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TILTED PARALLEL BARRIER PROGRAM - APPLICATION AND VERIFICATION

by

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ABSTRACT

There are increasing situations in the nation's urban and suburban highway system where noise barriers are considered to protect residences on both sides of a roadway. This scheme of two vertical parallel barrier walls constitutes the parallel barrier problem where in addition to the sound waves that reach the receiver by diffraction over the near barrier, additional sound waves caused by complex pavement-barrier-ground reflection and diffraction mechanisms can reach the receiver, thus degrading the effectiveness of the near barrier.

This paper presents the results of a first application of the Tilted Parallel Barrier Program (TPBP) to a highway project and attempts to verify aspects of the model through comparisons with data existing in the literature. The model provides excellent agreement for the classical problem of an impedance boundary. It also meets reasonable expectations for parallel vertical, tilted parallel, and parallel absorptive barrier performance where a frequency dependent optimum design can be selected.

1.0 INTRODUCTION

The current version of the FHWA Highway Traffic Noise Prediction Model (STAMINA 2.0) is a single screen-type barrier diffraction model which is independent of ground impedance. Ground effects are separately handled through site 'decay' input parameters (alpha factors) and the use of additional absorbing ground strips representing foliage/shrubbery. Provisions are made in STAMINA 2.0 to ignore the ground effects whenever a barrier is encountered (the alpha value is reset to 0.0). Whenever more than one barrier is encountered, the most significant barrier is retained in lieu of all other barriers even though the diffracted reflection or reflected diffraction is computed by user-specified reflective barrier computations. The user is referred to the single image nomogram method outlined in Section 4.3.7 of the FHWA "Noise Barrier Design Handbook" [1] to consider the degradation in barrier performance for parallel barriers.

Considering the fact that the effective noise insertion loss of many practical barrier schemes is typically on the order of 5 to 10 dBA for receivers 100 to 200 feet away from the barriers, degradations of 3 dBA or more as calculated using the nomogram method for the first order reflection-diffraction would significantly negate the benefits of this abatement measure. It thus becomes essential to have a tool to: (1) better gage the degradations due to parallel barriers, and (2) explore the effectiveness of treatments such as absorption and tilting to mitigate the degradation.

The Tilted Parallel Barrier Program (TPBP), developed by Slutsky and Bertoni [2] under contracts to FHWA and TSC, provides an investigative tool to study the complex problem of parallel tilted barriers on segmented impedance boundaries. In addition to accounting for the multiple reflection effect due to parallel barriers as considered by previous parallel barrier models (e.g. Bowlby and Cohn [3], Hajck [4]), TPBP considers the effect of tilting on multiple reflections, the effect of ground as an impedance boundary, and the interaction effect of ground reflection and barrier diffraction (Tables 1 and 2). Furthermore, the TPBP permits the segmentation to represent different types of surfaces, such as pavement, median strips, or grassland. This problem is referred to as wave propagation over segmented impedance surfaces due to the additional complexity of diffraction by impedance discontinuities. Lastly, barriers with absorptive or impedance surfaces (up to 3 segments) can also be accommodated. The program, which employs powerful mathematical and numerical techniques, has yet to be verified either through theoretical or experimental studies. This paper presents results of the first application of the TPBP to a highway project, and attempts to verify aspects of the model through comparison with existing data in the literature and with common sense expectations.

2.0 AN APPLICATION

The TPBP has been applied to a New York State Department of Transportation (NYSDOT) project on a section of the Long Island Expressway (LIE) in Suffolk County where parallel barriers are being considered to reduce the noise impact on the adjacent residential development. Typical roadway configuration consisting of six 10-foot lanes, a 60-foot median including inside shoulders, a 5-foot outside shoulder on each side, and an 85-foot terrain strip between the shoulder and the right-of-way is shown in Figure 1A. The barriers are located 150 feet from the roadway centerline. A total of 6,321 vehicles an hour travel at 55 mph on the roadway, with 3.7 percent medium trucks and 4.9 percent heavy-duty trucks. A STAMINA/OPTIMA 2.0 analysis (with alpha = 0.5) indicated that 15-foot barriers would be optimal and would reduce the noise level from approximately 70 dBA to 63 dBA at the closest residence approximately 80 feet from the right-of-way. Use of the nomogram method indicates that a degradation of up to 3 dBA could be expected. This would severely reduce the benefits of the proposed noise barriers. It was clear that a more detailed analysis would be required to ascertain the parallel barrier effect and to study the effectiveness of absorptive barriers and tilted barriers.

The mathematical and numerical aspects of the TPBP involving segmented impedance boundaries and edge diffractions are new and heretoforth untested.Since no experimental data is yet available to verify this method, attempts were made to gage the reasonableness of the model through its application results. The STAMINA 2.0 model which has been shown to provide excellent results for receivers in the range of 100 to 250 feet from the edge of the roadway with a 4.5 dB decay rate on flat ground either with or without a single barrier, was used for comparison.

Results of the STAMINA 2.0/TPBP (with air absorption coefficients corresponding to 20 degrees Celsius and 60 percent relative humidity) comparisons are shown in Figures 2 and 3 for the typical LIE configuration both without a barrier and with a single 15-foot barrier. Refering to Figure 2, it can be seen that the TPBP distance dropoff rate approaches that of STAMINA (4.5 dBA per distance doubling) at 100 to 250 feet away from the edge of the nearest lane (or 10 to 160 feet from the barrier location), increasing up to 9 dB per distance doubling at distances greater than 1,000 feet. From the literature on source decay characteristics [5] and ground effects on sound propagation over large distances [6], the TPBP dropoff curve is consistent with the expectation of an increasing ground attenuation rate as the distance increases. Figure 3 shows that the TPBP results for a single barrier agree with the STAMINA 2.0 predictions to within 2 dBA over the distance range of 40 to 320 feet from the barrier. It should be noted that the presence of the barrier raises the effective source height to the top edge of the barrier, and thereby drastically diminishes the excess ground attenuation effect of the real source at grazing incidence.

Applying the TPBP to parallel barriers with absorption coefficients corresponding to plywood, the degradation averaged about 6 dB (Figure 4), compared to the nomogram calculation of a 3 to 4 dB increase for the first order reflection-diffractions. When compared to measurements reported in the literature (e.g. Ullrich in West Germany [7]), the result is judged reasonable.

The TPBP may be used as an investigative tool for evaluating various mitigation treatments. Results indicate that increasing the barrier height is not an effective means to compensate for the parallel barrier effect (Figure 4). Results for absorptive barriers (Figure 5) indicate that barriers with very high absorption coefficients (0.9) in the 500 - 1000 Hz range could significantly reduce the degrading effect of vertical parallel barriers. Partial absorptive panels were also investigated though they were found to be less satisfactory. In this particular case, the placement of the absorptive material on the lower third of the barrier was found to be more effective than on the upper third because of the large number of automobiles with low source heights. Tilting the barrier however is shown (Figure 6) to be an extremely effective measure to compensate for the parallel barrier degradation. Results indicate that with a 3 degree tilt (i.e. the top of the barrier tilted away from the roadway), the degradation is totally compensated for. These results reflect the conclusions drawn in a French study conducted by Legillon [3] that for barrier height/roadway width ratios of between 1:20 and 1:10, tilting is favored over absorption; whereas absorption is favored if the ratio is larger than 1:10 and single barrier attenuation is below 12 dB.

