FINAL REPORT

VERIFICATION OF MICNOISE COMPUTER PROGRAM FOR THE PREDICTION OF HIGHWAY NOISE

Part II — Additional Verification of MICNOISE Version 5

by

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ABSTRACT

This is a continuation of an earlier report in which the MICNOISE computer program for the prediction of highway noise was evaluated. The outputs of the MICNOISE program are the L_{50} and L_{10} sound pressure levels, i.e., those levels experienced 50% and 10% of the time.

In the earlier report, it was noted that there were difficulties when truck volumes were low. To overcome these, a modified version was proposed, which is now referred to as MICNOISE 2X.

In this continuation of the earlier report, a new version of MICNOISE, Version 5, is evaluated. Also, an experimental variant, 5X, and a variant proposed by the Virginia Department of Highways and Transportation, 5V, are evaluated. In MICNOISE 5X, the elevation corrections due to trucks are modified as though the truck frequency spectrum were shifted to half the corresponding frequencies for autos. In MICNOISE 5V, truck noise is assumed to originate 13.5 ft. (4.1 m) above the highway, as compared with 8 ft. (2.4 m) for Version 5.

It had been found earlier that for 68% confidence 2 dB should be added to the predicted values of MICNOISE 2X. This is shown to increase to 3 dB for MICNOISE, Version 5, but falls again to 2 dB for MICNOISE 5V. However, results for 5V show greater standard deviations, the 68% confidence band being restored only because it is more conservative than MICNOISE 2X. The reduced accuracy of Version 5 and its variants is attributed to the methods used for handling vertical corrections.

It is concluded that MICNOISE 5V is acceptable, but that the earlier methods of elevation correction are preferable

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INTRODUCTION

The Virginia Department of Highways and Transportation has received several versions of the Michigan/117 and Michigan/144 time-sharing computer programs from the Michigan Department of State Highways and Transportation. Most of these have been converted to batch processing format and have been made available to IBM 360 users. During 1973, the Virginia Highway and Transportation Research Council initiated a study to verify these computer programs.

The original report,[1] of which this is Part II, presents the results of a verification of the MICNOISE Version 2 computer program, which is based on the recommendations of NCHRP Reports No. 117 and 144.[2,3] Because there were some obvious areas for improvement to the original program a so-called "modified MICNOISE" computer program, in which these improvements were included, was also evaluated.

At the time of writing the original report, it was believed that the forthcoming MICNOISE Version 5 would be virtually identical to the modified MICNOISE program. Therefore, premature conclusions about the accuracy of Version 5 were drawn in the original report. However, when Version 5 became available, it was found that changes suggested in NCHRP Report No. 144 had been made in the treatment of vertical (i.e., elevated or depressed roads) and barrier corrections, which have resulted in some lack of conservatism, so that predictions of noise levels tend to be somewhat lower than those made by the modified MICNOISE program.

In this report, Part II, the effects of the vertical corrections have been evaluated in some detail. For brevity, Version 2 is referred to as MICNOISE 2, the modified MICNOISE program is referred to as MICNOISE 2X, Version 5 is referred to as MICNOISE 5, and an experimental modification of 5, which is described later, is referred to as MICNOISE 5X. A version proposed by the Virginia Department of Highways and Transportation is referred to as MICNOISE 5V. In this version, truck noise is assumed to originate 13.5 feet(4.1 m) above the ground, whereas in Version 5 it is assumed to originate 8 feet (2.4 m) above the ground.

For 68% confidence, it was found necessary to add 2 dB to predictions made with MICNOISE 2X. This increased to 3 dB for MICNOISE 5, but becomes 2 dB again for MICNOISE 5V. However, the standard deviation of the error is greater for MICNOISE 5V than for MICNOISE 2X. Therefore, it is concluded that, although MICNOISE 5V is perfectly acceptable, the earlier method of computing vertical corrections used in MICNOISE 2 and 2X is preferable.

OBJECTIVES

The primary objective of this study was to evaluate MICNOISE 5, and the slightly modified version, MICNOISE 5V.

Because it was found that neither version gave such good predictions as did the earlier MICNOISE 2X, considerable emphasis was placed on an evaluation of the vertical corrections used, since these represented the major difference between Versions 2 and 5.

During this study, the experimental MICNOISE 5X was investigated, in the belief that it might give better results than MICNOISE 5. However, the improvement of the vertical correction method was never made an objective of this study.

DESCRIPTION OF MICNOISE 5 COMPUTER PROGRAM

In the original report, a listing of MICNOISE 2 was given, and the algorithm used was compared in some detail with that of NCHRP Report No. 117. Features of MICNOISE 2X (or modified MICNOISE) were discussed, and possible changes to be incorporated into MICNOISE 5 were indicated.

MICNOISE 5 is listed in Appendix A of this Part II of the report. It is based on NCHRP Report No. 144 and is similar to the MICNOISE 5V program proposed by the Virginia Department of Highways and Transportation, with the sole exception that truck noise in version 5V originates at 13.5 feet (4.1 m) above the road surface, as compared with 8 feet (2.4 m) for version 5.

Altogether, six programs are involved in this study. Some are only minor variations of others, but MICNOISE 5 is a major revision of MICNOISE 2, even though the computer results are not greatly different. To avoid lengthy and unnecessary discussions, only the essential differences between MICNOISE 2X, 5, 5X and 5V are covered below.

Input Format

The input format for MICNOISE 5 is different from that for MICNOISE 2, as is indicated by the comparison given in Table 1. For the purpose of this evaluation, in which a card input for MICNOISE 2 had already been prepared, a preprocessor was programmed to convert the Version 2 input to Version 5 format.

Table 1

Comparison of Input Data. MICNOISE 2 & 5.

