driven at various speeds, noise drop-off with distance increased over grass as vehicle speed increased. No changes with speed were noted over pavement surfaces.

PERCENTAGE LEVEL

In general, as the percentage level became smaller, the noise drop-off per doubling of distance increased. The difference in drop-off between the various percentage levels decreased as the traffic volume increased. At volumes over 4,000 vph, this difference disappeared.

TYPE OF VEHICLE

Individual noise readings indicated that noise propagation was influenced by vehicle type and speed. This was related to the differences in frequency distribution and source height of different vehicles and the changes that occur at different speeds. Noise attenuation generally increased with increased vehicle speed. On urban roads, automobile noise showed a larger drop-off with distance compared to heavy trucks; however, on high-speed interstate roads, heavy trucks had a larger drop-off than automobiles. Inconsistencies in the data made general conclusions difficult.

RECOMMENDATIONS

1. The reduction per doubling of distance used to predict $L_{10}$ noise levels should be increased to 5.0 dBA for volumes less than 1,000 vph.

2. For receiver heights of 10 feet (3.0 m) or below, a noise drop-off of 3.0 dBA per doubling of distance should be used for reflective ground covers (pavement), a 4.5-dBA reduction should be used for normally absorptive ground covers, and a 6.0-dBA reduction should be used for extremely absorptive ground covers (high weeds).
3. For receiver heights above 10 feet (3.0 m), a 3.0-dBA drop-off per doubling of distance should be used regardless of the type of ground cover.

4. The noise propagation factor should be constant per doubling of distance.

5. Traffic noise data should not be taken when the component of the wind either toward or away from the roadway exceeds 10 knots (11.5 mph (5/m)).

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REFERENCES

