550/9-77-355

Comparison of Highway Noise Prediction Models

May 1977

Office of Noise Abatement and Control
U.S. Environmental Protection Agency
Washington, D.C. 20460

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
550/9-77-355		

4. TITLE AND SUBTITLE	5. REPORT DATE
Comparison of Highway Noise Prediction Models	May 1977
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Kenneth J. Plotkin, R. G. Kunicki	WR 76-25
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Wyle Laboratories/Wyle Research 2361 Jefferson Davis Highway, Suite 404 Arlington, Virginia 22202	11. CONTRACT/GRANT NO. 68-01-3514
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
U.S. Environmental Protection Agency Office of Noise Abatement and Control 1921 Jefferson Davis Highway Arlington, Virginia 22202	Final 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

A review and comparison has been conducted of three highway noise prediction models: NCHRP, TSC, and Wyle. The first two are those approved by the Federal Highway Administration; the third was developed for EPA. The elements comprising each model are analyzed in detail, including basic formulation, vehicle noise levels, propagation, treatment of various road geometries, and shielding by barriers. Significant differences among the models were found. A series of charts is presented whereby differences among the models may be estimated for particular input data. Comparison between measured roadside levels and predictions from the three models are also presented.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Highway noise Environmental noise Prediction models		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Unlimited	Unclassified	44
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

550/9-77-355

COMPARISON OF HIGHWAY NOISE PREDICTION MODELS

MAY 1977

CONTRACT 68-01-3514

U.S. Environmental Protection Agency
Office of Noise Abatement and Control
Arlington, Virginia 22202

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1.0 INTRODUCTION

There are presently three major highway noise models in use in the United States. Two of these, known as NCHRP[1,2] and TSC,[3] are approved by the Federal Highway Administration for predicting levels as required for noise analysis of proposed federally funded highway projects.[4] The third model,[5,6] developed by Wyle Research under contract to the Environmental Protection Agency, is a more recent development, which takes a simpler point of view[7] than the earlier two.

A major difficulty with these models is that quite often they do not predict the same levels for identical situations. Even the two FHWA-approved models differ substantially in some cases. This casts serious doubt on the accuracy of the models, and can also lead to situations where a model is selected for use because it provides favorable results.

The present study has been undertaken to examine the discrepancies among the three models, and to assess their accuracy. There are two parts to this comparison. Section 2.0 compares the formulation and basic data for the three models. All three models purport to sum the noise contributions of individual vehicles over a traffic stream. It is straightforward to compare the formulation, vehicle levels, propagation adjustments, etc. In this way a "comparison map" for the three models can be developed, where the differences, due to various assumptions and/or data elements, can be assessed over a range of conditions.

Section 3.0 compares predictions with measurements. Published data from well-documented measurements have been collected, and have been compared with predictions from all three models. Comparisons are analyzed with respect to both the data and the results of Section 2.0. Section 4.0 presents conclusions of this review.

2.0 MODEL FORMULATION

2.1 Basic Formulation

All three models begin with simple straight-line elements for a stream of traffic. The Wyle and TSC models use a formulation based upon the equivalent noise level L_{eq}, and are in principle "exact", making no assumptions as to vehicle spacing and level variations. The NCHRP model is based on a theoretical calculation of L_{50} (the level exceeded 50 percent of the time) for a lane of equally spaced identical vehicles. The basic single-lane elements of the three models are summarized below.

Wyle. In the absence of propagation losses,

$$L_{eq} = L^{eq} + 10 \log_{10}\left(\frac{\pi d_o^2 Q}{Vd}\right) \qquad (1)$$

where Q = Vehicle flow, number per unit time

d = Distance from observer to road

d_o = Reference distance for vehicle pass-by levels (usually 50 ft (15 meters))

V = Vehicle speed

L^{eq} = Equivalent vehicle level (see Reference 5) — the intensity mean of the noise distribution for the vehicle population.

TSC. The basic formulation is identical to Wyle, except that vehicle levels are described in terms of average pass-by level and standard deviation, rather than L^{eq}. This gives

$$L_{eq} = \bar{L} + 0.115\,\sigma^2 + 10 \log_{10}\left(\frac{\pi d_o^2 Q}{Vd}\right) \qquad (2)$$

where $\bar{L}$ = Average vehicle level

σ = Standard deviation of vehicle levels

The TSC model assumes the distribution of vehicle levels to be Gaussian. This is less general than the use of L^{eq} in the Wyle model, but is of little practical importance when the models are used as design tools. The relation between the vehicle level definitions can be seen by comparing Equations (1) and (2).

NCHRP. This is based on Johnson and Saunders'[8] expression for L_{50}:

$$L_{50} = 40 \log_{10} V - 10 \log_{10} d + 10 \log_{10} \rho + 10 \log_{10} \left[\tanh (1.19 \times 10^{-3} \rho d)\right] + K \qquad (3)$$

where ρ = Vehicles per unit distance = Q/V

K = Constant, empirically determined

In Equation (3), ρ has units of vehicles per mile and d is in feet. (Note that Equations (1) and (2) are valid for any consistent set of units.) Metrics other than L_{50} are obtained by assuming a Gaussian temporal distribution of noise, with standard deviation based on empirical data. Figure 1 shows the adjustment to L_{50} to obtain L_{10}. The measurements shown in Figure 1 by Johnson and Saunders were performed in England. Also shown are typical data measured in the United States.[7,9] The difference in vehicle types in the two countries apparently does not affect the statistics of variations. Note that the theoretical curve in Figure 1, obtained from the same model used to develop Equation (3), differs substantially from the measurements.

Figure 2 shows a comparison of the Wyle and NCHRP predictions of L_{eq} as a function of vehicle volume. At large vehicle volumes, both models have the same slope. (For vehicle spacing less than 4d, the log tanh term in Equation (3) becomes approximately zero, so that the traffic volume dependence is the same as Equations (1) and (2).) Shown as dashed lines are linear extrapolations of the NCHRP prediction from its high value asymptote, with volume dependence the same as for the L_{eq} models. The difference in level at high volume is due to differences in vehicle levels (discussed below). The additional difference at low volume is due to the inadequacy of the Johnson and Saunders formulation for real traffic flow. Predictions from the TSC model (not shown) differ from the Wyle model by amounts corresponding to differences in source noise level.

2.2 Vehicle Noise Levels

The Wyle and TSC models have vehicle levels as direct inputs in the form of 50-foot (15-meter) maximum pass-by levels. The NCHRP model is not explicitly based on individual vehicle levels, but rather fits a constant to highway noise data. It is possible, however, to compare the final NCHRP expression to the final Wyle expression and thereby extract an equivalent vehicle level from the NCHRP model.

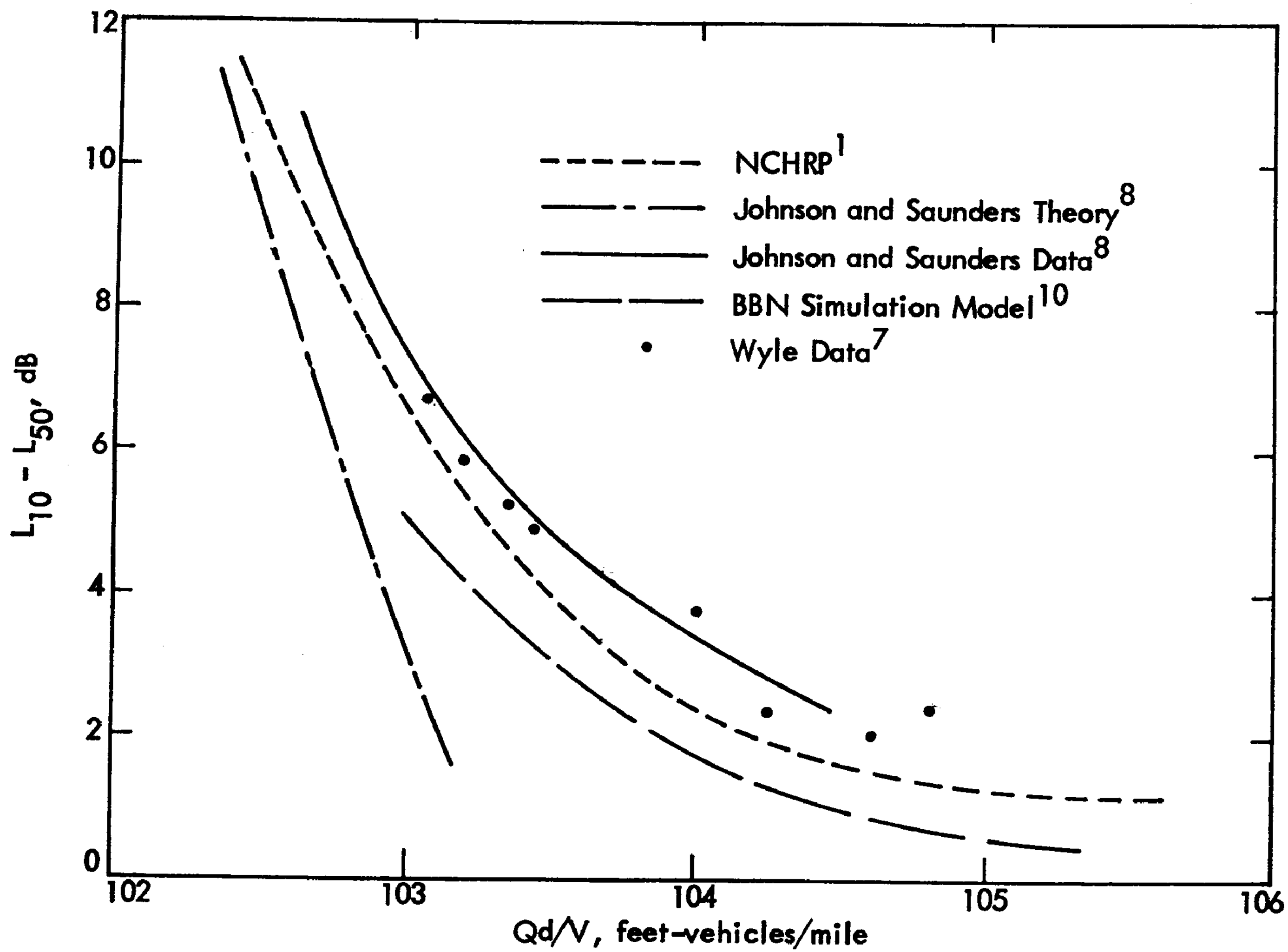

Figure 1. Difference Between L_{10} and L_{50}

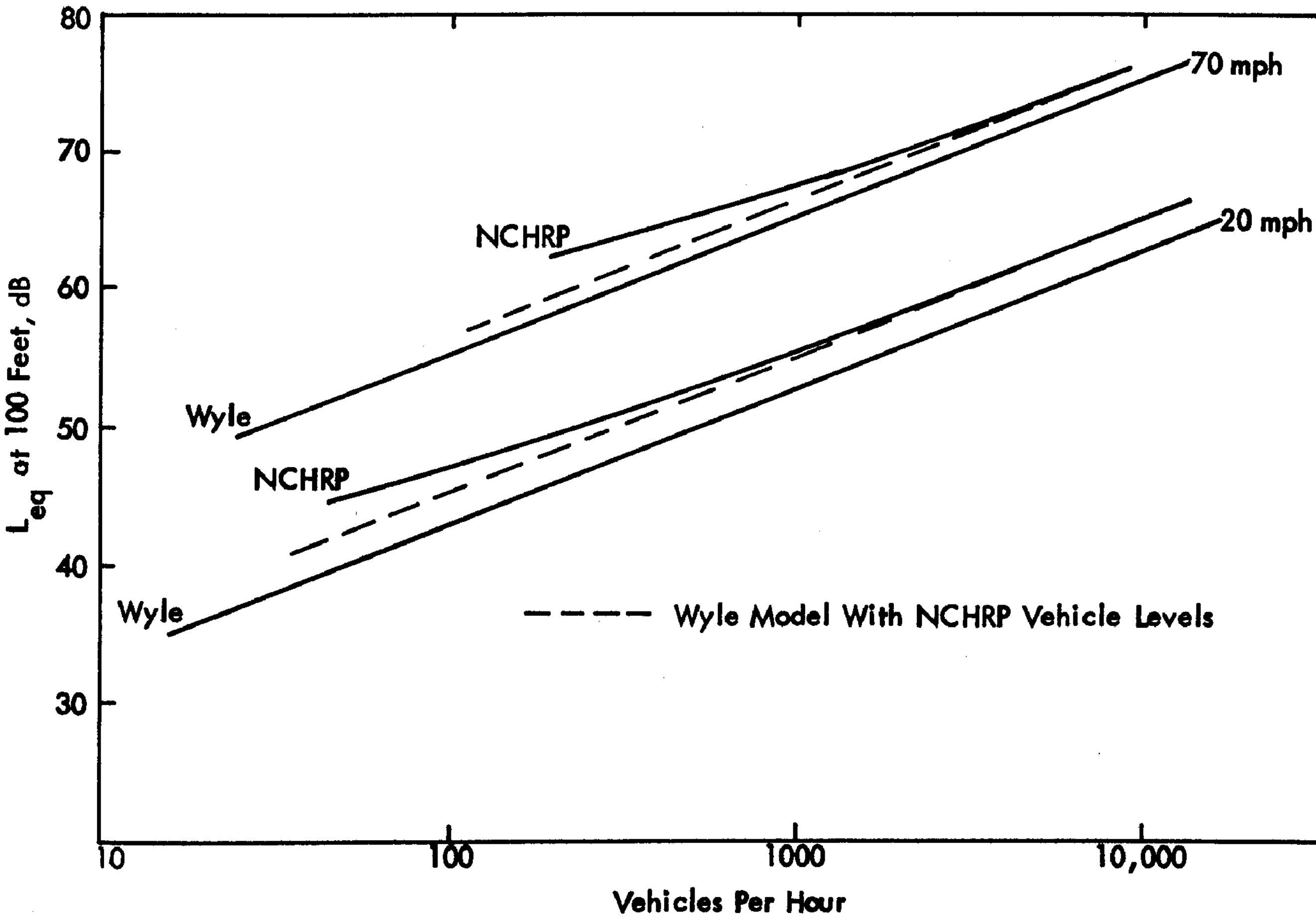

Figure 2. Comparison of Wyle and NCHRP Vehicle Flow Dependence.
TSC Agrees With Wyle Except For Vehicle Levels.