(Note: All data input in English units, the program is not compatible for SI units)

MICNOISE 2			MICNOISE 5		
No.	Symbol	Description	No.	Symbol	Description
1	REN	No. of Road Els.	1	REN*	
2	NLG	No. of Lane Grps.	2	NLG*	
3	ADT	Avg. Daily Tr.	3	Q	Vehicles Per Hour
4	PCADT	% ADT per hr.			
5	TMIX	% Trucks	4	TMIX*	
6	ST	Truck Sp. (mph)	5	ST*	
7	SA	Auto Sp. (mph)	6	SA*	
8	HD	Road Elev. Type	7	HE	Roadway Elev. (ft.)
9	DN	Obs. to Road (ft.)	8	DN*	
10	RL	Road Length Type	9	RL*	(= 0, 1 or 2)
11	BL	Barr. Length Type	10	BL*	(= 0, 1 or 2)
12	FLO	Traffic Flow			
13	P	No. of Lanes	11	P*	
14	DEL3	Grade Corr.	12	DEL3*	
15	DEL5	Road Surf. Corr.	13	DEL5*	
16	DEL7	Struc. Corr.	14	DEL7*	
17	MED	Median Width (ft.)	15	MED*	
18	THETA	Road Incl. Angle	16	THETA*	
19	H1	Road Elev. (ft.)	17	HO	Obs. Ht. (ft.)
20	DS	Obs. Shoulder (ft.)	18	DS*	
21	H2	Road Depress. (ft.)			
22	DC	Obs. to Cut (ft.)	19	DC*	
23	H	Barrier Ht. (ft.)	20	H*	
24	DB	Obs. to Barr. (ft.)	21	DB*	
25	ALPHA	Barr. Incl. Angle	22	ALPHA*	
26	HO	Obs. Ht. (ft.)	23	BETA	Barrier End Angle

*No change from corresponding MICNOISE 2 item which is on same line.

Correction for L_{10}

The values of $L_{10} - L_{50}$ used in MICNOISE 2 and 5 are shown in Figure 1 as curves plotted against the parameter VD/S, which has units of vehicle ft/mile (0.1894 vehicle m/km). There is a small difference between the two curves, however a careful examination of the results of the evaluation reported here showed that the effects of this difference were of little consequence.

Vertical Corrections

The corrections for elevated or depressed highways and barriers are shown in Figures 2, 3, and 4. Figure 2 shows the corrections for MICNOISE 2X, which are identical to those given in the original report. Figure 3 shows the corrections for MICNOISE 5, which are based on the recommendations of NCHRP Report No. 144. In this application, one curve is used for all cases, but, in place of the 5 dB reduction for trucks, each truck is analyzed as though its principal noise source were eight feet (2.4 m) above the road in MICNOISE 5 and 13.5 feet (4.5 m) in MICNOISE 5V. Figure 4 shows the trial correction used for MICNOISE 5X, in which the curve for trucks was shifted to the right as though the frequency of noise from a truck were half that from an automobile. This correction was made on a trial basis, because it was felt that a more realistic prediction of the effects of acoustical barriers on trucks would result if the relatively lower frequency of sound from trucks were taken into account. In MICNOISE 5, overall corrections for finite roads and barriers stay almost the same as in MICNOISE 2, however, these corrections were not evaluated.

Miscellaneous Changes

In programming MICNOISE 5 several minor changes and improvements were made over MICNOISE 2. Amongst these changes were:

1. A test for line-of-sight conditions was introduced to eliminate incorrect application of vertical corrections in such cases.

2. Handling of elevation coordinates in vertical corrections was simplified by referring all elevations to one reference plane, (the roadway elevation, HE, given in Table 1). (With small modifications, the program could take care of a combination of elevation and barrier corrections.)