Referring to Figure 2 and Figure 3 it is seen that, at distances greater than 320 feet from the barrier or 410 feet from the edge of the nearest lane, TPBP predicts noise levels without the barrier to be lower than those with a single 15 foot barrier. This again demontrates the significant ground attenuation around 500 Hz at grazing incidence, which can be greater than 15 dB at such distances [6]. The presence of a 15-foot barrier greatly reduces the ground attenuation effect which is greater than the barrier attenuation in this case, thus resulting in higher noise levels than without the barrier. This effect is accentuated in this particular application by the dominance of auto traffic with low source heights and the low diffractive loss due to the geometry.

3.0 GROUND AS AN IMPEDANCE BOUNDARY

The propogation of sound near the ground is a classic problem the study of which dates back to Sommerfeld [8] in 1909. Even though the solution to this problem is well-known today, the numerical procedures used vary greatly. Furthermore, a common reference describing the surface impedance of the ground is not universally used, making direct comparisons with existing data difficult.

Figures 7 and 8 present Chessell's [5] data for comparison. Values corresponding to octave-band centered frequencies in Chessell's work are plotted for comparison. It can be seen that the agreement between ground treatment in TPBP and Chessell's work is excellent. In general, grazing incidence would generate much higher attenuations. It is seen in Figure 8 that with grazing incidence, the ground attenuation at 500 Hz amounts to more than 35 dB. This explains why it is possible to ~~achieve~~ obtain higher noise levels with the erection of a barrier than without the barrier, if the very large ground attenuation for grazing incidence is lost through the placement of a barrier.

An attempt was made to compare the TPBP results with work done by Embleton [10] as shown in Figures 9 and 10. These figures show only the general agreement of the trend, since (1) the surface impedance was assumed to match, and (2) the original graph was highly erratic and difficult to read accurately.

4.0 BARRIER-GROUND INTERACTION AND TILTING

A comparison between TPBP and Thomasson [11] was attempted for the case of a simple screen over an impedance ground. Thomasson's approach involved Kirchhoff-type approximation with a four paramter model for the ground impedance, thus the impedance was not matched exactly and the screen surface was assumed to be perfectly reflective. The results are shown in Figure 11. Even though the impedance parameters used by Thomasson were grossly approximated using the single parameter flow resistance model, the agreement in frequency of peak attenuation was surprisingly good.

The TPBP was tested for reasonableness in handling various tilted barrier configurations. Intuition would indicate that continued tilting should eventually lead to a decrease in barrier effectiveness. The TPBP was once again used to model a second typical section of the LIE project, where the roadway configuration consists of the same six 10-foot traffic lanes, a 20-foot median, a 5-foot outside paved shoulder, and a 5-foot terrain strip (Figure 1B). The 10-foot barriers were located 50 feet from the roadway centerline. The STAMINA source emission levels at 50 feet were first adjusted for the ground effect over a hard surface to arrive at the free-field levels for model input. The adjustments for the three vehicle types (auto, medium-trucks and heavy-trucks) are shown in Figure 12. The results of analysis on highway noise for the second roadway configuration are shown in Figures 13 to 16.

Under this geometry with a barrier to roadway ratio of 1:10, the parallel barrier degradation is approximately 9 dBA as indicated in Figure 13. At 100 feet from the barrier, the noise level with parallel barriers is higher than without the barriers. Figure 14 shows that for this highway configuration, absorption and tilting are equally as effective in eliminating the parallel barrier effect. Nevertheless, a residual degradation of 2 dBA still remains, unlike the previous case (1:20 barrier to roadway ratio), where tilting was more effective and no residual effect remained as would be expected.

Figure 15 shows the results of further tilting the 10-foot barriers. It can be seen that the effect of tilting a few degrees (5 degrees) results in drastic improvement in barrier performance and that further tilting quickly reverses the situation. In this case, the optimum tilting could easily be ascertained to within a degree or two of 5 degrees. Figure 16 presents the same roadway configuration with a 20-foot barrier (a barrier to roadway ratio of 1:5). It is seen that for such a configuration, the tilt angles are no longer critical as one would expected due the limit of the noise source heights. It is also seen that absorptive treatment is slightly more effective for distances within 25 feet of the barrier where the barrier insertion loss would be greater than 12 dB. These results are very much in line with Legillon's observation [3].

The joint effects of tilting and source height variations within parallel barriers are shown in Figures 17 to 19 for point source heights of 0.5, 2.3, and 8.0 feet corresponding to auto, medium trucks, and heavy trucks. The barrier/roadway configuration was chosen to accentuate the effect (1:5 ratio – a single 30-foot lane, 5-foot shoulders, and 5-foot terrain strips with 10-foot barriers) for a receiver 50 feet away from the roadway centerline and 5 feet above ground. The increase and then decrease in attenuation in the dominant 1 KHz band as the tilt angle increases is evident. These figures demonstrate that there exists a frequency-dependent optimum tilt angle for a specific barrier/roadway configuration which can compensate for the parallel barrier degradation.

5.0 CONCLUSION

By applying the TPBP model to a highway design project, and by comparing TPBP results with existing data in the literature for a point source above an impedance boundary and behind a screen above an impedance boundary, aspects of the TPBP model were explored and performance documented. The model provides excellent agreement for the classical problem of an impedance boundary. It also meets reasonable expectations for parallel vertical, tilted parallel, and absorptive parallel barrier performance where a frequency dependent optimum design can be selected for a specific barrier roadway/configuration. Due to the complexity of the problem, however, it must be pointed out that the results presented here, such as critical tilt angle, must not be generalized to other roadway configurations but modeled on a site-specific basis. The TPBP model should be regarded as a useful investigative research tool to be applied meticulously to specific situations, until the procedure is experimentally verified and qualified through field tests as an operational tool.

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Table 1.

Ground Reflection - Point Source over Impedance Ground

$f := 500$ frequency in Hz

$\sigma := 200 \cdot 10^{3}$ ground flow resistance in Nsm^{-4}

$i := \sqrt{-1}$ $c := 343$ sound velocity in air m/sec

$\rho c := 415$ characteristic impedance of air at 20 C

$$Z := \rho c \cdot \left[1 + 0.0511 \cdot \left[\frac{f}{\sigma} \right]^{-0.75} + i \cdot 0.0768 \cdot \left[\frac{f}{\sigma} \right]^{-0.73} \right]$$ specific ground impedance

$$\beta := \frac{1}{Z}$$ specific acoustic admittance

$$k := \frac{2 \cdot \pi \cdot f}{c}$$ wave number

$r_1 := 2100$ $r_2 := 2300$ direct and reflected path length, m

$\theta := 60$ angle of incidence, deg

$$Pe := \sqrt{\frac{1}{2} \cdot i \cdot k \cdot r_2} \cdot (\beta + \cos(\theta))$$ $\operatorname{erfc}(z) := 1 - \operatorname{erf}(z)$

$$E(Pe) := 1 + i \cdot \sqrt{\pi} \cdot Pe \cdot \exp\left[-Pe^{2}\right] \cdot \operatorname{erfc}(-i \cdot Pe)$$

$$R(\theta) := \frac{\cos(\theta) - \beta}{\cos(\theta) + \beta}$$ the plane wave reflection coefficient

$Q(\theta) := R(\theta) + (1 - R(\theta)) \cdot E(Pe)$ the spherical wave reflection coefficient

The velocity potential for a point source over impedance ground is

$$\varphi(z) := \frac{\exp\left[i \cdot k \cdot r_1\right]}{k \cdot r_1} + Q(\theta) \cdot \frac{\exp\left[i \cdot k \cdot r_2\right]}{k \cdot r_2}$$

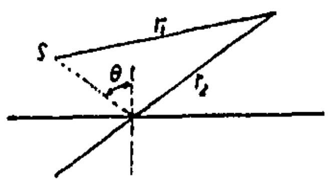


Table 2.