Automobile and truck levels for the three models, expressed as L^{eq}, are shown in Figures 3 and 4. Analytic expressions describing the curves are shown on the figures. The origins of vehicle levels are:

Wyle. Automobile levels are based on Olson's roadside measurements.[9] Truck levels are based on roadside measurements of over seven thousand trucks at high and low speeds in eight states.[11]

TSC. Automobile levels are based on Olson's data. The discrepancy between TSC and Wyle levels is apparently due to interpretation and fitting of an analytic curve. The truck noise levels are based on Olson's roadside measurements of 466 trucks,[9] predominantly at high speeds, and on measurements of truck noise on the New Jersey Turnpike.[3,10] The speed dependence of tire noise is specifically neglected.

NCHRP. Automobile levels are based on fitting Equation (3) to Johnson and Saunders' roadside measurements of traffic noise in England. Truck levels are based on limited roadside measurements which indicate that trucks at 50 mph are 15 dB greater than automobiles.

The automobile levels are in reasonable agreement over most of the speed range, except for the NCHRP levels being consistently high. The speed dependency is in reasonable agreement with theoretical considerations of tire noise. The truck levels are in serious disagreement, especially with regard to speed dependence. In view of the larger data base for the Wyle truck noise relation, the TSC and NCHRP truck noise levels are considered to be unreliable. The influence of different vehicle levels on differences between the three models is shown in Figure 5. This is a set of charts of contours of differences, as a function of speed and truck percentage. At typical highway speeds of 55 mph, agreement between the models is reasonably good. At low speeds, where the truck levels disagree, discrepancies can be 4 dB or more. In some cases, there are sharp changes of difference at small truck percentages when the dominant noise source changes between cars and trucks. Differences for the case of no trucks may be obtained from Figure 3.

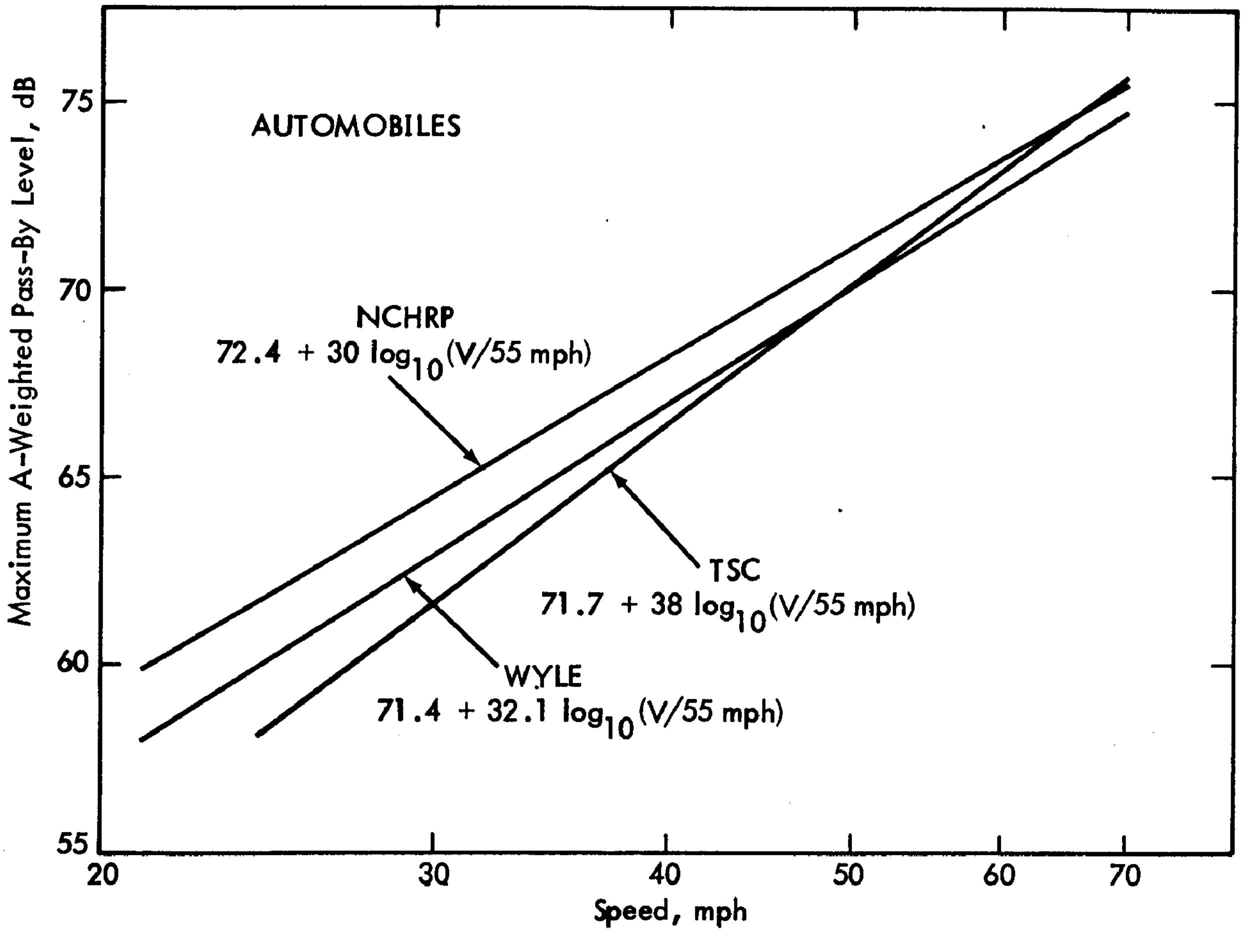

Figure 3. Automobile Maximum Pass-By Levels at 50 Feet

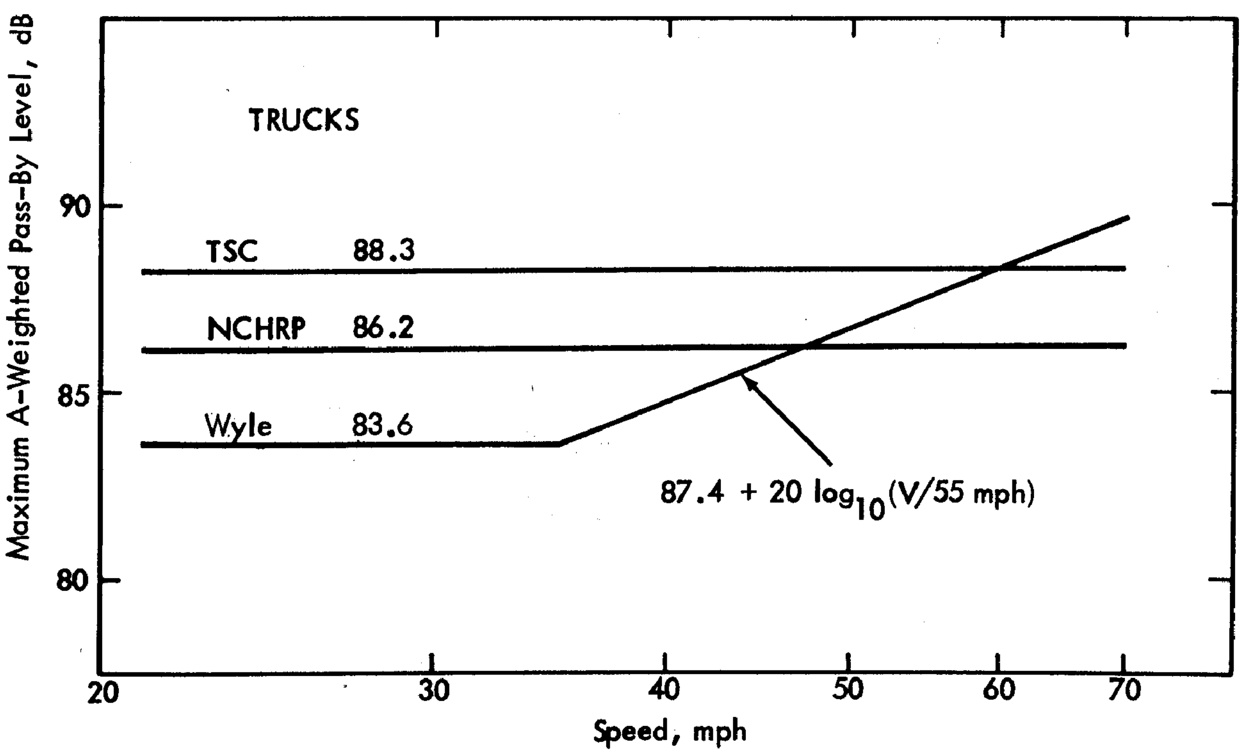

Figure 4. Truck Maximum Pass-By Levels at 50 Feet

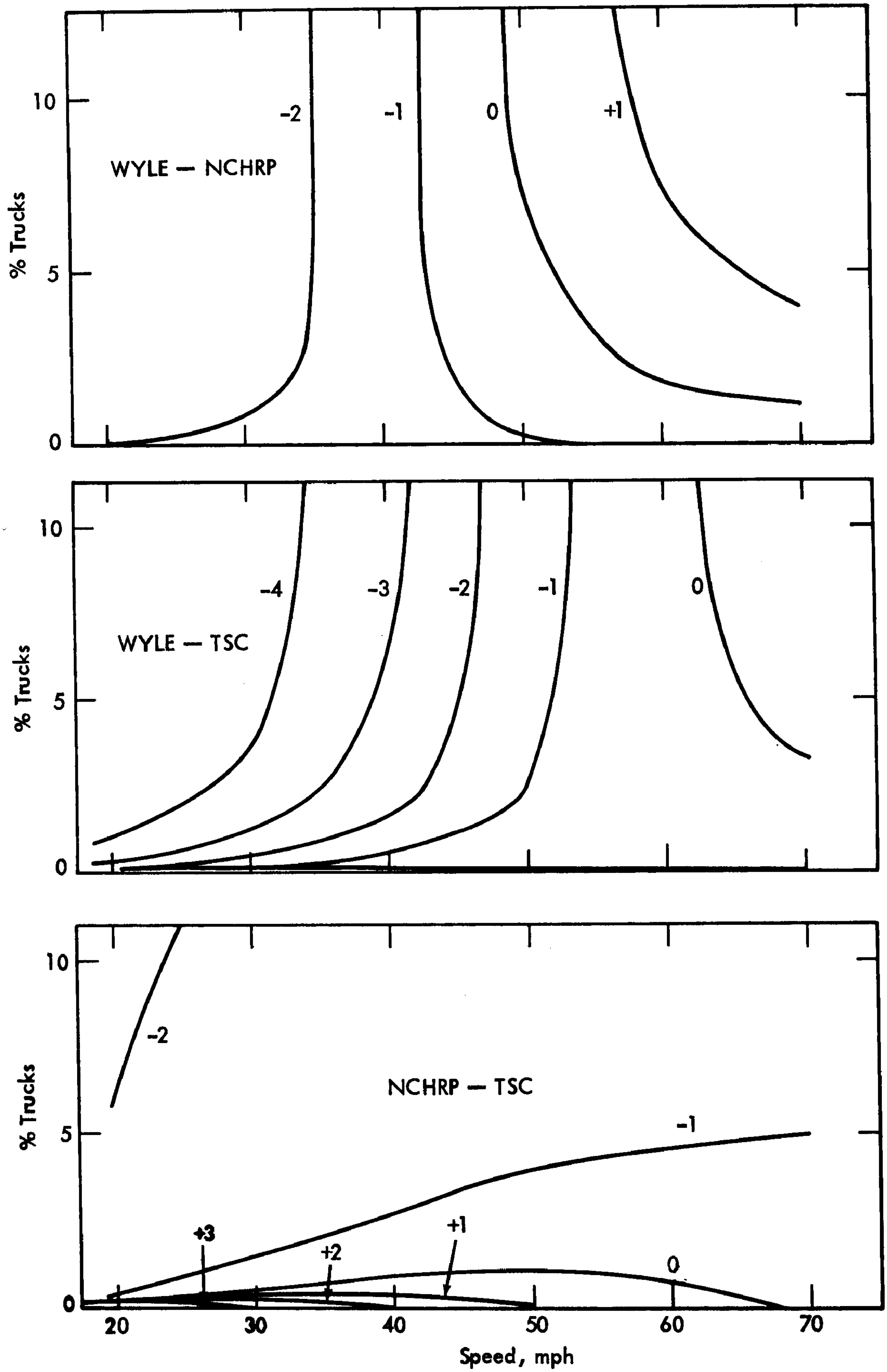

Figure 5. Differences Between Predictions Due to Vehicle Level Differences

2.3 Propagation

In the absence of propagation losses, noise from a straight line source decays as $10 \log_{10} d$, or 3 dB per doubling of distance. Air absorption is always present, and can be calculated from standard tables.[12] Air absorption loss for highway noise is typically about 2 dB/1000 ft., so is often negligible. For propagation near the ground, finite ground impedance leads to additional attenuation. Theoretical computation of ground absorption is quite complex,[13,14] and requires ground impedance data not readily available. All three models therefore use simplified, empirical representations.