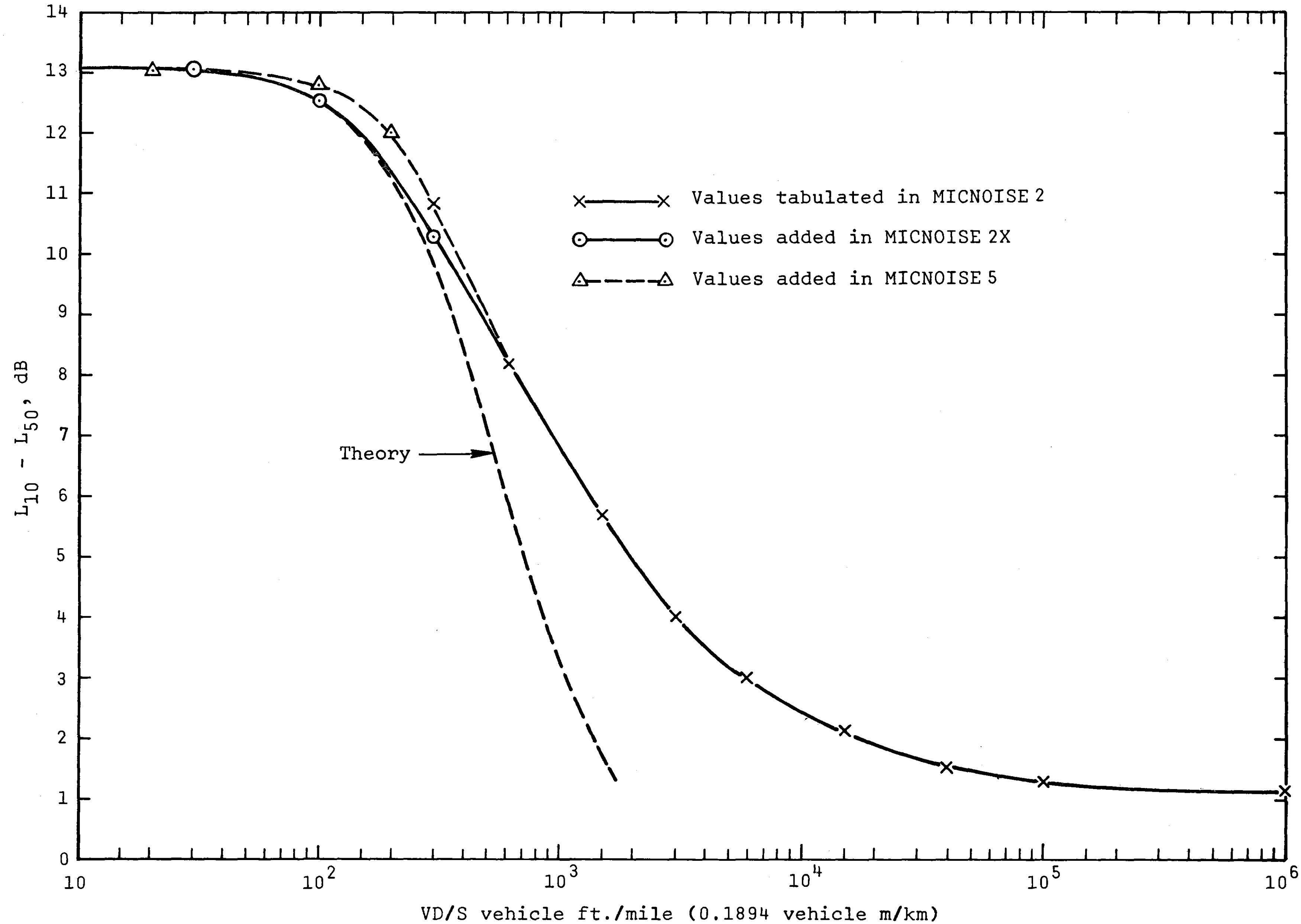


Figure 1. Values of L_{10} - L_{50} vs. vehicle spacing.

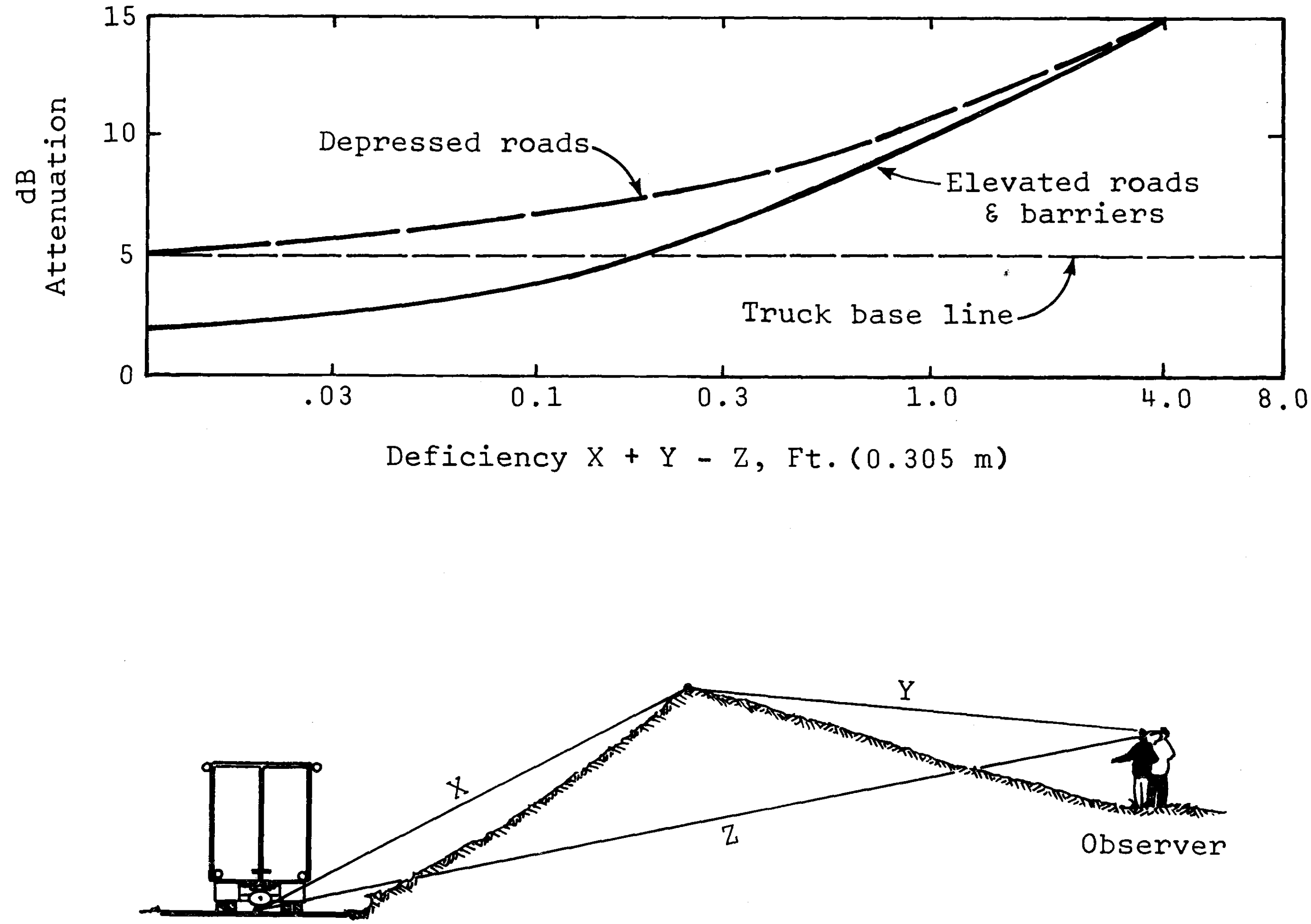
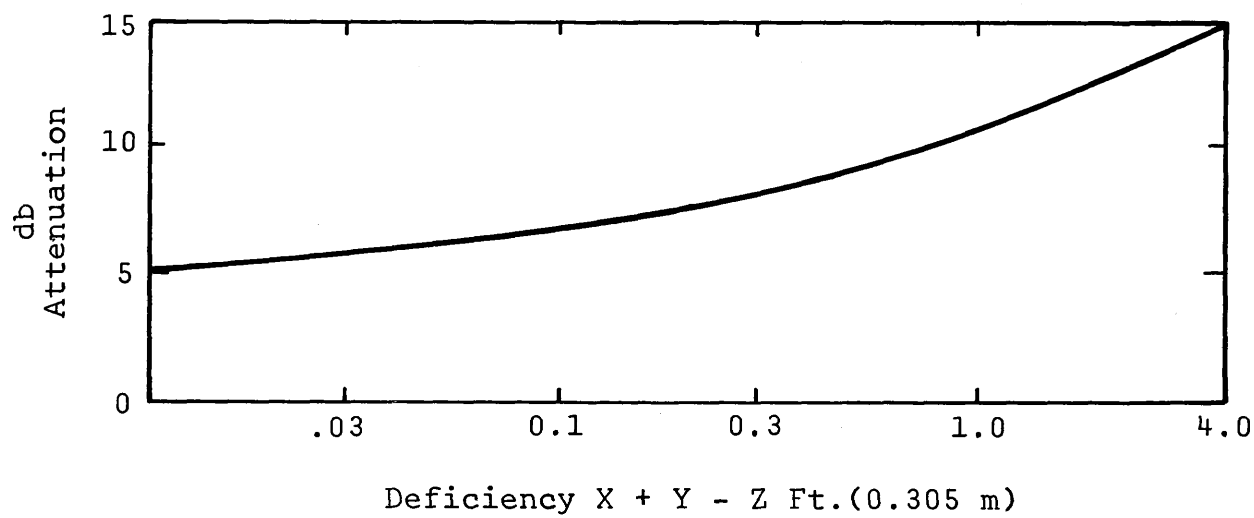