Diffraction by a thin screen on Ground

$r0 := 100 \qquad r1 := 300 \qquad \theta0 := 45 \qquad \theta1 := 290$

$R0 := r0 + r1$

$$R1 := \left[r0^2 + r1^2 - 2\cdot r1\cdot r0\cdot \cos(\theta 1 - \theta 0)\right]^{0.5}$$

$$R2 := \left[r0^2 + r1^2 - 2\cdot r1\cdot r0\cdot \cos(\theta 1 + \theta 0)\right]^{0.5}$$

$$i := \sqrt{-1}$$

$$F(x) := \int_x^{\infty} \exp\left[i\cdot t^2\right] dt$$

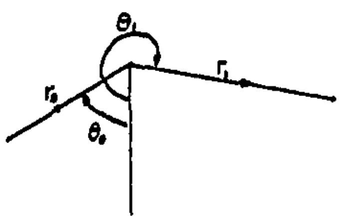
$$A := \mathrm{sign}(\pi + \theta 0 - \theta 1)\cdot\left[\frac{2\cdot R0}{R0 + R1}\right]^{0.5}\cdot \exp(i\cdot k\cdot (R0 - R1))^{0.5}\cdot\frac{\exp(i\cdot k\cdot R0)}{k\cdot R0}$$

$$B := \mathrm{sign}(\pi - \theta 0 - \theta 1)\cdot\left[\frac{2\cdot R0}{R0 + R2}\right]^{0.5} \exp(i\cdot k\cdot (R0 - R2))^{0.5}\cdot\frac{\exp(i\cdot k\cdot R0)}{k\cdot R0}$$

$$\varphi d(r0,r1) := \frac{\exp\left[-i\cdot\frac{\pi}{4}\right]}{\sqrt{\pi}}\cdot\left[A\cdot F\left[(k\cdot(R0 - R1))^{0.5}\right] + B\cdot F\left[(k\cdot(R0 - R2))^{0.5}\right]\right]$$

The total field is

$$\varphi := \varphi d(r3,r5) + \varphi d(r4,r5)\cdot Q(\theta 4) + \varphi d(r3,r6)\cdot Q(\theta 6) + \varphi d(r4,r6)\cdot Q(\theta 6)$$



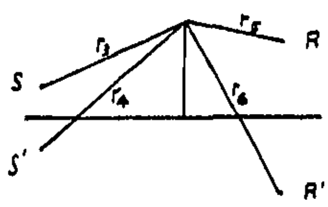


Figure 1A. Typical Roadway Configuration
Wide Median Case

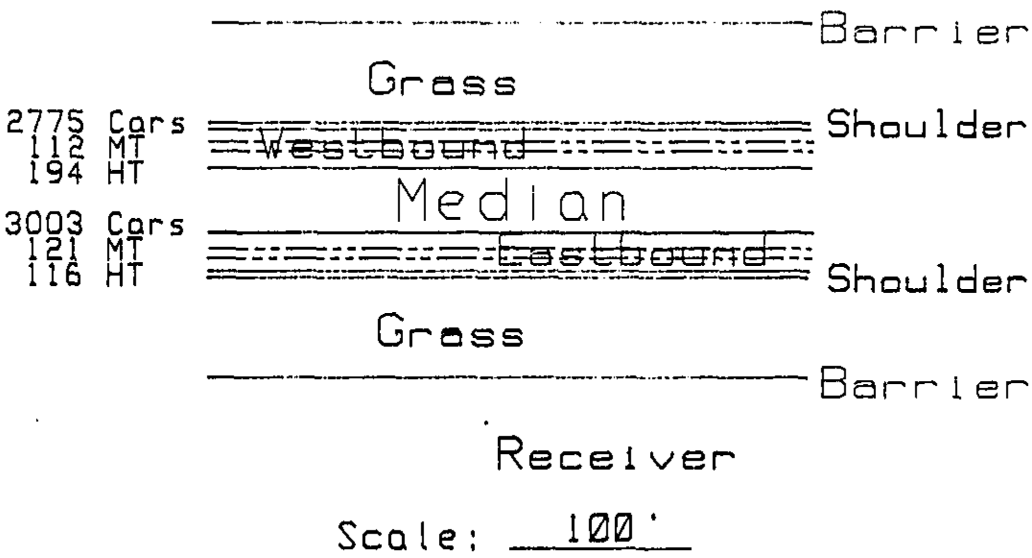


Figure 1B. Typical Roadway Configuration
Narrow Median Case

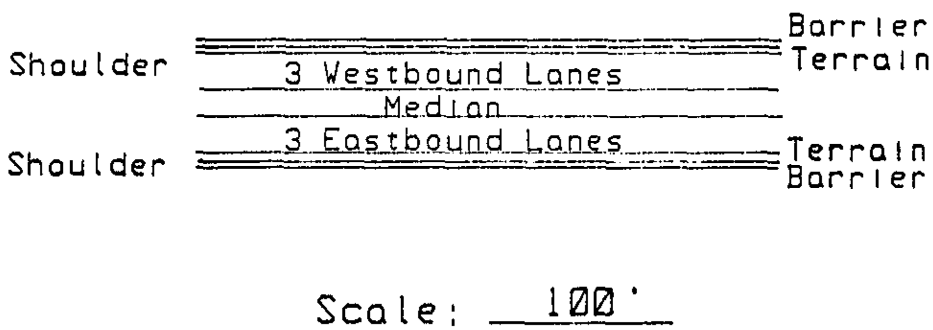
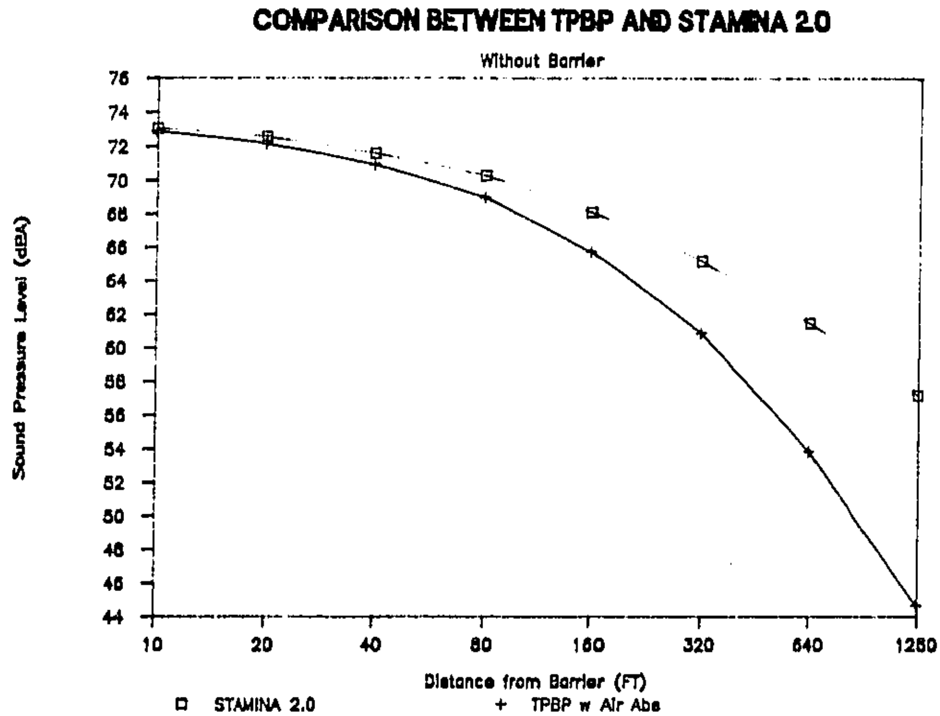