Wyle. Ground absorption is represented in terms of excess dB per doubling, a form suggested by the geometrical nature of theoretical calculations.[13,14] Measurements by Nelson[15] on individual vehicles show that the excess can be from 0 to 4 dB per doubling of distance, depending on ground surface. Highway noise measurements indicate 1.2 to 1.5 dB per doubling excess attenuation for typical clear terrain situations. The Wyle computer model[5] permits the user to specify a value. The Wyle nomogram method[6] uses a conservative value of 1 dB per doubling, plus 2 dB per 1000 feet air absorption. This propagation relation is shown in Figure 6.

TSC. Over bare ground, no ground attenuation is used. For propagation over thick grass and shrubs and through trees, excess attenuation is based on data collected in Reference 16. These data provide frequency dependent coefficients of absorption per unit distance. Figure 6 shows the TSC propagation relation over clear terrain (no excess attenuation) and over the two types of ground cover. Attenuations for automobiles and trucks differ because of spectral differences. Shown is a worst case example of ground cover extending up to the highway; the TSC model permits specifying limited patches of ground cover. The value of ground absorption depends to some degree on how the shape of the area is described to the program. Reference 16 specifies that ground absorption should not be used within 200 feet of the source. It is not clear whether the TSC program checks for this, or whether this is the responsibility of the program user.

The ground absorption model used in the TSC model is not considered to be satisfactory. There is some question as to the validity of the data. The frequency dependence is opposite that predicted by recent well-supported theory.[13,14] The grass considered is

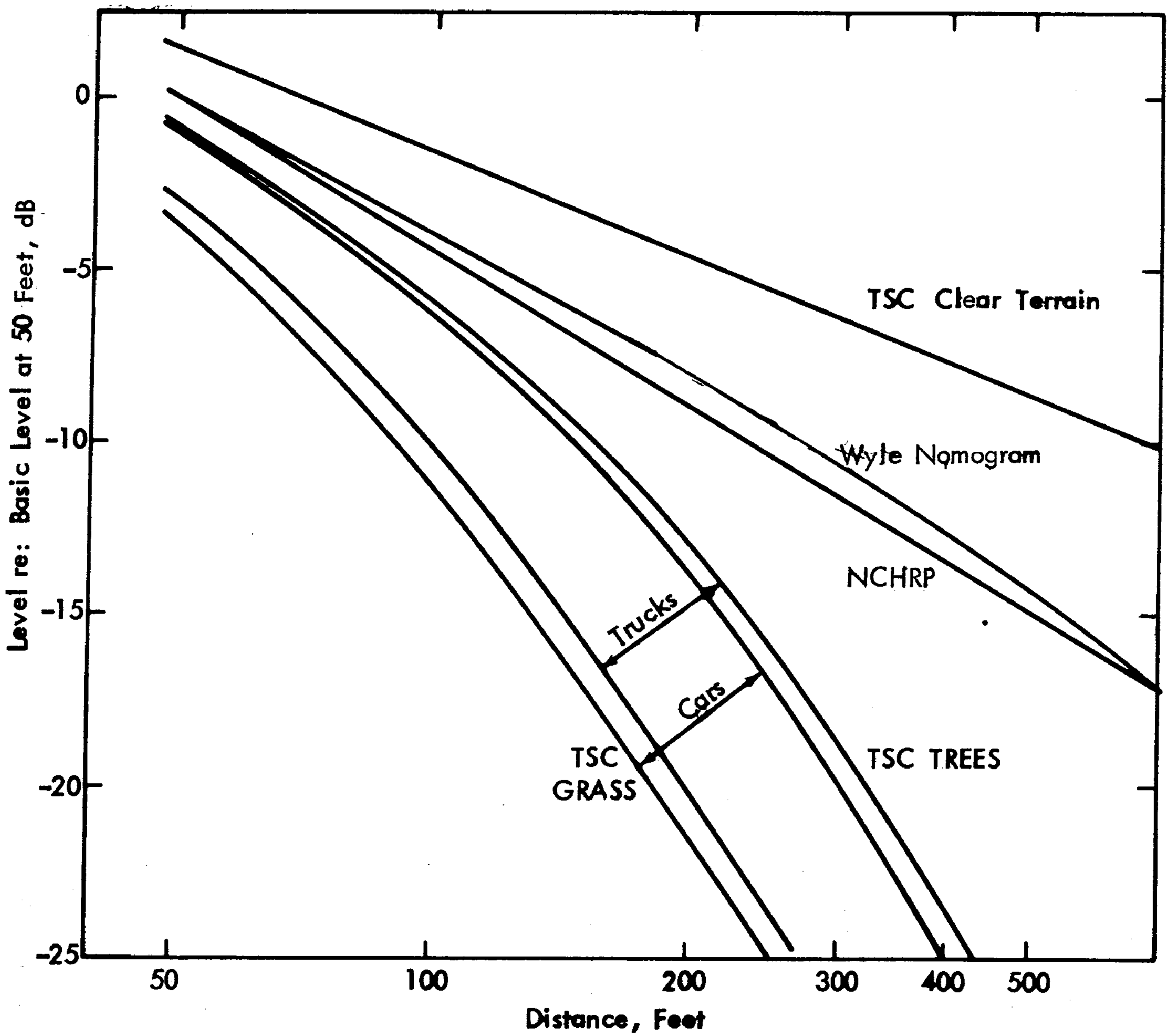

Figure 6. Comparison of Propagation Relations Used in the Three Models

also very high and dense, and is not representative of lawn-type grass usually used in highway landscaping. The dense shrubbery considered is also not applicable to sparse scrub often found in the southwestern United States. Caution should therefore be used before using the TSC ground cover correction.

Reference 3 describes values of air absorption which are presently obsolete. It appears, however, that the current version of the TSC program contains data consistent with that of Reference 12.

NCHRP. Based on empirical data, all attenuation over clear terrain is represented by 1.5 dB per doubling of distance excess attenuation. The NCHRP propagation relation is shown in Figure 6. Agreement between this and the Wyle model is very good.

Although the Wyle and NCHRP propagation relations show better agreement with data, they must be taken with some reservations. Propagation does vary with ground cover, so that using a single relation cannot be adequate for all cases. The computerized version of the Wyle model permits the user to specify a value of propagation loss, but without local measurements it is difficult to determine what that value should be. Even with this potential flexibility, this version of the Wyle model (or a similar modification of the others) cannot compensate for variations in vehicle levels at 50 feet observed over various paved and unpaved surfaces.[11] The difference between a paved and unpaved site is on the order of 2 dB. This added uncertainty must be considered to exist for all models. More basic work must be done to establish correct highway noise propagation characteristics.

Figure 6 may be used to assess differences between the models due to propagation.

2.4 Multiple-Lane Geometry

The elements discussed so far are for a single-lane road. Multiple-lane roads are treated as follows:

Wyle. The computer version accounts for actual lane geometry, and combines the contribution of all lanes. The process properly accounts for the traffic distribution among the lanes, number of lanes, median width, and propagation effects. A nomogram version of the Wyle method uses an approximate adjustment, based on an average fit to the computer calculation for various numbers of lanes. As shown in Figure 7, the adjustment

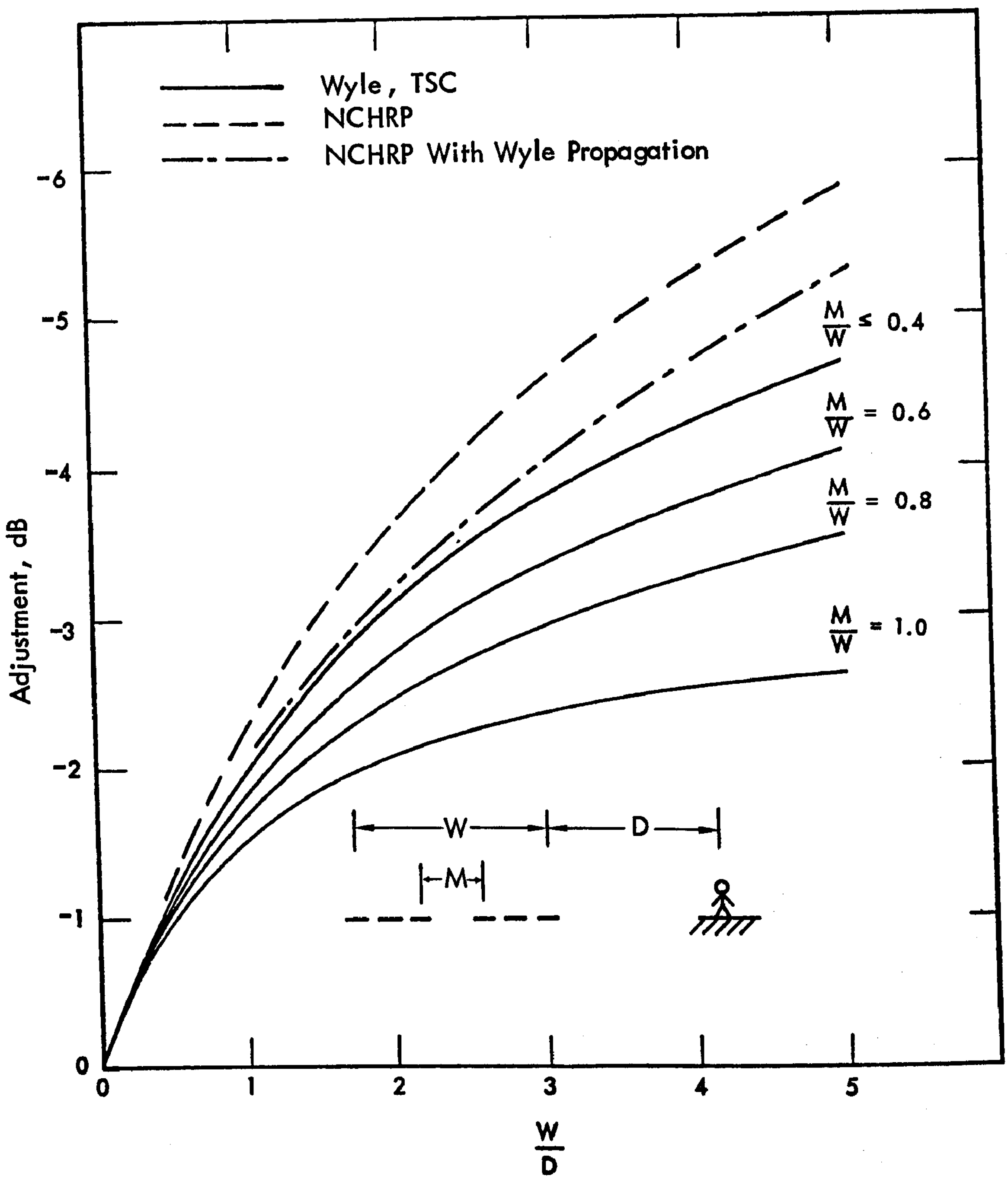

Figure 7. Comparison of Road Width Adjustment

depends only on road width, median width, and observer distance. For W/D = 5, accuracy is within ±.5 dB of an exact calculation over extremes of traffic distributions and number of lanes; accuracy is proportionately better at smaller W/D.

TSC. Actual lane geometry is used, just as in the Wyle model. Lane adjustment is thus similar to the Wyle adjustment shown in Figure 7.