Figure 2. Vertical corrections in MICNOISE 2X.



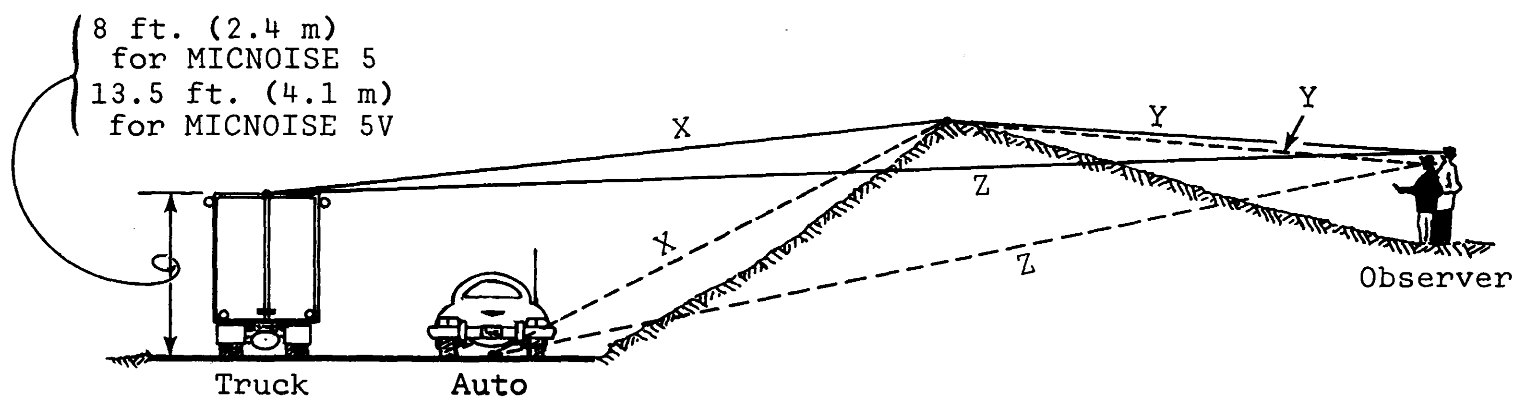


Figure 3. Vertical corrections in MICNOISE 5 & 5V.