Figure 2



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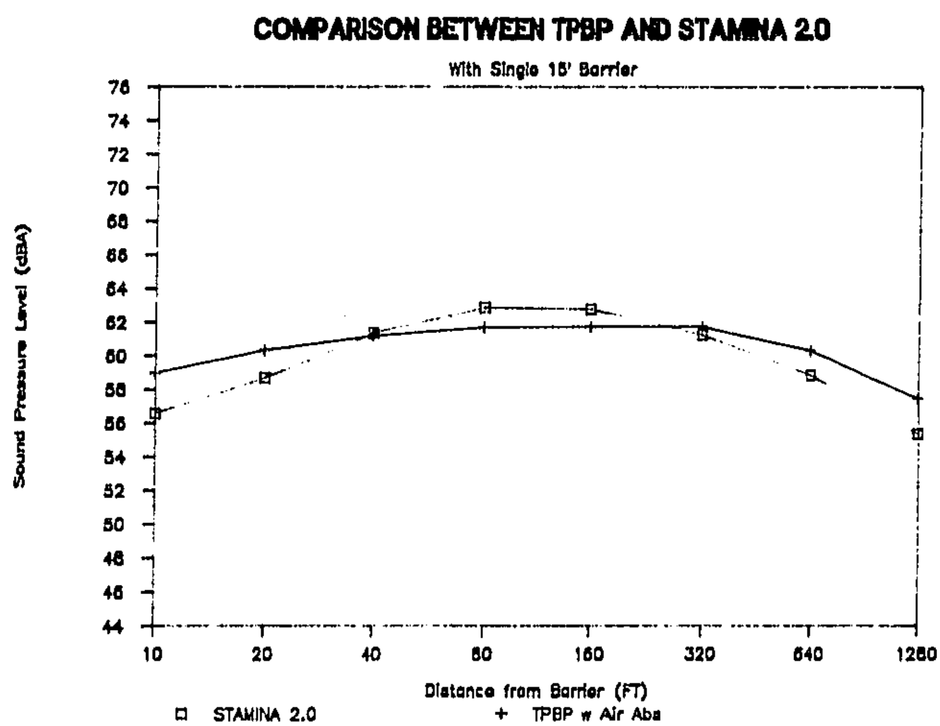

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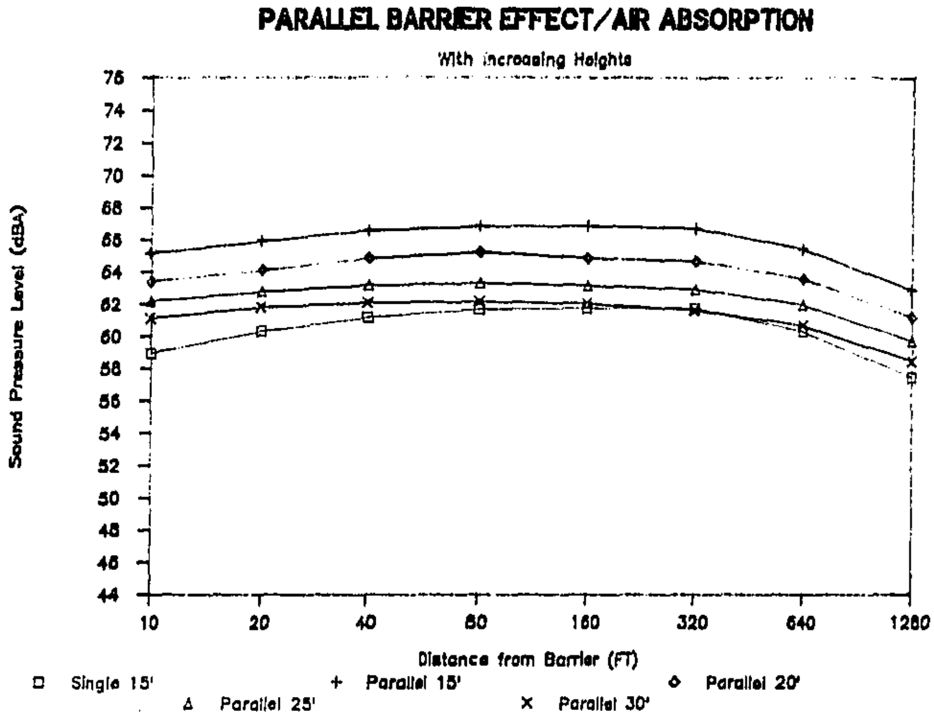

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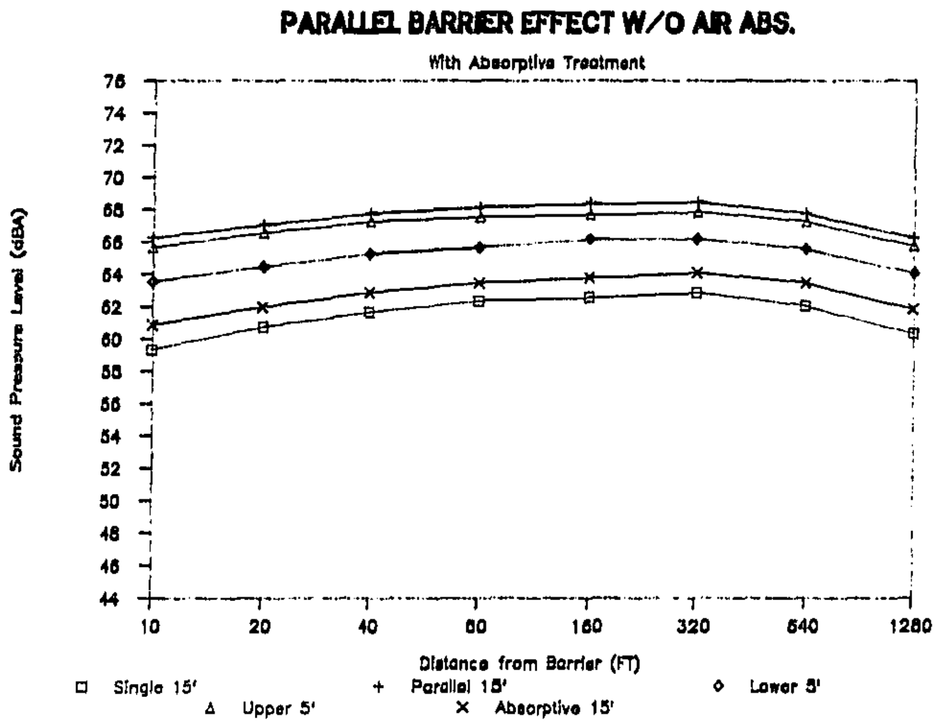