NCHRP. Noise levels are computed on the basis of a single equivalent lane located at

$$d_E = \sqrt{d_n d_f} \tag{4}$$

where d_n and d_f are observer distances to the centers of the near and far lanes, respectively. There is no theoretical basis for this formula. Figure 7 shows the adjustment based on this equivalent distance. Shown are the adjustment based on 1.5 dB/doubling excess attenuation (as used in the NCHRP model) and based on 1 dB/doubling excess attenuation, for a fairer comparison with the Wyle adjustment. Agreement with the multi-lane zero median case (M/W = 0) is reasonable, but there are significant differences for wide median strips.

2.5 Barriers

Calculation of barrier shielding in all three models is based on Fresnel diffraction as represented by Maekawa.[17] The Wyle and NCHRP models use a line source adaptation,[18] while TSC uses a numerical application of Maekawa's original point source curve. Point and line source shielding curves are shown in Figure 8 as a function of path length difference, δ (in feet), for a 500 Hz tone. This is very close to the curve for typical A-weighted vehicle spectra. The three models utilize different assumptions of vehicle source height and other details in applying these shielding curves.

Wyle. Automobile source height is assumed to be two feet (0.6 meter), and truck source height is assumed to be eight feet (2.4 meters). The line source curve shown in Figure 8 is used. When barriers are present, ground attenuation is neglected.

TSC. Automobile source height is at pavement level, and truck source height is eight feet (2.4 meters). The point source curve shown in Figure 8 is used, with a maximum of

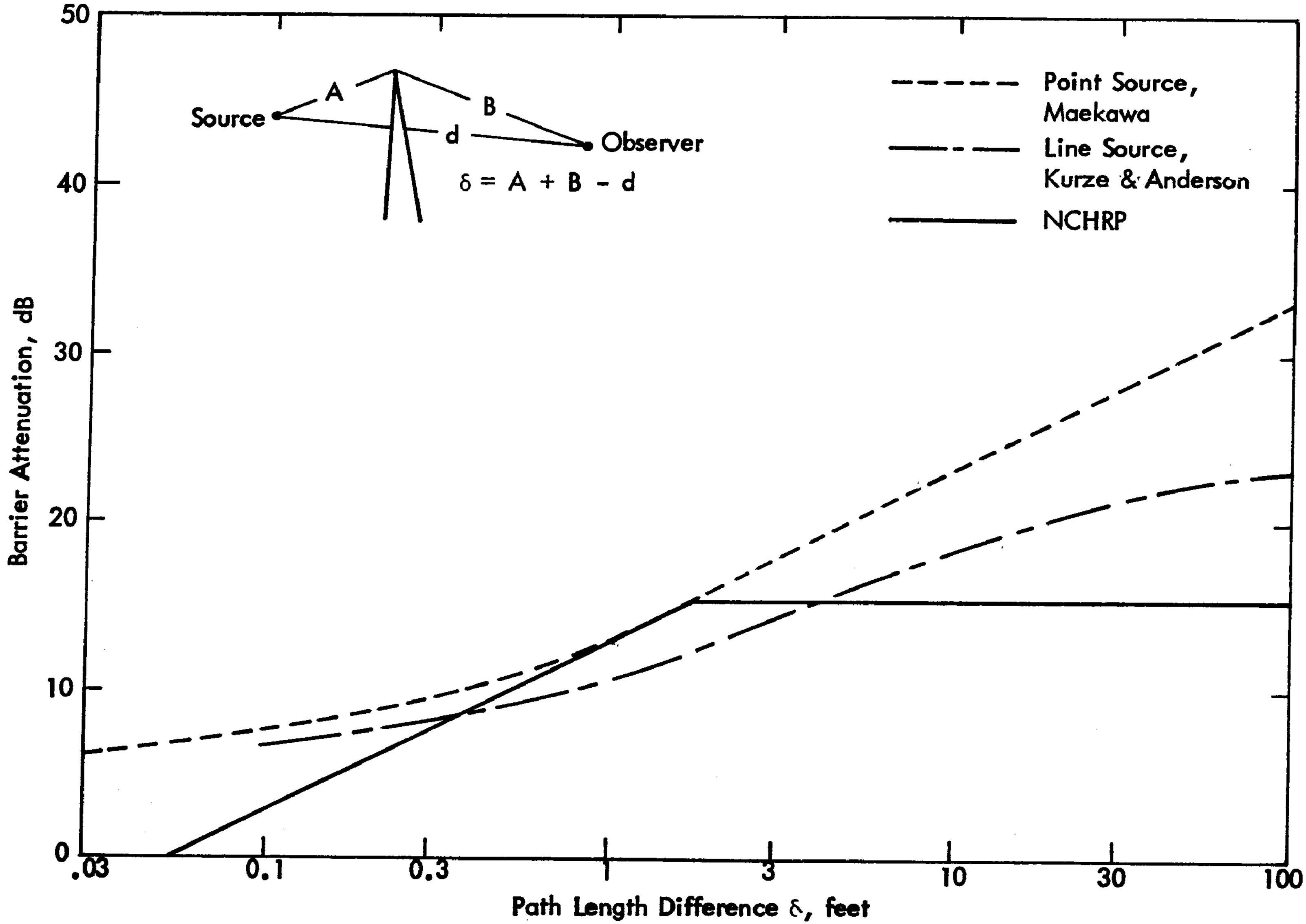

Figure 8. Comparison of Barrier Attenuation Curves

24 dB attenuation at large δ. The roadway and barrier are subdivided by the program into short elements, where the point source model is reasonable to apply, and the shielded contributions combined. This provides a numerical approximation of the line source shielding result. It was found that in cases of large shielding, computational time could become excessively long due to the program subdividing the road into many elements. When barriers are present, ground attenuation is neglected.

NCHRP. Automobile source height is at pavement level. Truck shielding is assumed to be 3 dB less than automobile shielding, with a minimum of zero. There does not appear to be any substantive support for this assumption. The line source curve in Figure 8 is used with two modifications: maximum shielding at large δ is assumed to be 15 dB, and shielding is assumed to be zero for negative δ (i.e., line-of-sight exists between source and observer). These two modifications appear to be intuitive. When barriers are present, ground attenuation is still included.

Figures 9, 10 and 11 compare shielding for various single lane cases for the three models, for automobiles and for trucks. The values shown are insertion losses, i.e., the level computed with the barrier minus the level computed for the same distance and traffic flow over clear terrain without a barrier. Shielding for multiple lane cases will lie somewhere between shielding based on the location of the nearest and farthest lanes.

The large differences between the shielding calculations for the three prediction methods demonstrate the sensitivity of shielding to the assumptions of lane location and source height. Since there is little question over the correctness of the basic diffraction calculation, more work must be done to establish correct effective source heights for automobiles and trucks, and to assess the effect of the ground when a barrier is present.

2.6 Finite Road Elements

The model elements described thus far are straight infinite line sources. These are obtained by integrating vehicle pass-bys from plus and minus infinity along the road. If a road has finite length, the integration may be carried out over this length only. All three models use essentially this method for finite road lengths; curved roads are approximated by a series of straight elements. Differences between the models arise, however, due to differences in handling propagation losses.

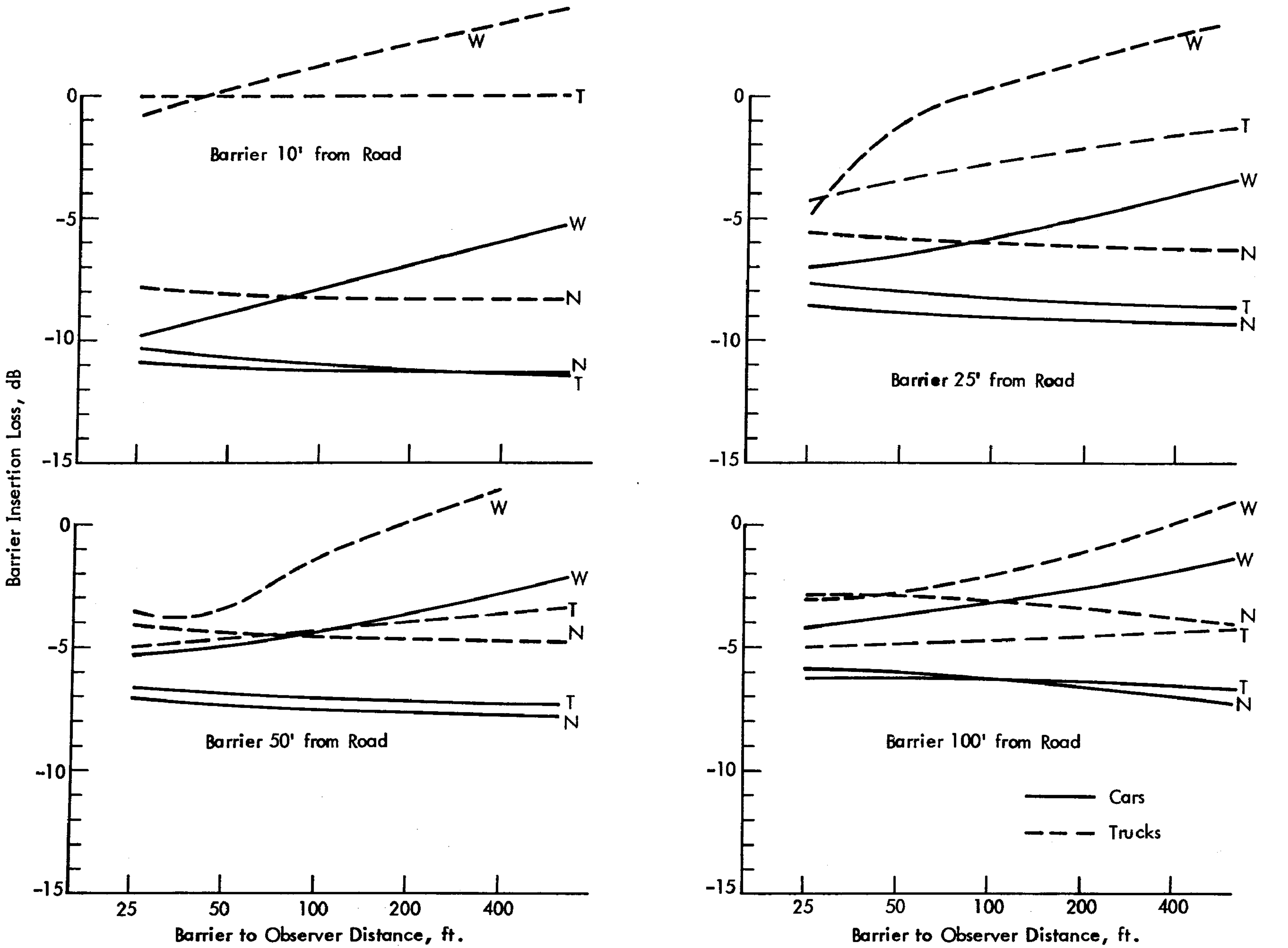

Figure 9. Barrier Insertion Loss, 5-Foot-High Barrier
W = Wyle T = TSC N = NCHRP

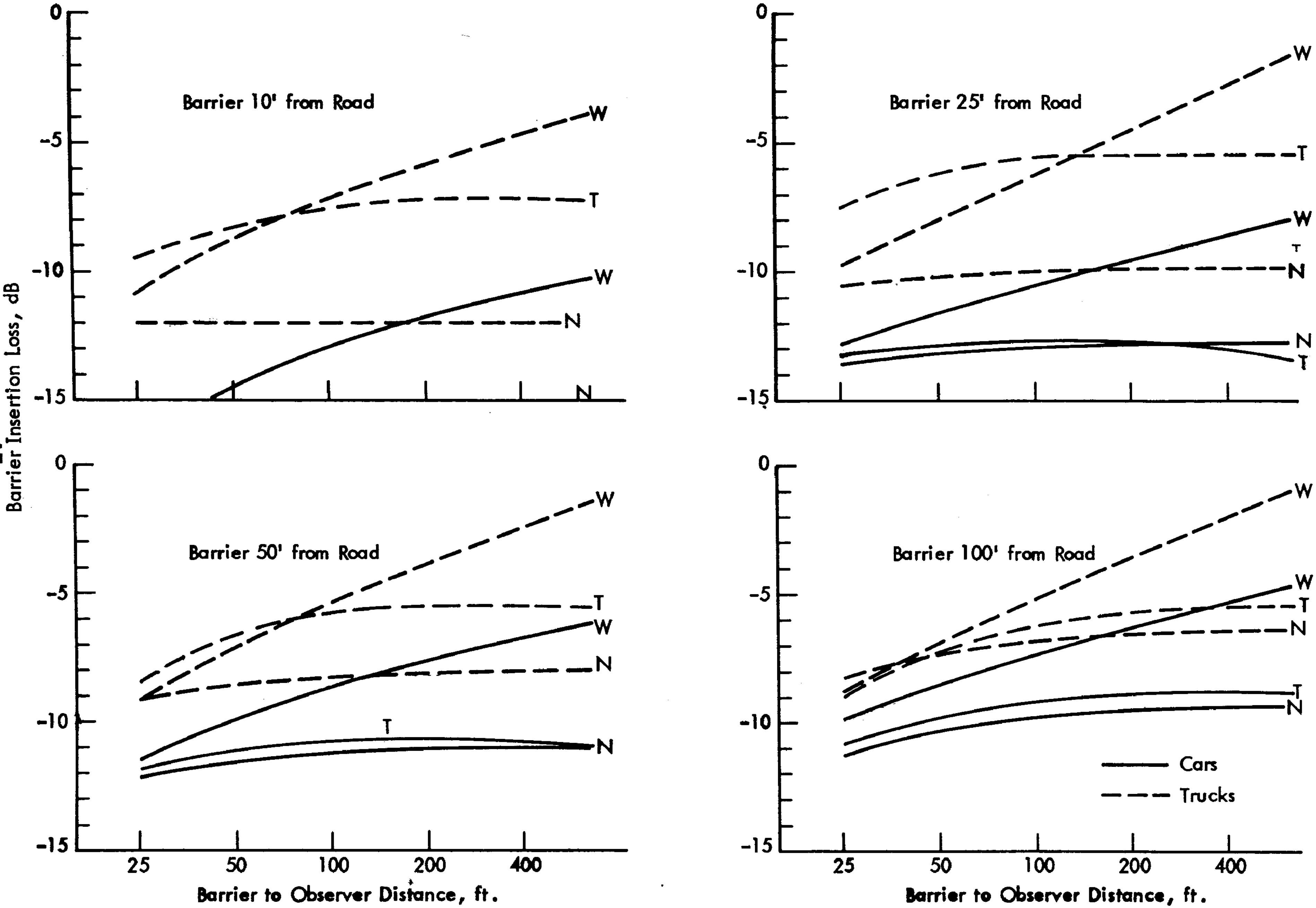

Figure 10. Barrier Insertion Loss, 10-Foot-High Barrier
W = Wyle T = TSC N = NCHRP