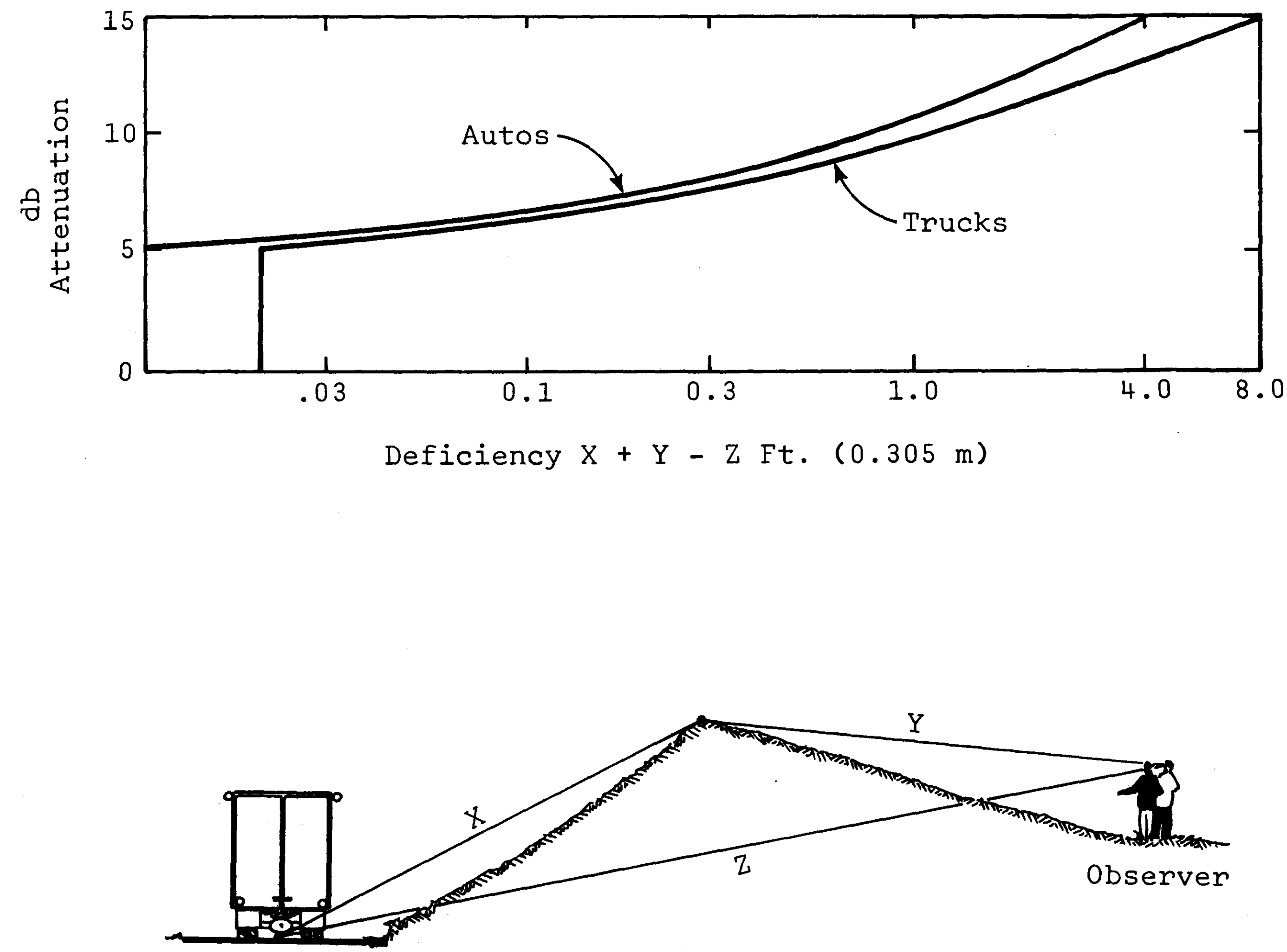


Figure 4. Vertical corrections in MICNOISE 5X.

EVALUATION OF COMPUTED NOISE LEVELS

The computed noise levels from MICNOISE 2X are given in Tables B-1 through B-5 of Appendix B. These are identical to the values given for "Modified MICNOISE" in Tables A-28 through A-32 of the original report. Using a preprocessor to convert the Version 2 input to Version 5 format, as detailed in Table 1, noise levels were computed from MICNOISE 5, 5X and 5V, and are given in Tables B-6 through B-20 of Appendix B. Statistical analyses of the computed results for MICNOISE 2X, 5, and 5V are given in Table 2 using the same format as in Table 9 of the original report. The 68% confidence limits, that is, the mean value plus and minus one standard deviation, are also shown in Figure 5 for each of the L_{10} and L_{50} values given in Table 9. Remembering that a negative error represents underprediction of the actual noise level, and is therefore unconservative, it will be noted that MICNOISE 5 is somewhat unconservative with respect to MICNOISE 2X, with MICNOISE 5V showing some improvement, and falling between the two. However, standard deviations for the Version 5 programs are somewhat larger than for Version 2, the improvement in MICNOISE 5V being due to greater conservatism in the mean value.

Present requirements are that L_{10} not exceed 70 dB, so consider here errors in L_{10} only. According to Table 2, the lower 68% confidence limits on MICNOISE 2X, 5 and 5V are -2.10, -3.06, and -2.68 respectively. If 2 dB were added to the MICNOISE 2X predictions, the lower 68% confidence limits on error would be 0 dB or above to the nearest decibel. However, it would be necessary to add 3 dB to the MICNOISE 5 predictions to achieve the same results. With MICNOISE 5V, the error for site 5 would be below 0 dB (actually -0.68 dB) if 2 dB were added, but would be 0 dB or better for the other sites. To find the 95 and 99% confidence limits two and three standard deviations are subtracted, from the mean, respectively. Examining the values given in Table 2 for MICNOISE 2X, one sees that these correspond to lower confidence limits of -3.85 and -5.6 dB, therefore, to the nearest decibel, 2, 4 and 6 dB must be added to predicted levels for 68, 95 and 99% confidence respectively. However, standard deviations for MICNOISE 5 and 5V are larger, in general, than for MICNOISE 2X, so that in some cases, larger increments must be added to the Version 5 results, for a given degree of confidence.

Because the changes have evidently resulted from changes in the method of computing vertical corrections, the accuracy of vertical corrections has been studied in more detail, as reported in the following sections.