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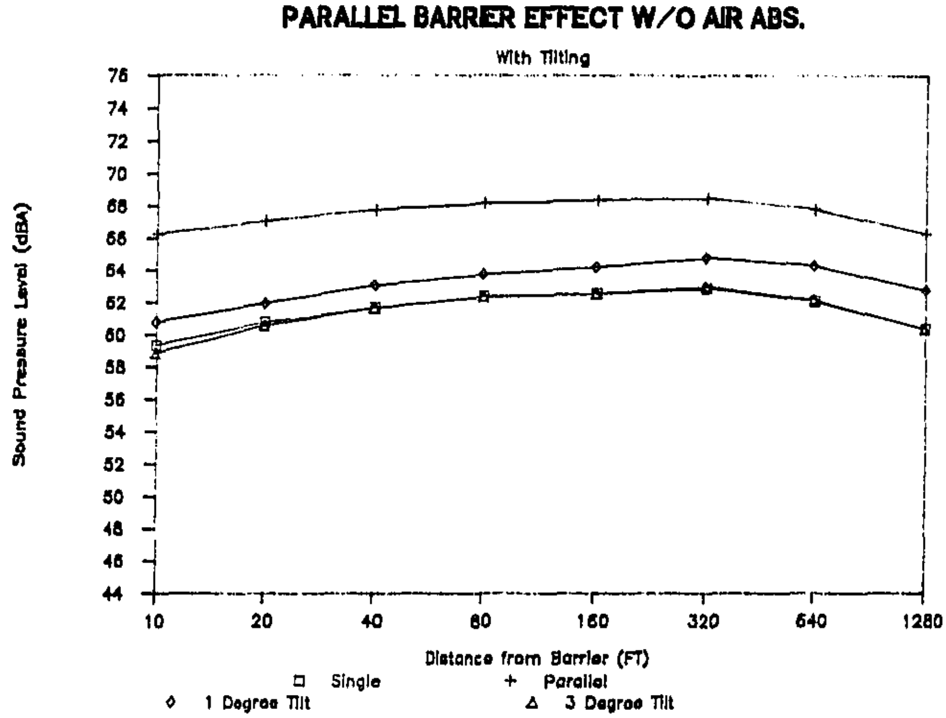