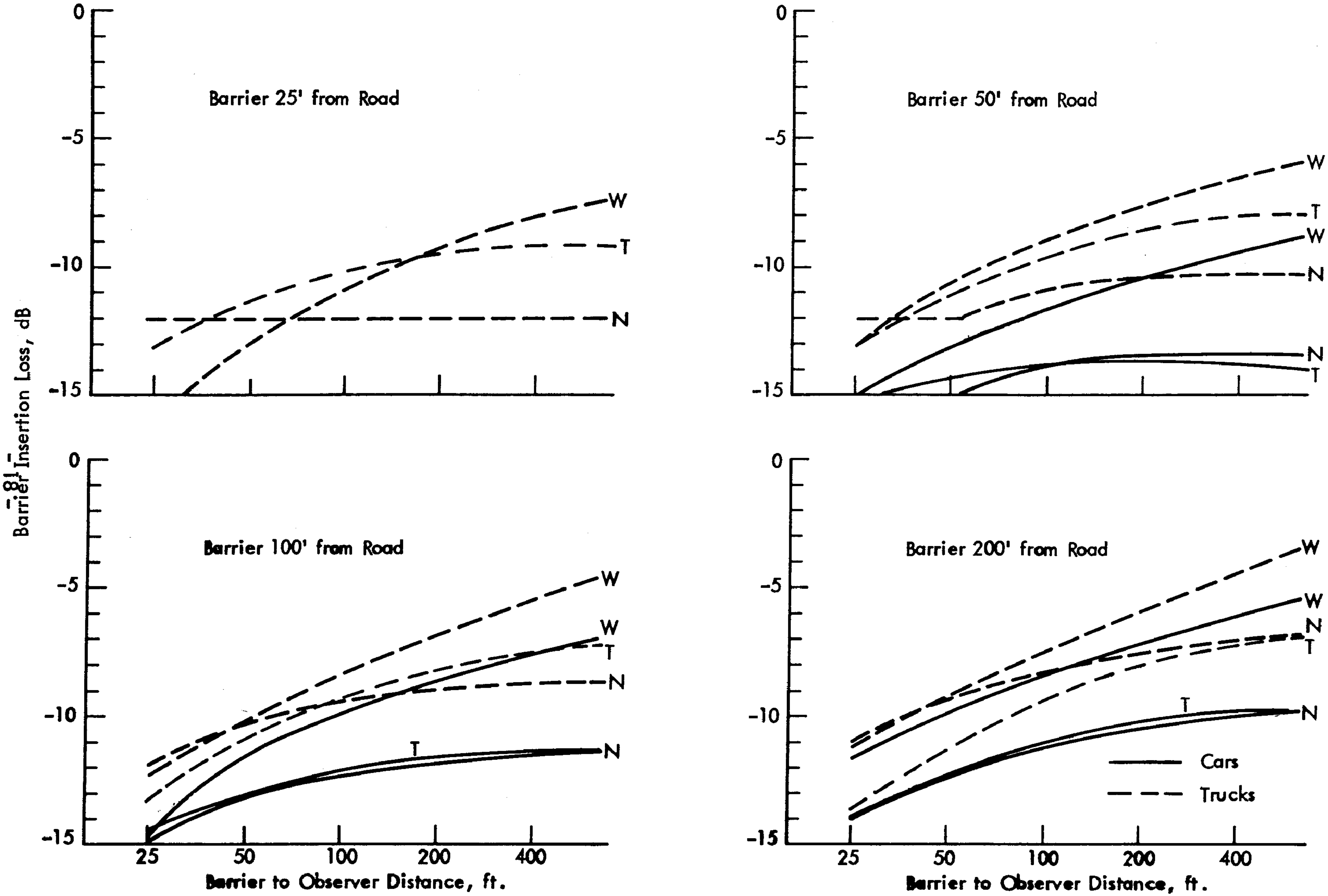

Figure 11. Barrier Insertion Loss, 15-Foot-High Barrier
W = Wyle T = TSC N = NCHRP

Wyle. Figure 12 shows the finite length adjustment used in the Wyle model. It represents the difference between a symmetric finite road within an included angle $\pm\theta$ and an infinite road. By reason of symmetry, the figure also represents the difference between a semi-infinite road and one from 0° to θ. It is possible by a series of steps to obtain from this figure the adjustment for shielding of a central portion of a road; instructions are given in Reference 6. Figure 12 was obtained by integrating a finite line source with 1 dB/doubling excess attenuation.

TSC. The TSC model considers the adjustment for a finite road element to be:

$$\Delta L = 10 \log_{10} \theta/180^{\circ} \qquad (5)$$

where θ is the total included angle between observer and road element ends. This result is obtained by integrating a finite line source with no excess attenuation. The use of Equation (5) tends to overestimate the noise contribution of distant road elements. The program does compute propagation losses individually for each road element (based on the nearest distance for each) so that the results are not always exactly as Equation (5) would give. This depends, however, on exactly how the road is defined in terms of separate elements.

NCHRP. The finite element adjustment is based on Equation (5).

Figure 12 also compares Equation (5) with the Wyle adjustment for finite length roads. Note that the Wyle adjustment becomes negligibly small at smaller angles than Equation (5); since the length of the corresponding road element is proportional to tan θ, much smaller road lengths are involved. Only a relatively short segment of road need be accounted for in detail to obtain accurate predictions. This is an important result, and leads directly to the much simpler structure of the Wyle model as compared to the others.

2.7 Finite Barriers

Cases of finite barriers are divided into shielded and unshielded elements, and the finite road adjustment (discussed above) used to compute the noise contribution for each. Due to differences noted above, the TSC and NCHRP models tend to underestimate the effectiveness of a finite barrier, relative to the Wyle model. For the TSC model, this depends to some degree on the specified road geometry.

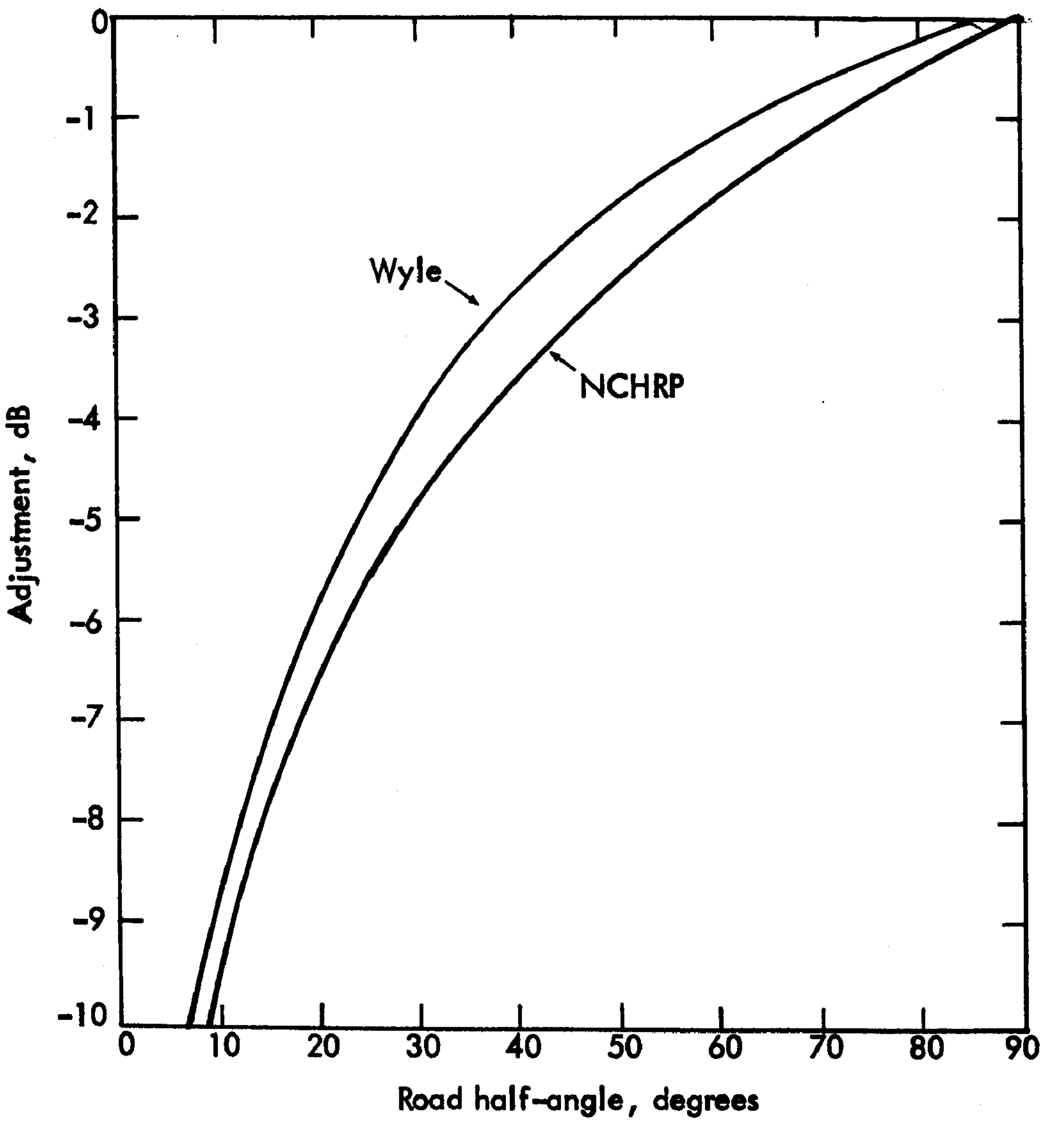

Figure 12. Adjustment for Finite Road Elements

2.8 Miscellaneous Adjustments

Table I lists various other adjustments considered in the three models. Most of these are based on limited data, so it is not possible to offer more than general comments on their accuracy. Subjective judgments are required for application of the road surface and dense tree correction in NCHRP. The NCHRP roadside structure adjustment is intended for detached houses; connected row houses could be treated as a barrier, but no quantitative criteria is given for when to do so. The Wyle and TSC roadside structure approaches are probably inadequate for detached houses.

2.9 Combination of Sources

All three models combine noise from separate sources by decibel addition. For L_{eq} this is the correct approach and is, in fact, one of the major computational advantages of L_{eq}. Combinations of levels expressed in terms of the statistical metrics requires knowledge of the full temporal distributions. The combination of separate sources even with Gaussian distributions is far from trivial. Nelson[18] provides a simplified procedure for combining such distributions.

The TSC model includes a mathematically sophisticated approach to obtain statistical metrics. Quantities called "cumulants" are computed for each source element, based on a theoretical model of randomly spaced equal vehicles.[19] Cumulants have the property of being additive, and are related to the distribution. The cumulants for separate sources are simply added to give the cumulants for the total noise; the temporal distribution of the total noise may then be obtained. In this way the total L_{eq} can be converted to other metrics. The approach has the disadvantage of being somewhat complicated. Also, a number of physically questionable assumptions are made to make the calculation tractable. These assumptions are also included in the calculation for a single road. Since a Gaussian distribution is usually adequate to relate L_{eq} to L_{10},[20] the TSC approach offers little practical benefit, and may even be a disadvantage. This is especially true when the assumptions in the cumulant analysis introduce errors larger than present when empirical data such as Johnson and Saunders relation for σ are used to fit a Gaussian distribution. In Reference 20 it is shown that measured values of $L_{10} - L_{eq}$ are generally within a few tenths of a dB of that predicted from Johnson and Saunders relation.