Table 2

Errors in Noise Levels Computed by MICNOISE 2X, 5, and 5V

Site #	1			2		3			4			5		
No. of Recordings	13[a]			12		6[b]			7			8[c]		
MICNOISE Variant	2X	5	5V	2X	5 & 5V	2X	5	5V	2X	5	5V	2X	5	5V
L_{50} Mean Error	0.20	-0.98	- .68	0	0	0.25	-1.52	.22	3.46	3.73	4.57	0.70	0.80	1.06
RMS Error	1.33	1.72	1.40	1.15	1.15	1.74	2.76	1.86	4.01	4.45	5.03	1.50	2.26	2.22
Standard Deviation	1.36	1.47	1.27	1.20	1.20	1.87	2.52	2.02	2.19	2.62	2.27	1.42	2.26	2.08
68% Confidence Range	-1.16	-2.45	-1.95	-1.20	-1.20	-1.62	-4.04	-1.8	1.27	1.11	2.3	-0.72	-1.46	-1.02
	1.56	0.49	.59	1.20	1.20	2.12	1.00	2.24	5.65	6.35	6.84	2.12	3.06	3.14
L_{10} Mean Error	0.32	-0.90	-0.39	0.49	0.57	0.77	-0.05	1.90	4.10	4.84	5.97	-0.35	0.24	0.40
RMS Error	1.60	1.73	1.45	1.00	1.06	2.56	2.75	3.36	4.91	5.81	7.26	1.68	2.92	2.91
Standard Deviation	1.62	1.54	1.45	0.91	0.93	2.67	3.01	2.99	2.90	3.47	4.46	1.75	3.11	3.08
68% Confidence Range	-1.30	-2.44	-1.84	-0.42	-0.36	-1.90	-3.06	-1.09	1.2	1.37	1.51	-2.10	-2.87	-2.68
	1.94	0.64	1.06	1.40	1.50	3.44	2.96	4.89	7.0	8.31	10.43	1.40	3.35	3.48
$L_{10}-L_{50}$														
Mean Error	0.12	0.08	.29	0.50	0.57	0.52	1.47	1.68	0.64	1.11	1.40	-1.05	-0.56	-0.66
RMS Error	0.78	0.79	.84	0.92	1.01	1.25	1.75	2.12	3.54	3.68	4.06	1.91	1.86	1.85
Standard Deviation	0.80	0.82	.82	0.82	.87	1.25	1.04	1.42	3.76	3.79	4.12	1.71	1.90	1.85
68% Confidence Range	-0.68	-0.74	- .53	-0.32	-0.30	-0.73	0.43	0.26	-3.12	-2.68	-2.72	-2.76	-2.46	-2.51
	0.92	0.90	1.11	1.32	1.44	1.77	2.51	3.10	4.40	4.90	5.52	0.66	1.34	1.19

(a) The three records taken on a slope at 106 feet (32 m) were not included.
(b) Trial number 1 was excluded. Therefore, results are not the same as those given in Ref. 1.
(c) The predicted noise of trucks on the side road was deleted for trial number 1.

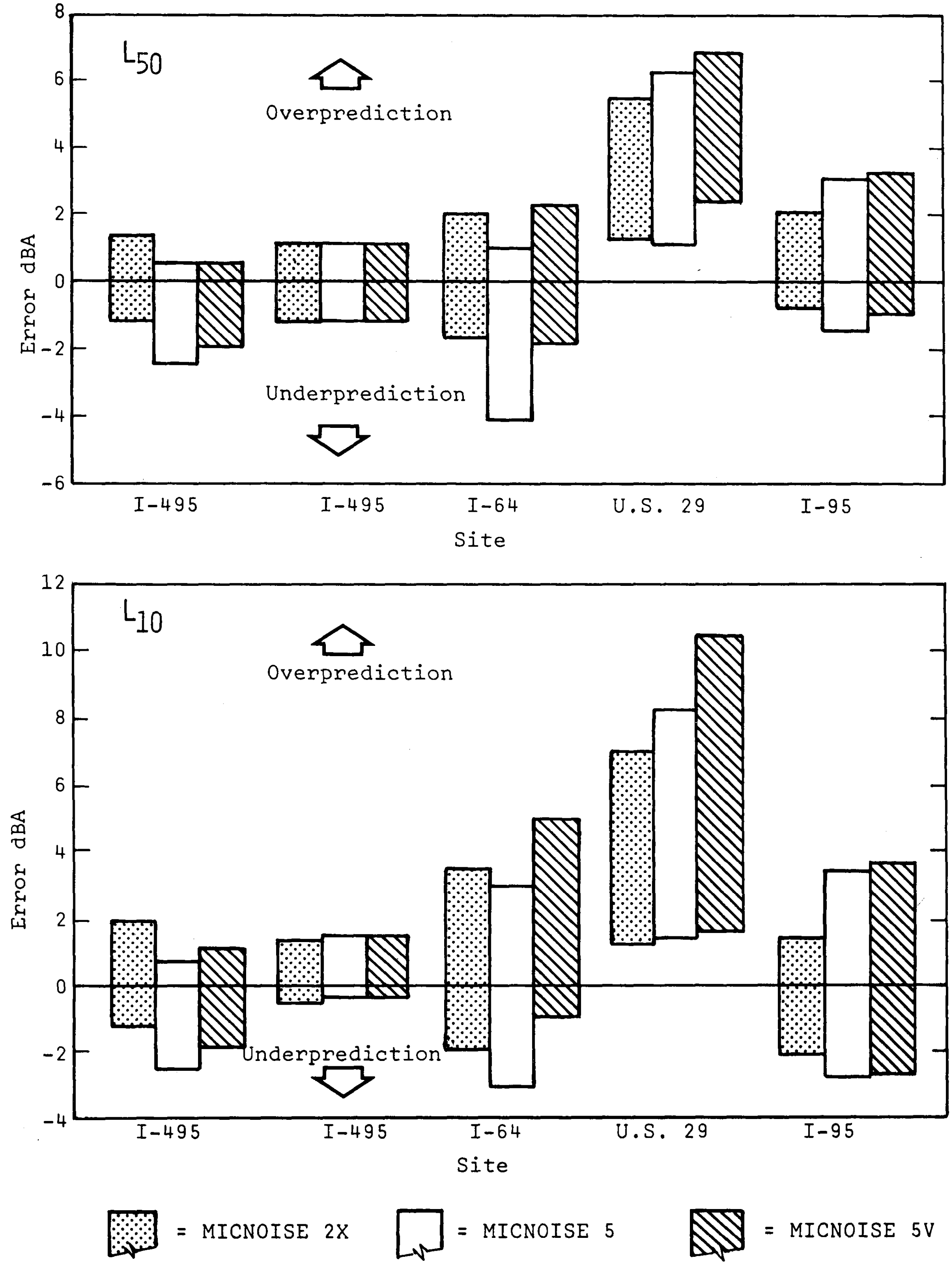


Figure 5. 68% confidence levels with three versions of MICNOISE.