Figure 7

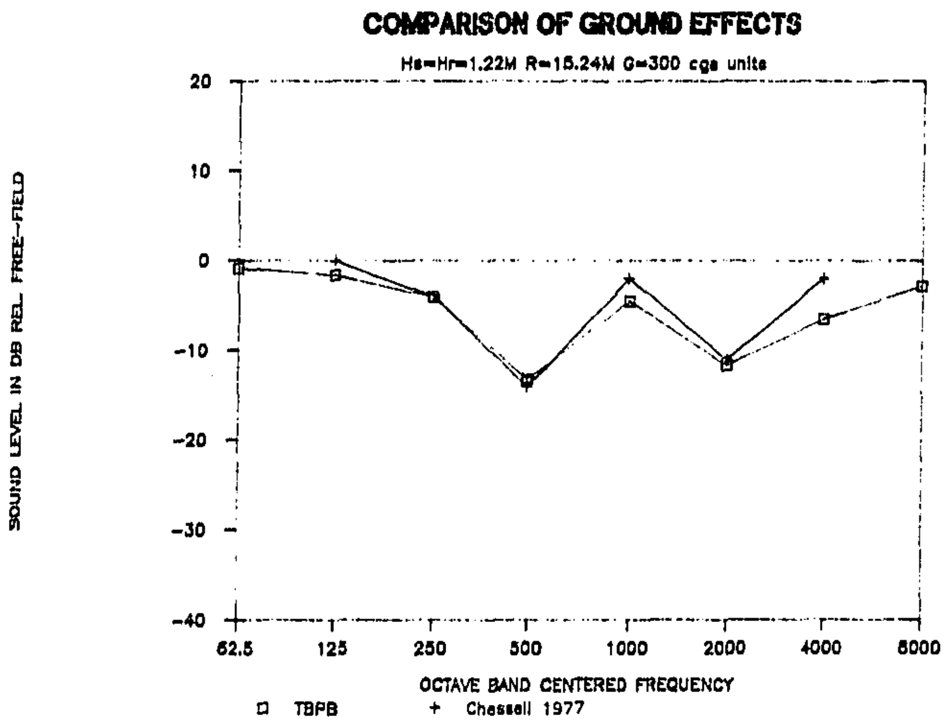

Figure 8

EFFECT OF SOURCE HEIGHTS

Hr=1.52M R=1000.M G=200 cgs units

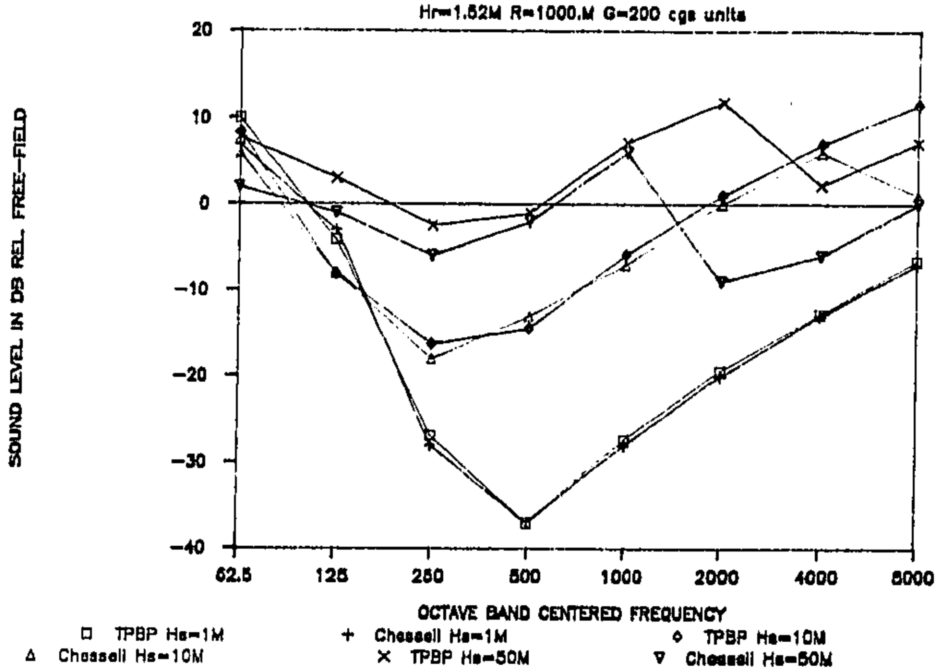

Figure 9

GROUND EFFECT ON RECEIVER HEIGHTS

Hs=0.1 ft R=50 ft over Grassland

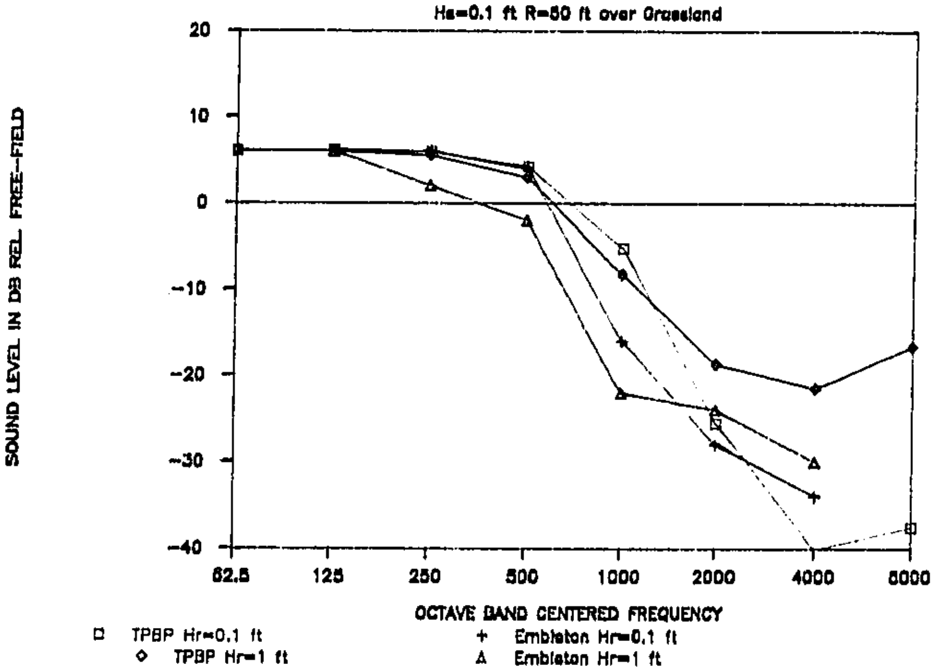

Figure 10

GROUND EFFECT ON RECEIVER HEIGHTS

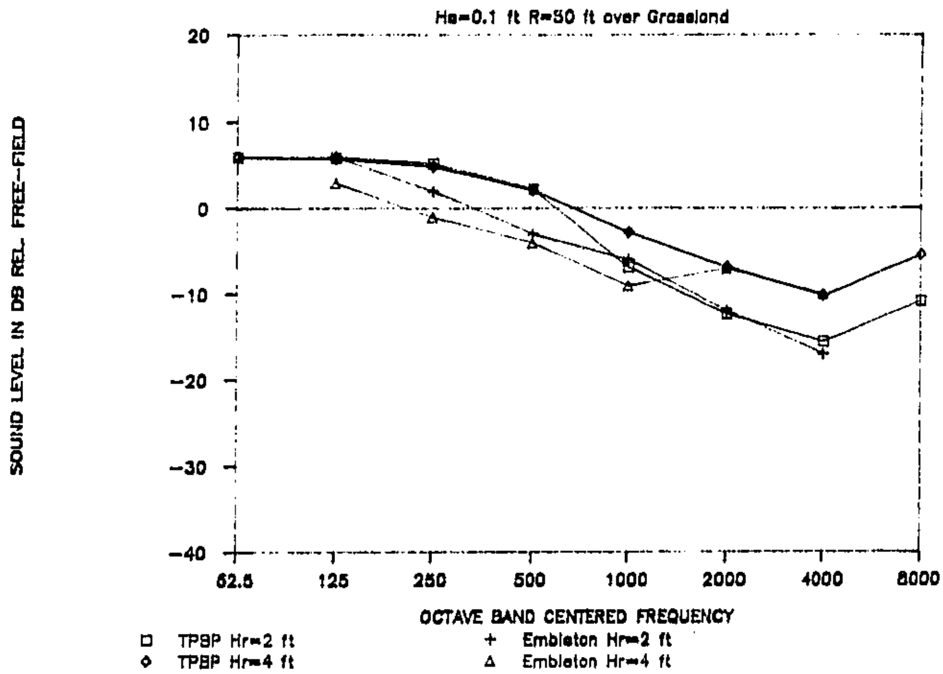

Figure 11

GROUND EFFECT ON RECEIVER HEIGHTS