TABLE I

Miscellaneous Adjustments

	WYLE	NCHRP	TSC
STOP-GO TRAFFIC	+2 to 4 dB*	Up to +4 dB	----
GRADES	Up to +2 dB (Trucks Only)	Up to +5 dB (Trucks Only)	----
ROAD SURFACE	----	±5 dB for Very Rough or Very Smooth	----
ROADSIDE STRUCTURES	Treat as Barriers	-4.5 dB for First Row of Houses, -1.5 dB for Each Additional, Up to -10 dB Maximum	Treat as Barriers
DENSE TREES	No Correction	-5 dB/100 Ft., Up to -10 dB Maximum	Included in Propagation Corrections
REFLECTIONS	----	----	Up to 3 dB per Reflecting Surface

* Preliminary. See Reference 25, Appendix A

The NCHRP model makes no attempt to correctly combine statistical levels. In fact, for a highway with automobile and truck traffic, L_{10} is computed separately for automobiles and trucks, and the two combined by decibel addition. This step is mathematically incorrect. It is only because highway noise distributions are similar over a wide range of conditions, and because of empirical corrections built into the NCHRP model, that the final results are often correct. Even if it is argued that L_{10} is a more accurate measure of annoyance than L_{eq}, the benefit is clearly negated by the gross oversimplification in the NCHRP method of obtaining L_{10}. (It should be recalled that the basic NCHRP expression for L_{50}, which is subsequently corrected to L_{10}, is based on an oversimplified model for traffic which assumes uniform spacing of identical vehicles.)

2.10 Conversion Between Models

It may sometimes be necessary to convert predictions obtained from one model into those which would have been obtained with another. This can be to determine how great a difference exists in a specific case, or it may be necessary to check predictions originally made with a different model. This latter case often occurs in the review of environmental impact statements, where the preparing agency and the reviewing agency may use different models.

Differences between the various curves in Figures 5 through 7 and 9 through 12 provide a basis for an approximate conversion from one model to the other. The procedure is:

1. From Figure 5, obtain the difference due to vehicle noise levels. This accounts for different speed and traffic mix behavior of the three models.

2. From Figure 6, obtain the difference due to propagation. Note that only limiting cases are shown here for the TSC model. For cases of partial ground cover, the TSC propagation loss must be either interpolated or estimated from the discussion in Section 2.3.

3. From Figure 7, obtain the difference due to different road width corrections.

4. Estimate barrier differences using Figures 9, 10 and 11. The procedure is to take the height closest to the actual barrier height, then find the shielding

differences corresponding to the nearest lane and the farthest lane. Some interpolation will usually be necessary. The difference is the average of these two differences.

5. For unshielded finite roads, obtain the finite road difference from Figure 12.

In each of the above steps, the sign of the difference should be clear from the figure and previous discussion. The final conversion is the sum of all differences.

3.0 COMPARISON OF MEASUREMENTS AND PREDICTIONS

The three models have been used to predict levels for thirteen well-documented measurement sites. Measurements at eight sites, numbered 1 through 8, were conducted by Wyle Research. All of these sites are in Southern California, in the area between Los Angeles and San Diego. These sites were straight level and unobstructed freeways and arterials. Road geometry and microphone positions are given in Table II. Five sites, numbered 9 through 13, are from Reference 2 and represent various elevated, depressed, and shielded configurations. Geometries are given in Figures 13 through 17. These thirteen sites include eighty separate measurements at various traffic flow, mix, and receiver distances.

Predictions were made from the three models. The TSC predictions were made from the computer program presented in Reference 3. The NCHRP predictions were made from the batch version of the Michigan computer version of the NCHRP model.[21,22] This program purportedly is equivalent to the method of References 1 and 2, but apparently contains some undocumented differences. NCHRP predictions for Sites 1-8 were also made with the charts in References 1 and 2. The Wyle predictions were made using the nomogram method of the Wyle model.[6]

Table III shows the measured and predicted sound levels. Differences between predictions for the three models are in general consistent with the differences noted in Section 2.0. General trends are difficult to identify because all factors are combined. In order to formally assess the accuracy of the three models, statistical comparisons between measured and predicted values have been performed. Table IV shows the 90 percent confidence intervals for the differences between predictions and measurements of L_{eq}. A positive value indicates a predicted level greater than measured. Also shown is the standard deviation, σ, for each model. The confidence limits are illustrated in Figure 18.

The Wyle model has the best agreement in terms of the standard deviation and the 90 percent confidence interval about the mean. The corresponding quantities for the other two models are not significantly worse, however. It would not be reasonable on the basis of standard deviation and confidence interval to select one model as being better than the others. The NCHRP model has almost zero average deviation, while

TABLE II.

Geometry of Sites 1-8

SITE	1	2	3	4	5	6	7	8
No. of Lanes	6	6	8	2	8	2	2	4
Highway Type	Arter.	Arter.	Frwy.	Arter.	Frwy.	Arter.	Arter.	Arter.
Median Width	9	17	46	--	46	--	10	1
Outer Lanes ℄ to ℄ Distance	61	77	130	12	130	13	22	37
	$\frac{M}{W}$ = .31	$\frac{M}{W}$ = .37	$\frac{M}{W}$ = .45					
Inner Lanes ℄ to ℄ distance	19	29	58	--	58	--	--	13
Upgrade, %	--	--	0.046	--	0.010	--	--	0.050
Mic. Distance/Height*	50/4.5	56/4.5	95/2.5	50/4.5	56/1.5	50/0.5	50/2.5	50/1.0
			145/2.5	100/4.5	100/1.5	100/-3.0	100/2.5	100/1.0
			245/2.5	200/4.5	200/1.5	200/-10.5	200/2.5	200/1.0
			445/2.5				360/2.5	400/1.0