ANALYSIS OF VERTICAL CORRECTION ERRORS

In planning the original program of roadside measurements, it was decided that all recordings should be made in pairs, with one microphone at a fixed location.

Out of a total of 26 trials, there was one microphone failure, and three trials included measurements on the side of a large embankment, where the MICNOISE program underpredicted by 5 dB. The remaining 22 trials, covering five sites, provided 22 pairs of data for the evaluation of vertical correction errors.

Because all of the measurements were made on divided highways, and therefore involved the combination of highway noises subjected to different vertical corrections, the following procedure was adopted.

1. Only L_{50} errors were studied. There is, of course, no difference between the respective vertical corrections used for L_{50} and L_{10}.

2. The dependent variable studied was the correction error, which may be defined as

   E = [Calculated L_{50} at far microphone <u>minus</u> calculated L_{50} at near microphone] <u>minus</u> [Measured L_{50} at far microphone <u>minus</u> measured L_{50} at near microphone].

   or

   $$E = (L_{50})_{CALC} - (L_{50})_{MEAS}.$$

   Thus, a positive error, E, represents an overpredicted L_{50} level at a distance, and is therefore a conservative correction for distance.

3. The first independent variable is the calculated distance correction.

   $$(L_{50})_{DIST}.$$

   This is obtained by supressing the vertical corrections in the computer program, in which case all MICNOISE versions, (2X, 5, 5X, and 5V) give the same values. It is an overall distance correction, applicable to a particular case, because it depends on the relative traffic levels in the different roadways. Calculated values for $(L_{50})_{DIST}$. obtained without vertical corrections are given in Tables B6-B10 of Appendix B.

4. The second independent variable is the calculated vertical correction.

$$(L_{50})_{VERT} = (L_{50})_{CALC} - (L_{50})_{DIST}$$

This is different for the different MICNOISE versions, and is again applicable only to a particular case.

Table 3 contains a listing of $(L_{50})_{MEAS}$, $(L_{50})_{CALC}$, $(L_{50})_{DIST}$, $(L_{50})_{VERT}$ and E for the three versions of MICNOISE studied. For brevity, these are referred to as "MEAS", "CALC", "DIST", "VERT", and "E" respectively.

For further clarification of these results for MICNOISE 2X and 5, they are presented as three-dimensional plots in Figures 6 and 7. These show the error, E, which is the dependent variable, as an arrow of the appropriate length, directed upwards if E is positive (corresponding to overprediction). The independent variables $(L_{50})_{DIST}$ and $(L_{50})_{VERT}$ are indicated by the oblique axes. Positive $(L_{50})_{VERT}$ values correspond to cases where the highway is elevated, so that the attenuation due to the vertical correction becomes less as the observer moves away from the road.

For each of the four cases, a least squares fit or regression plane was determined, its edges are indicated by dotted lines in Figures 6 and 7. It is immediately evident that the least square fit plane is closest to the zero error plane for the MICNOISE 2X results.

Table 4 shows the parameters relevant to the least squares study. The plane may be represented by the equation

$$E_{FIT} = C_o + C_{DIST} \times (L_{50})_{DIST} + C_{VERT} \times (L_{50})_{VERT}$$

where the coefficients C_o, C_{DIST} and C_{VERT} are given in the table. Also shown are the RMS values of E relative to the E_{FIT} plane,

$$E_{RMS} = \sqrt{\Sigma(E - E_{FIT})^2}$$

and the original values of E_{RMS} and $\bar{E}$ (mean value) as calculated from the appropriate columns in Table 3.

Table 3

Analysis of Correction Errors

				MICNOISE 2X			MICNOISE 5			MICNOISE 5X			MICNOISE 5V		
TEST	SITE	MEAS	DIST	CALC	E	VERT	CALC	E	VERT	CALC	E	VERT	CALC	E	VERT
1-2	1	-13.8	-6.4	-12.6	1.2	-6.2	-15.8	-2.0	- 9.4	-15.7	-1.9	- 9.3	-15.1	-1.3	- 8.7
1-3	DEPR	-18.4	-8.7	-17.6	0.8	-8.9	-20.5	-2.1	-11.8	-20.1	-1.7	-11.4	-19.5	-1.1	-10.8
2-1		-13.8	-6.6	-13.5	0.3	-6.9	-16.4	-2.6	- 9.8	-16.3	-2.5	- 9.7	-15.7	-1.9	- 9.1
3-2		-15.2	-6.3	-12.2	3.0	-5.9	-15.6	-0.4	- 9.3	-15.5	-0.3	- 9.2	-14.9	0.3	- 8.6
3-3		-15.5	-7.8	-15.8	-0.3	-8.0	-18.9	-3.4	-11.1	-18.6	-3.1	-10.8	-18.2	-2.7	-10.4
4-1	2	- 1.8	-2.3	- 2.3	-0.5	0	- 2.3	-0.5	0	- 2.3	-0.5	0	- 2.3	-0.5	0
4-2	LEV	- 5.2	-5.6	- 5.6	-0.4	0	- 5.6	-0.4	0	- 5.6	-0.4	0	- 5.6	-0.4	0
4-3		- 8.0	-7.7	- 7.7	0.3	0	- 7.7	0.3	0	- 7.7	0.3	0	- 7.7	0.3	0
5-1		-10.2	-7.8	- 7.8	2.4	0	- 7.8	2.4	0	- 7.8	2.4	0	- 7.8	2.4	0
5-2		- 5.9	-5.6	- 5.6	0.3	0	- 5.6	0.3	0	- 5.6	0.3	0	- 5.6	0.3	0
5-3		- 2.7	-2.2	- 2.2	0.5	0	- 2.2	0.5	0	- 2.2	0.5	0	- 2.2	0.5	0
7-1	3	- 2.1	-3.8	- 1.5	0.6	2.3	2.4	4.5	6.2	- 2.5	-0.4	1.3	- 4.0	-1.9	- 0.2
7-2	EL	- 2.0	-5.1	- 0.7	1.3	4.4	- 1.2	0.8	3.9	- 2.6	-0.6	2.5	- 2.6	-0.6	2.5
7-3		- 2.2	-8.9	- 3.0	-0.8	5.9	- 4.2	-2.0	4.7	- 5.1	-2.9	3.8	- 5.1	-2.9	3.8
7-4		0.6	-7.3	- 3.2	-3.8	4.1	- 5.9	-6.5	1.4	- 4.3	-4.9	3.0	- 5.0	-5.6	2.3
8-1	4	- 4.3	-3.5	- 6.3	-2.0	-2.8	- 4.2	0.1	- 0.7	- 7.4	-3.1	- 3.9	- 4.2	0.1	- 0.7
8-2	DEPR	-12.6	-7.0	-13.1	-0.5	-6.1	-12.1	0.5	- 5.1	-15.7	-3.1	- 8.7	-10.1	2.5	- 3.1
8-3		- 7.3	-3.6	- 8.5	-1.2	-4.9	- 8.5	-1.2	- 4.9	- 8.6	-1.3	- 5.0	- 8.5	-1.2	- 4.9
9-1	5	+ 1.1	-2.9	+ 0.4	-0.7	3.3	- 2.9	-4.0	0	- 1.0	-2.1	1.9	- 2.8	-3.9	0.1
9-2	EL	- 0.8	-1.5	- 0.8	0	0.7	- 1.5	-0.7	0	- 1.3	-0.5	0.2	- 0.4	0.4	1.1
9-3		- 2.9	-3.8	- 2.4	0.5	1.4	- 2.4	0.5	1.4	- 2.6	0.3	1.2	- 2.5	0.4	1.3
9-4		- 4.3	-5.4	- 3.9	0.4	1.5	- 4.1	0.2	1.3	- 3.9	0.4	1.5	- 4.2	0.1	1.2