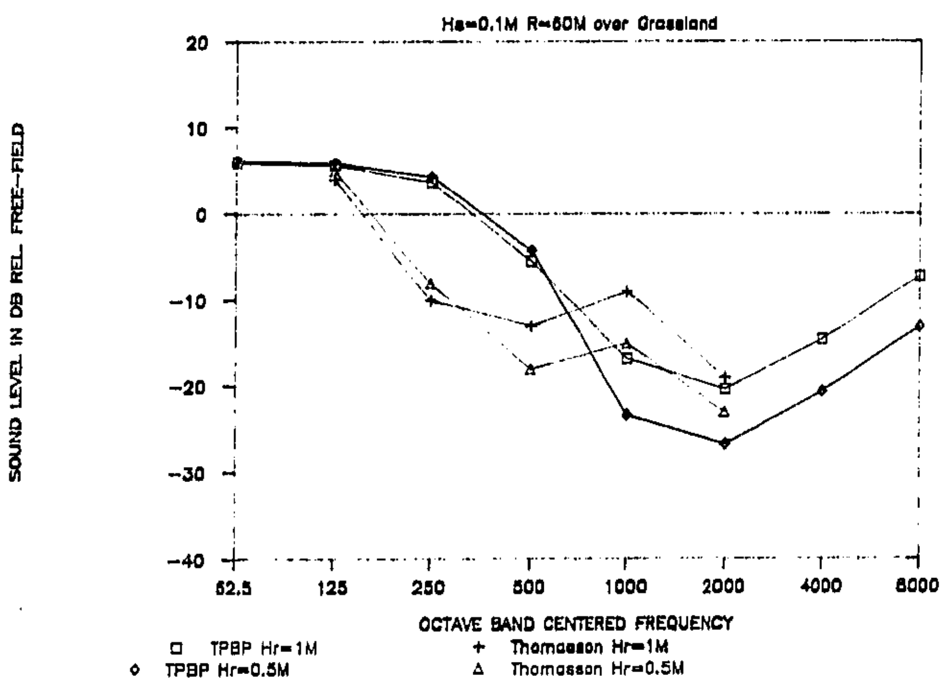

Figure 12

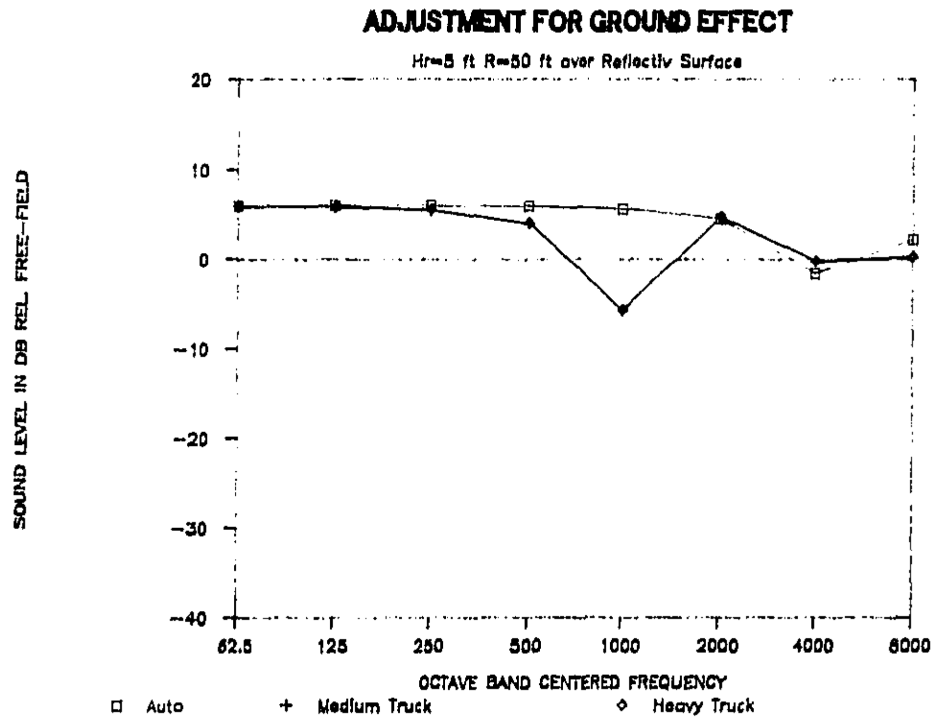

Figure 13

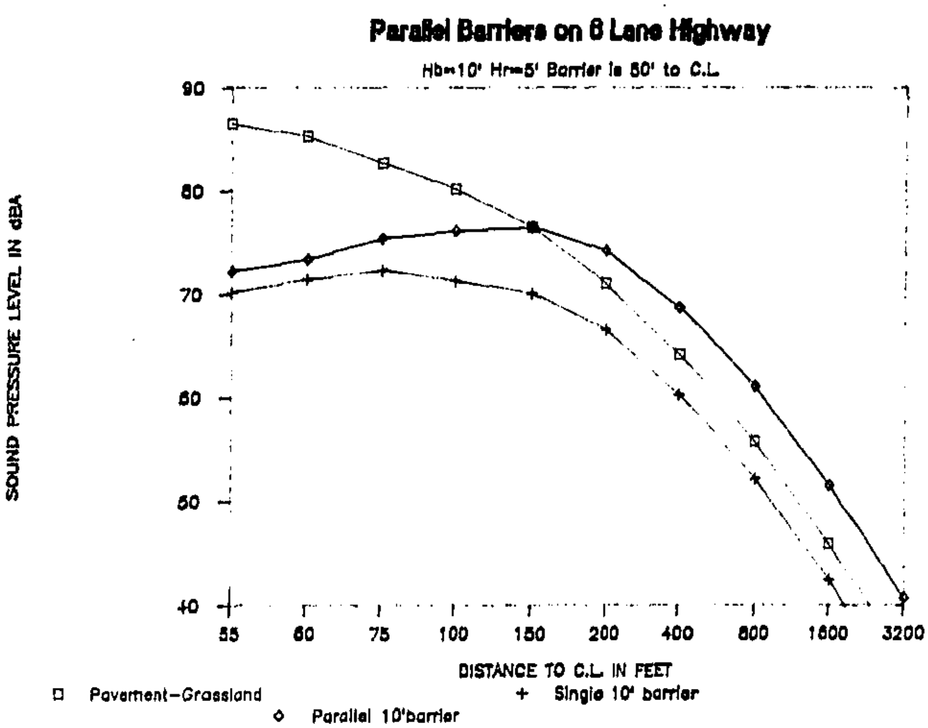

Figure 14

Parallel Barriers on 8 Lane Highway

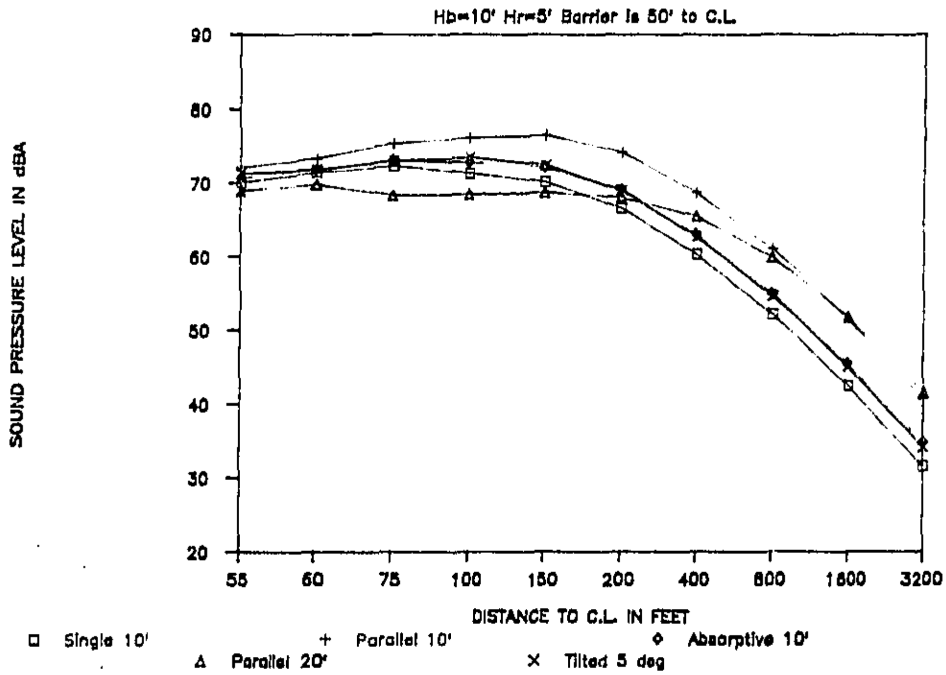

Figure 15

Parallel Barriers on 8 Lane Highway

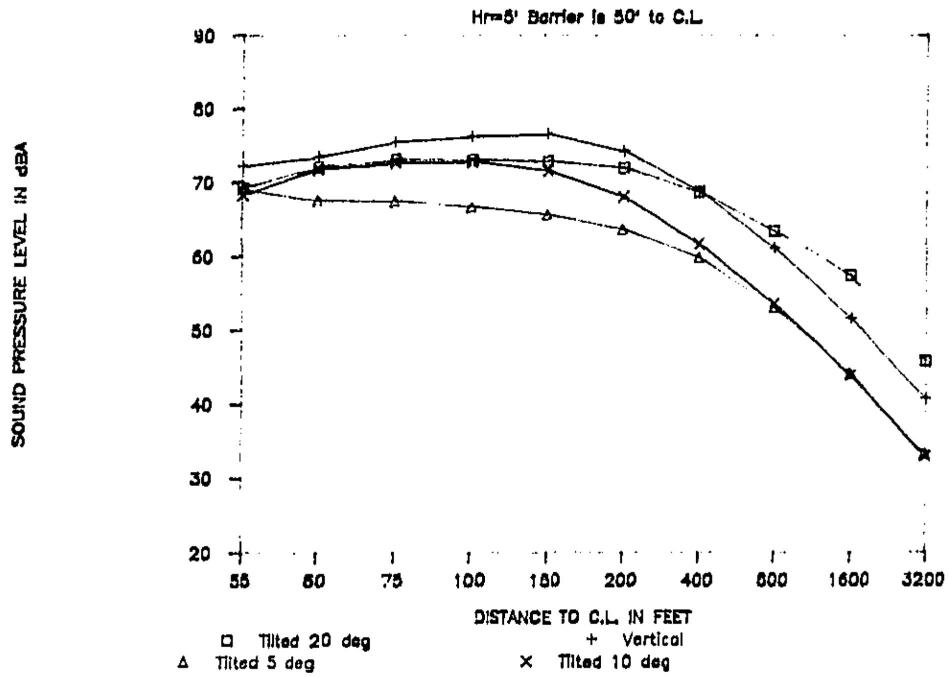

Figure 16

Tilted Barrier on 8-Lane Highway

Hb=20' Hr=5' Barrier is 50' from C.L.