All Dimensions for All Sites are in Feet

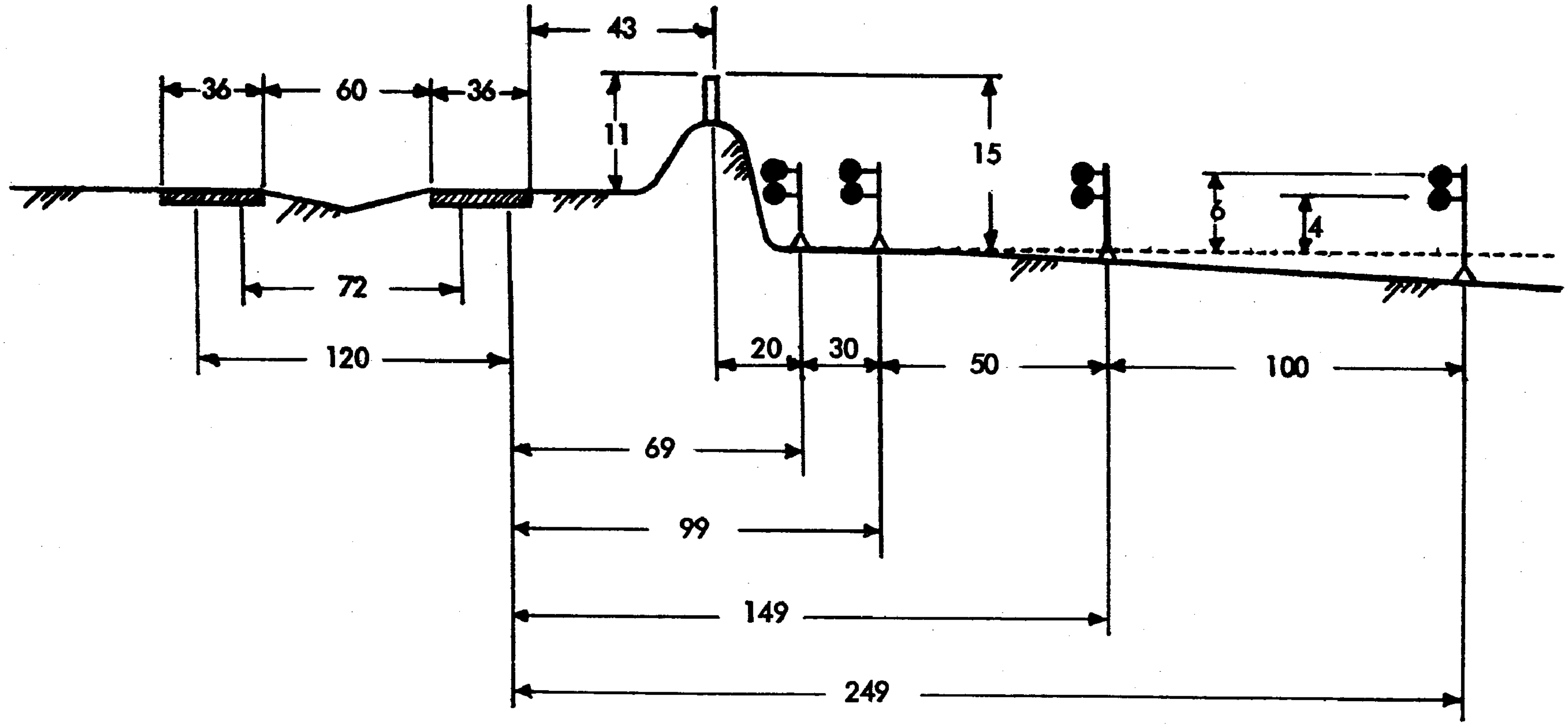

Figure 13. Site 9: Roadside Barrier & Earthmound
6-Lane Freeway

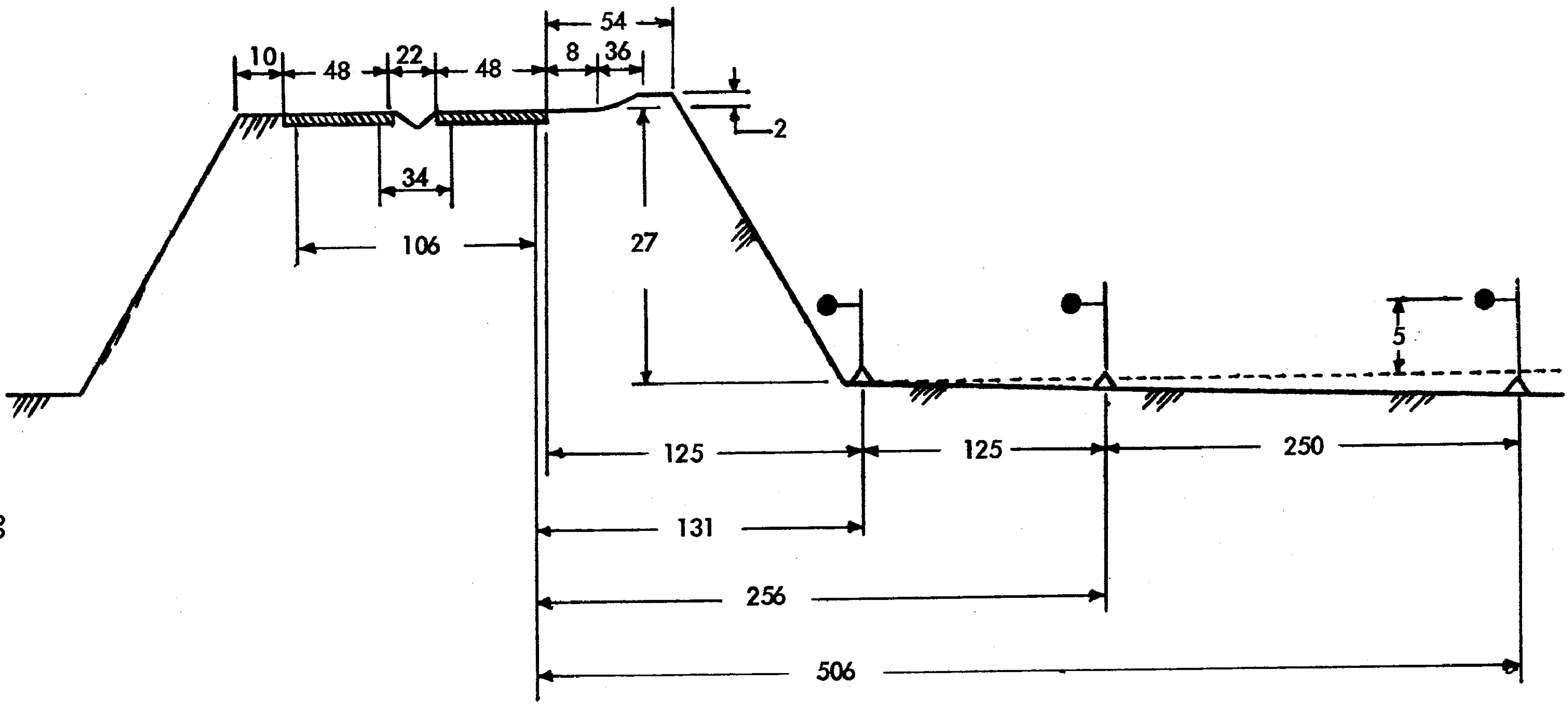

Figure 14. Site 10: Elevated Highway Configuration
8–Lane Freeway

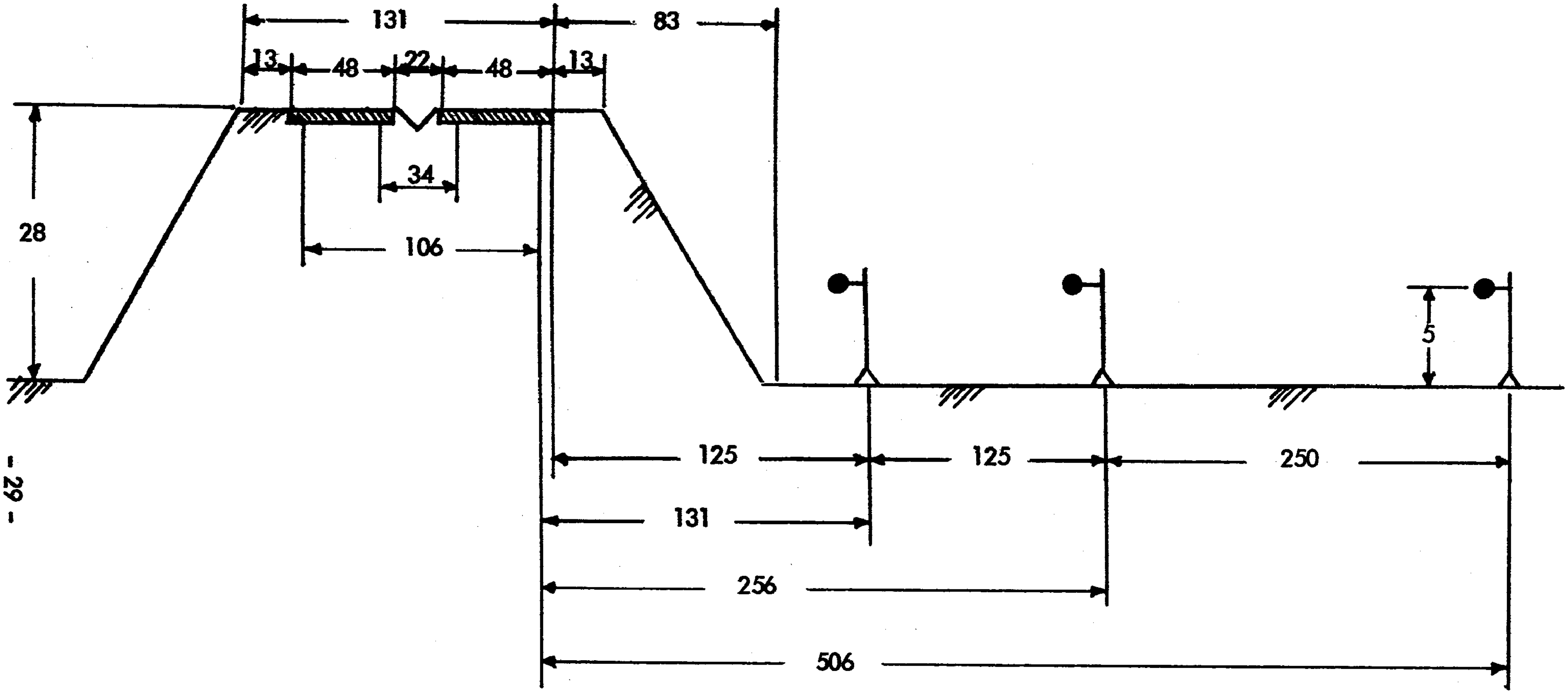

Figure 15. Site 11: Elevated Highway Configuration
8-Lane Freeway

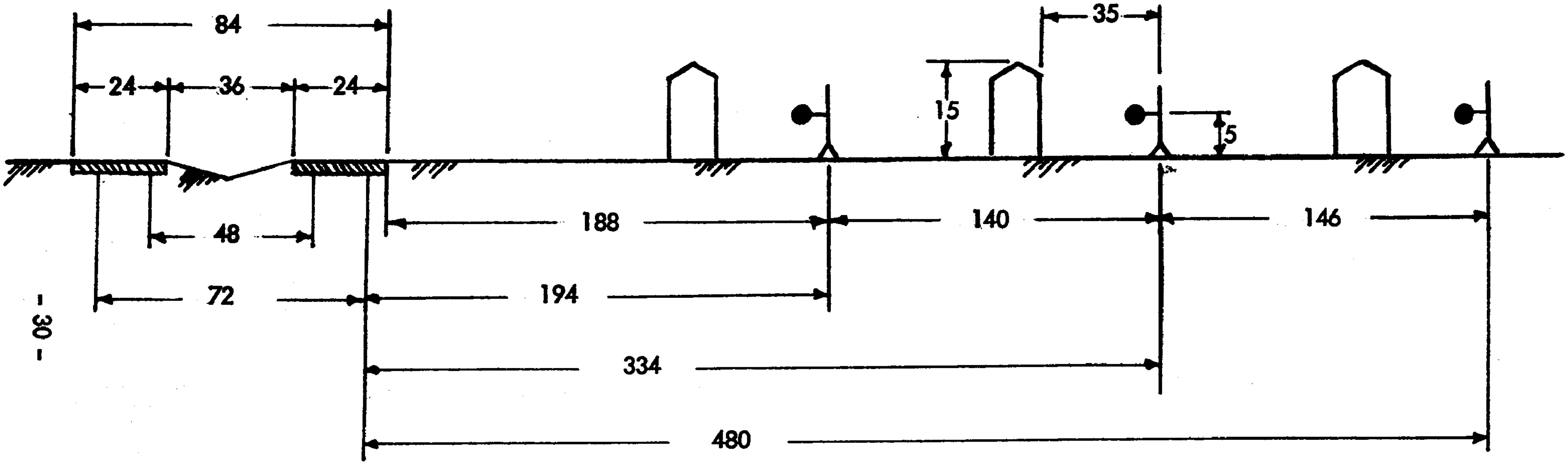

Figure 16. Site 12: Roadside Structures
4-Lane Freeway

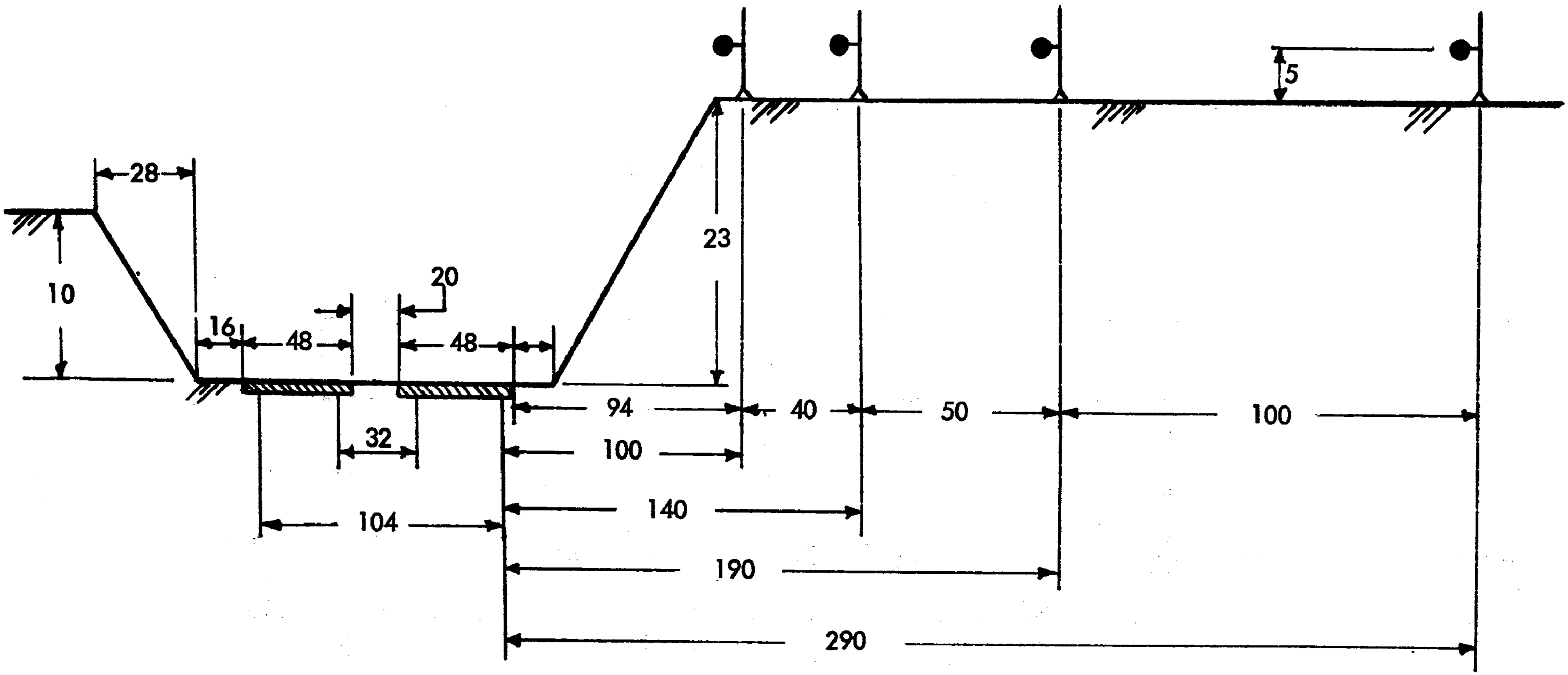

Figure 17. Site 13: Depressed Highway Configuration
8-Lane Freeway

TABLE III.

Comparison of Measurements With Predictions

SITE	HWY TYPE	TRAFFIC FLOW (VEH/HR)	% TRUCKS	MIC. DISTANCE (FT.)	MEAS. L_{eq} (dB)	PREDICTIONS			
						TSC	NCHRP Program	NCHRP Nomogram	Wyle
1	6A	1,557	4%	50	68.9	72.7	70.0	73.0	71.0
2	6A	1,200	11%	56	67.2	75.1	75.0	76.9	72.8
3	8F	5,552	6%	95	71.5	75.0	78.0	74.9	74.2
				145	69.1	73.5	74.0	73.0	72.2
				245	66.6	71.6	70.0	69.2	69.7
				445	62.5	69.0	65.0	65.9	66.3
4	2A	275	4%	50	62.0	66.5	65.0	64.5	63.9
				100	56.8	63.5	----	60.0	59.8
				200	52.4	60.2	----	55.5	55.6
5	8F	5,145	7%	56	73.2	78.7	80.0	78.2	77.4
				100	69.9	76.6	75.0	74.9	74.7
				200	66.9	73.8	70.0	69.8	71.3
6	2A	228	16%	50	68.6	71.2	72.0	72.6	67.5
				100	61.7	68.2	62.0	68.1	63.5
				200	58.5	62.1	56.0	62.8	59.5
7	2A	948	1%	50	59.1	65.2	52.0	66.2	64.3
				100	54.8	62.4	----	61.5	60.8
				200	52.3	59.3	----	56.1	57.1
				360	47.3	57.5	----	51.0	53.5
8	4A	529	3%	50	60.3	68.9	68.0	68.7	65.4
				100	60.0	66.0	62.0	63.0	62.1
				200	55.8	62.9	58.0	57.4	58.4
				400	51.6	59.5	52.0	53.1	54.4
9A	6F	588	2%	99	54.5	52.0	50.0		51.3
				149	51.7	52.2	49.0		52.1
				249	50.2	51.1	43.0		50.7
B		496	2%	99	51.6	52.8	50.0		52.0
C		486	10%	99	53.6	57.9	54.0		54.7
D		456	8%	69	49.3	53.3	51.0		52.8
E		348	8%	99	52.2	58.0	53.0		55.6
				149	51.5	58.0	51.0		55.6
F		492	0%	99	51.2	50.3	51.0		48.8
				149	49.8	50.1	49.0		47.6
				249	49.3	48.6	46.0		45.5
G		618	2%	99	51.2	55.2	51.0		52.8
				149	49.6	55.1	48.0		52.6
				249	49.3	53.5	43.0		50.9
H		522	6%	69	50.6	55.6	54.0		53.4

TABLE III (Cont'd)