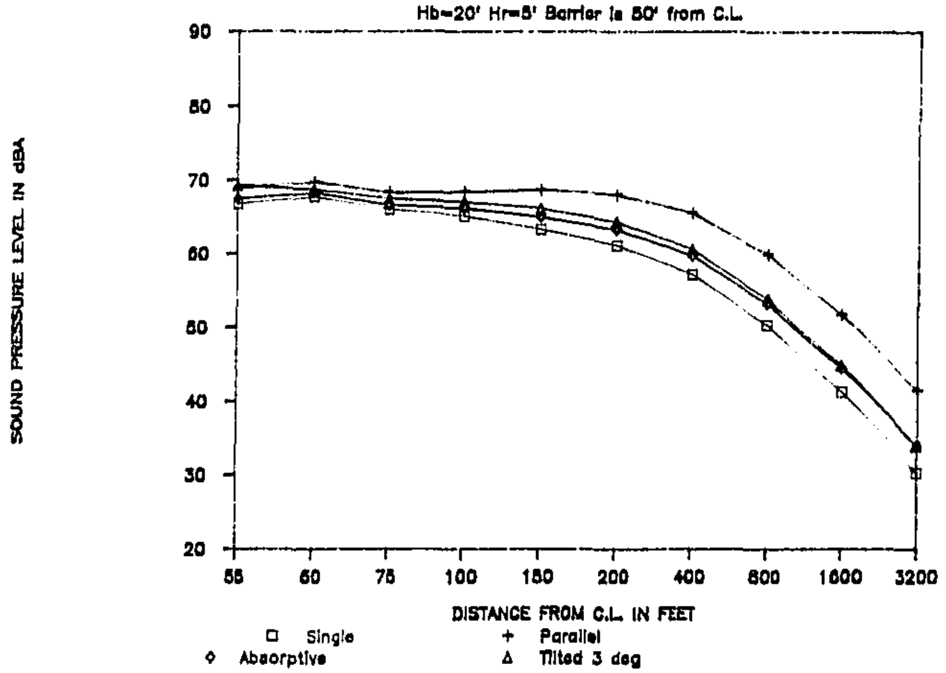

Figure 17

Effect of Tilting for Sources within

Parallel Barriers Hs=0.5 Hb=10 R=50ft

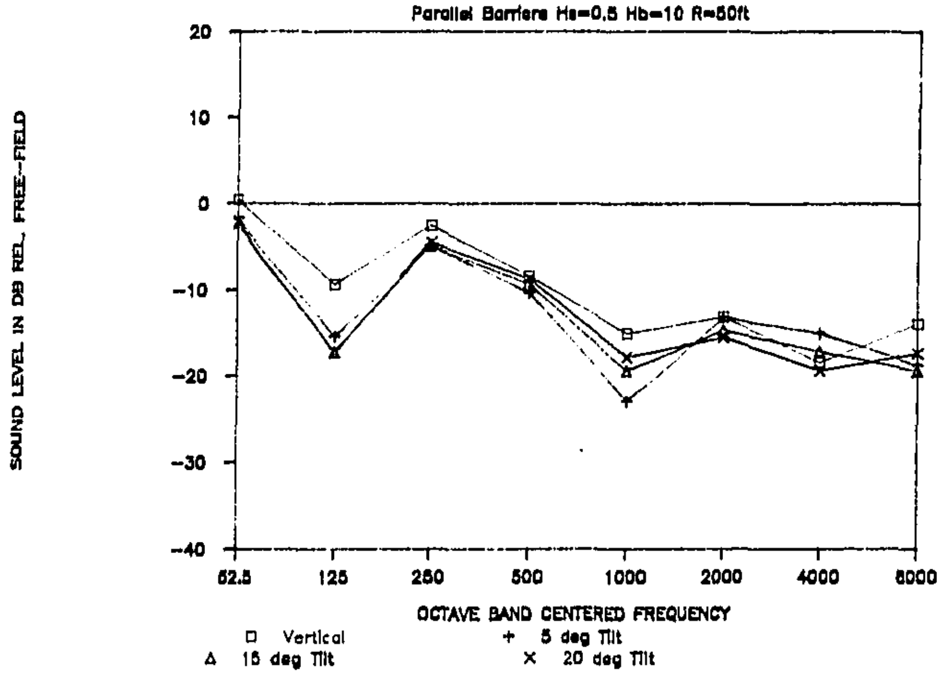

Figure 18

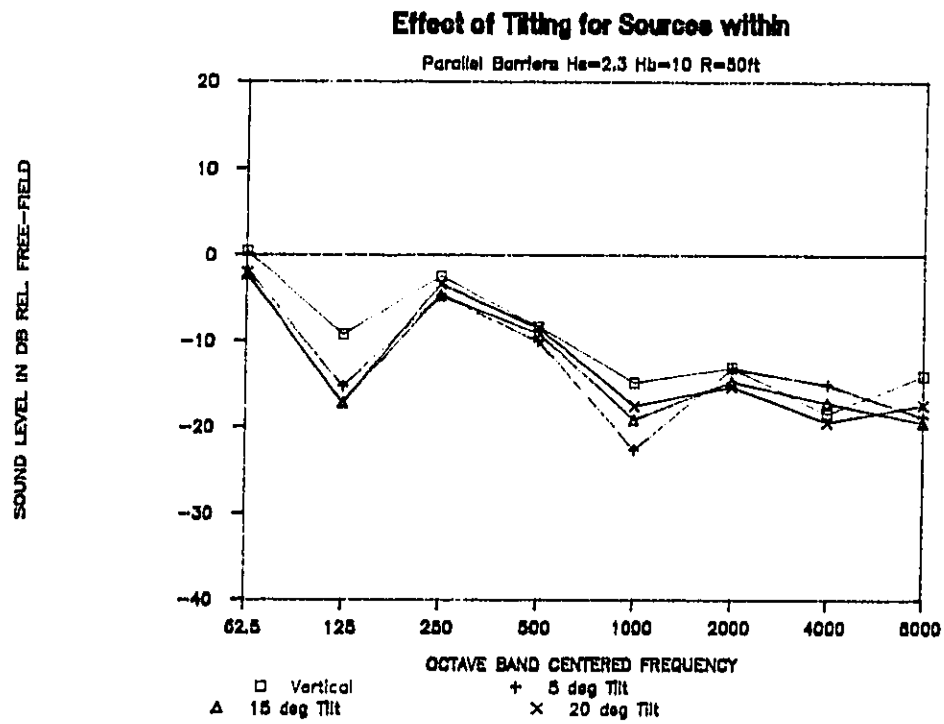

Figure 19