SITE	HWY TYPE	TRAFFIC FLOW (VEH/HR)	% TRUCKS	MIC. DISTANCE (FT.)	MEAS. L_{eq} (dB)	PREDICTIONS			
						TSC	NCHRP Program	NCHRP Nomogram	Wyle
10A	8F	13,650	3%	131	60.9	----	73.0		59.2
				256	66.3	----	67.0		61.8
				506	65.5	----	62.0		62.0
B		11,280	3%	131	60.3	77.1	72.0		59.2
				256	62.7	74.5	66.0		61.5
				506	64.8	71.5	61.0		61.7
C		13 140	2%	131	60.0	----	71.0		59.2
				256	62.6	----	66.0		61.6
				506	64.3	----	61.0		61.9
11A	8F	7,440	0.5%	131	61.7	71.7	64.0		59.2
				256	62.4	69.2	61.0		63.0
				506	59.3	66.2	57.0		61.4
B		7,950	1%	131	64.0	72.2	66.0		59.7
				256	64.6	69.5	52.0		65.3
				506	52.0	66.4	58.0		63.6
C		3,090	3%	131	60.4	69.4	64.0		57.4
				256	61.4	66.8	60.0		66.1
				506	59.1	63.8	55.0		63.8
D		6,000	2%	131	62.5	71.7	66.0		59.7
				256	64.6	69.0	61.0		66.6
				506	62.2	65.9	57.0		64.5
E		8,250	3%	131	65.1	73.6	70.0		61.5
				256	65.8	71.0	65.0		70.2
				506	62.7	68.0	60.0		68.0
12A	4F	2,184	17%	194	68.2	----	61.0		63.3
				334	64.5	----	----		63.8
				480	60.6	----	----		62.9
B		2,028	24%	194	64.4	----	62.0		63.7
				334	60.6	----	----		64.5
				480	62.0	----	----		63.7
C		3,054	9%	194	66.1	----	62.0		62.0
				334	63.0	----	----		63.0
				480	62.0	----	----		61.9
13A	8F	6,303	7%	100	75.2	71.7	71.0		77.0
				140	70.8	70.3	62.0		65.4
				190	66.1	69.1	58.0		64.1
B		6,318	9%	290	59.6	68,0	54.0		65.7
C		8,130	8%	100	76.7	73.3	73.0		77.8
				140	71.6	71.9	65.0		66.5
				190	67.0	70.6	60.0		65.2
D		5,772	9%	100	62.1	71.7	72.0		67.4
				290	52.6	67.2	54.0		62.7

TABLE IV

Confidence Limits and Standard Deviations

Model	Mean Difference	90% Confidence Limits		Standard Deviation
		Lower	Upper	
Wyle	1.26	.61	1.90	3.5
TSC	5.50	4.68	6.31	3.9
NCHRP	.01	-1.01	1.04	5.1

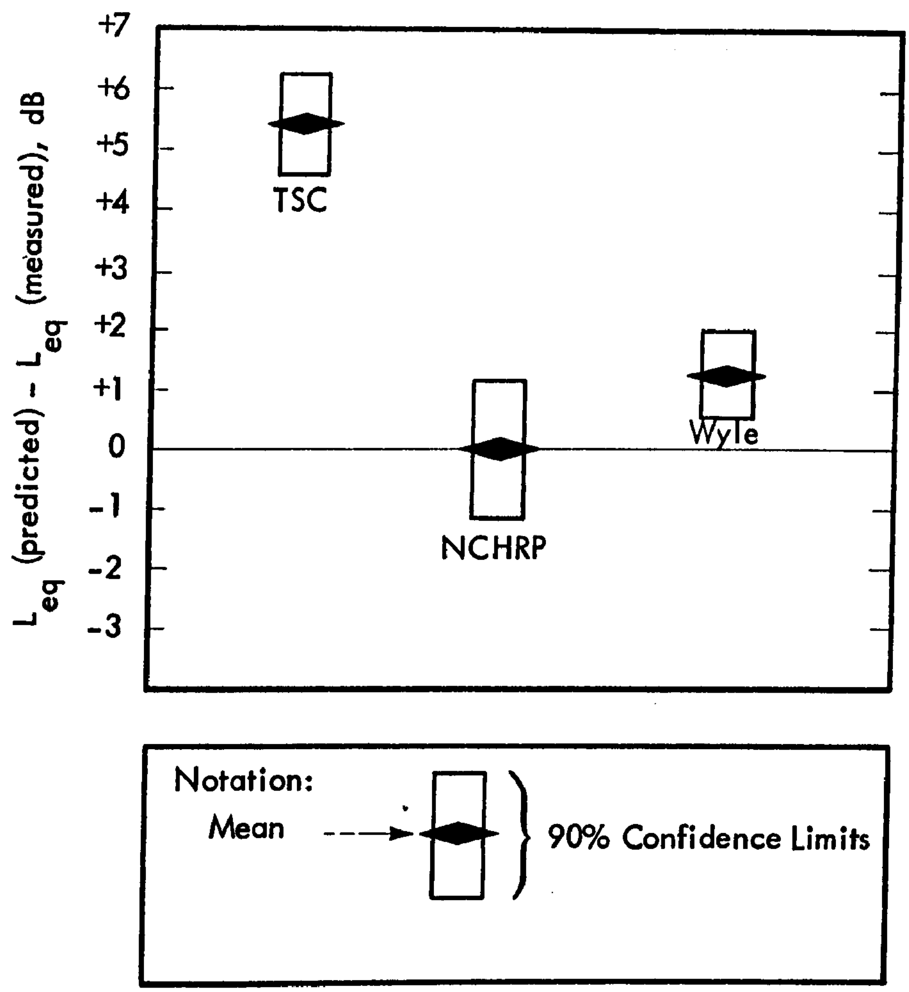

Figure 18. **Comparison of Differences Between Measured and Predicted L_{eq}**

the Wyle model has an average overprediction of about 1 dB and the TSC model has an average overprediction of about 5 dB. These average differences must be considered cautiously, however, because they are to a large degree a function of the particular highway sites considered. The major consideration in comparing the three models must remain the detailed review of Section 2.0.

One serious point to be noted in Table III is that the two versions of NCHRP do not always give the same results. Differences on the order of 1 dB are reasonable because of inherent inaccuracy in reading the charts and because of rounding of computer output. Differences of up to 14 dB occur in some cases, however. In some cases the program would not run, although the chart method could be used. Error messages obtained in these cases did not seem pertinent to the input data.

A similar problem was noted, to a much lesser degree, for the TSC program. It appears that the program uses reasonably correct values of atmospheric absorption, rather than the obsolete values reported in the original documentation. This problem could simply be one of updating documentations.

4.0 CONCLUSIONS

The NCHRP, TSC and Wyle highway noise prediction models have been reviewed and compared. The following conclusions have been reached:

- The Wyle and TSC models predict L_{eq} directly and are based on fundamentally sound theory. The NCHRP model is based on a model which assumes a flow of equally spaced identical vehicles.
- Automobile noise levels in all three models are in reasonable agreement with each other, within a few dB. It would be desirable, however, to obtain more recent automobile data and select one consistent set for all models.
- The TSC and NCHRP models use truck levels based on meager data, and neglect the speed dependence of tire noise. The Wyle model uses truck levels based on several thousand roadside measurements at high and low speeds.
- None of the models handles propagation in an entirely satisfactory way. The TSC model, in particular, uses questionable values for ground attenuation. More research on highway noise propagation must be done.
- All three models use essentially correct diffraction theory for shielding calculations, although intuitive modifications are employed in some cases at high and low shielding. Varying assumptions as to vehicle source heights cause great differences in shielding predictions. None of the models adequately documents source heights used. In view of the sensitivity of shielding calculations to source height, this must be better established.
- Treatment of multiple-lane roads and finite roads is often crudely done, leading to errors of up to several dB. Inadequate consideration of propagation losses adds to this problem.
- Analysis of differences between measurements and predictions, summarized in Table IV, shows the Wyle and NCHRP models to have the most consistent agreement, although none could be said to be entirely satisfactory. Propagation effects and measurement errors are felt to be the greatest source of error.

- Theoretical calculations of L_{10} and other statistical metrics require assumptions which make the usefulness of such calculations questionable. Since adequate empirical data exist to relate L_{eq} to these metrics, there is little need for a highway model to predict other than L_{eq}. Other metrics can be obtained empirically from this measure with an accuracy entirely adequate within the context of annoyance assessment.

A general difficulty with the computer programs — NCHRP in particular and TSC to a lesser degree — is that original versions have been revised through the years, often for cases where it might have been more appropriate to abandon the original method and start again with a sounder approach. An example is the NCHRP model at low volumes. Johnson and Saunders' model is clearly inadequate here, but the approach has been to retain the basic formulation and add an empirical correction factor.[23] A much better approach is employed in the TSC and Wyle models which adopt an L_{eq} formulation initially.

Finally, it should also be noted that a highway model need not be complicated. This review has noted certain areas where detail is not important. These include road width effects at large distances, and distant road elements. Complete detail of these need not be included. The computerized models tend to include too much detail of road geometry, without regard for its importance to accuracy. This situation apparently arises because the use of a computer permits such detailed complications with very little effort on the part of the user. Inclusion of such detail, however, adds little to the accuracy of noise prediction and greatly obscures its simplicity.

REFERENCES

1. Gordon, C.G., Galloway, W.J., Kugler, B.A., and Nelson, D.L., "Highway Noise — A Design Guide for Engineers", NCHRP Report 117 (1971).

2. Kugler, B.A., and Piersol, A.G., "Highway Noise — A Field Evaluation of Traffic Noise Reduction Measures", NCHRP Report 144 (1973).

3. Kurze, U.J., Levison, W.H., and Serben, S., "User's Manual for the Prediction of Road Traffic Noise Computer Programs", DOT-TSC-315-1, May 1972.

4. "Noise Standards and Procedures", Federal Highway Administration PPM 90-2, February 1973.

5. Plotkin, K.J., "A Model for the Prediction of Highway Noise and Assessment of Strategies for Its Abatement Through Vehicle Noise Control", Wyle Research Report WR 74-5, for the Environmental Protection Agency, September 1974.

6. Sharp, B.H., Plotkin, K.J., Glenn, P.K., and Slone, R.M., "A Manual for the Review of Highway Noise Impact", Wyle Research Report WR 76-24, for the Environmental Protection Agency, May 1977. Also EPA Report 550/9-77-356.

7. Plotkin, K.J., "A Case for Simple Highway Noise Models", Paper KK3, 91st Meeting of the Acoustical Society of America, April 1976.

8. Johnson, D.R., and Saunders, E.G., "The Evaluation of Noise from Freely Flowing Road Traffic", Journal of Sound and Vibration, 7, 2, pp. 287-309, 1968.

9. Olson, N., "Statistical Study of Traffic Noise", APS-476, National Research Council of Canada, Division of Physics, 1970.

10. Galloway, W.J., Clark, W.E., and Kerrick, J.S., "Highway Noise Measurement, Simulation, and Mixed Reactions", National Cooperative Highway Research Program Report 78 (1969).

11. Sharp, B.H., "A Survey of Truck Noise Levels and the Effect of Regulations", Wyle Research Report WR 74-8, December 1974.

12. Society of Automotive Engineers, "Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise", ARP 866, August 31, 1964.

13. Ingard, U., "On Sound Transmission Anomalies in the Atmosphere", Journal of the Acoustical Society of America, 45, pp. 1038-1039, 1969.

14. Pao, S.P., "Prediction of Excess Attenuation Spectrum for Natural Ground Cover", Wyle Laboratories Research Staff Report WR 72-3, February 1972.

15. Nelson, P.M., "A Computer Model for Determining the Temporal Distribution of Noise from Road Traffic", TRRL Report LR 611, Environmental Division, Transport Systems Department, Transport and Road Research Laboratory, Crawthorne, Berkshire, 1973.

16. Kurze, U., and Beranek, L.L., "Sound Propagation Outdoors", Noise and Vibration Control, edited by L. L. Beranek, McGraw-Hill, 1971, Chapter 7.

17. Maekawa, Z.E., "Noise Reduction by Screens", Applied Acoustics, 1, pp. 157-173 (1971).

18. Kurze, U., and Anderson, G.S., "Sound Attenuation by Barriers", J. Applied Acoustics, 4, 1, pp. 35-53 (1971).

19. Nelson, P.M., "The Combination of Noise from Separate Time Varying Sources", J. Applied Acoustics, 6, pp. 1-21, 1973.

20. Kurze, U.J., "Noise from Complex Road Traffic", Journal of Sound and Vibration, 19, 2, pp. 167-177, 1971.

21. Plotkin, K.J., "The Assessment of Noise at Community Development Sites. Appendix A — Noise Models", Wyle Research Report WR 75-6, October 1975.

22. Grove, G.H., "Traffic Noise Level Predictor Computer Program", Research Report No. R-942, Michigan State Highway Commission, October 1974.

23. FHWA's User Instruction Manual for Converted Michigan Department of State Highways and Transportation's Traffic Noise Level Predictor Computer Program — Version No. 10 (10/1/74)

24. Kentucky Department of Transportation Bureau of Highways Prediction Procedure Correction Factor Nomograph, FHWA Notice N 6640.5, June 1975.

25. Plotkin, K.J., Kunicki, R.G., and Sharp, B.S., "National Impact of Highway Noise and Effectiveness of Noise Abatement Strategies", Wyle Research Report WR 76-14.

* U.S. GOVERNMENT PRINTING OFFICE : 1977 O-241-037/39