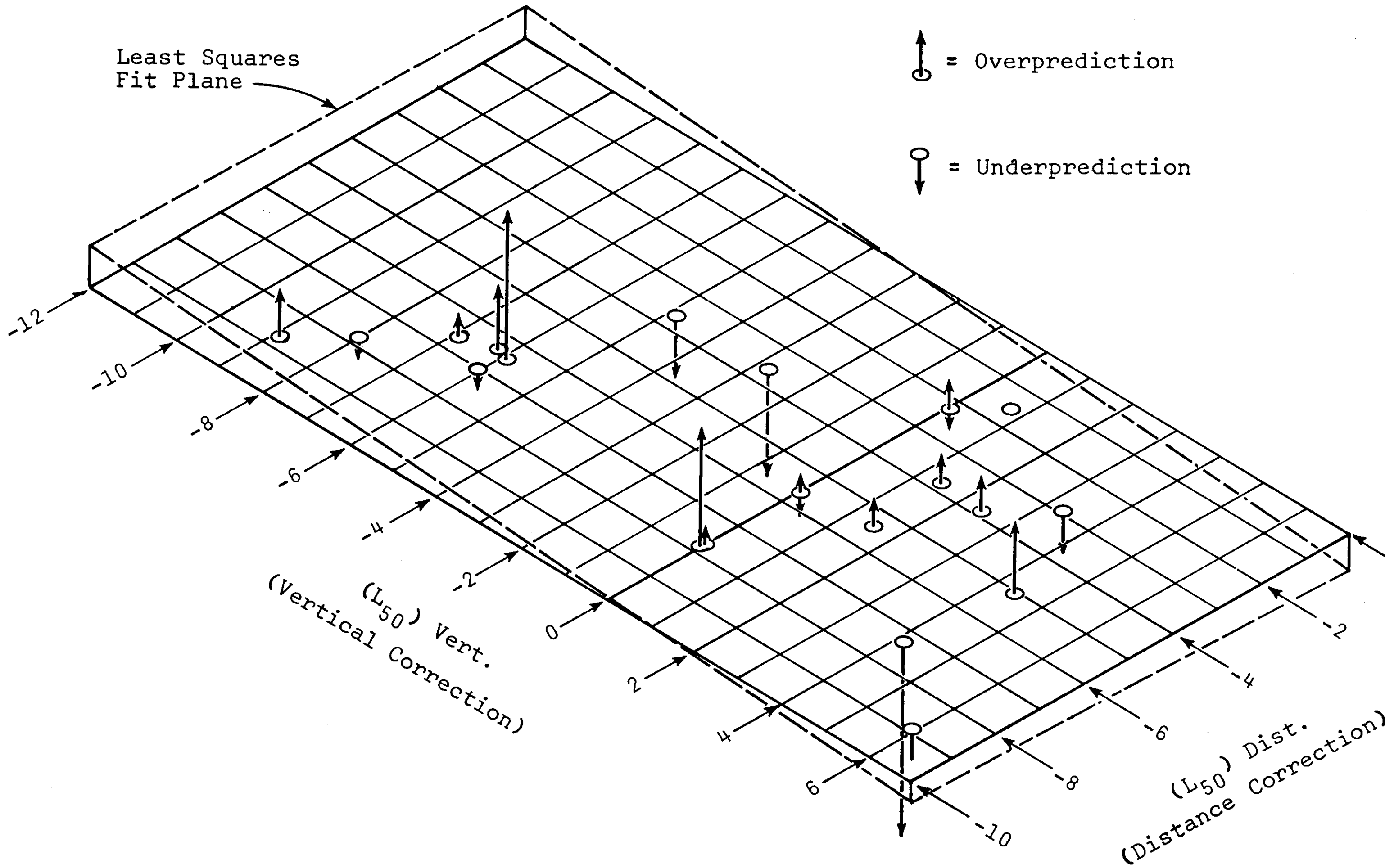


Figure 6. Correction errors in MICNOISE 2X.

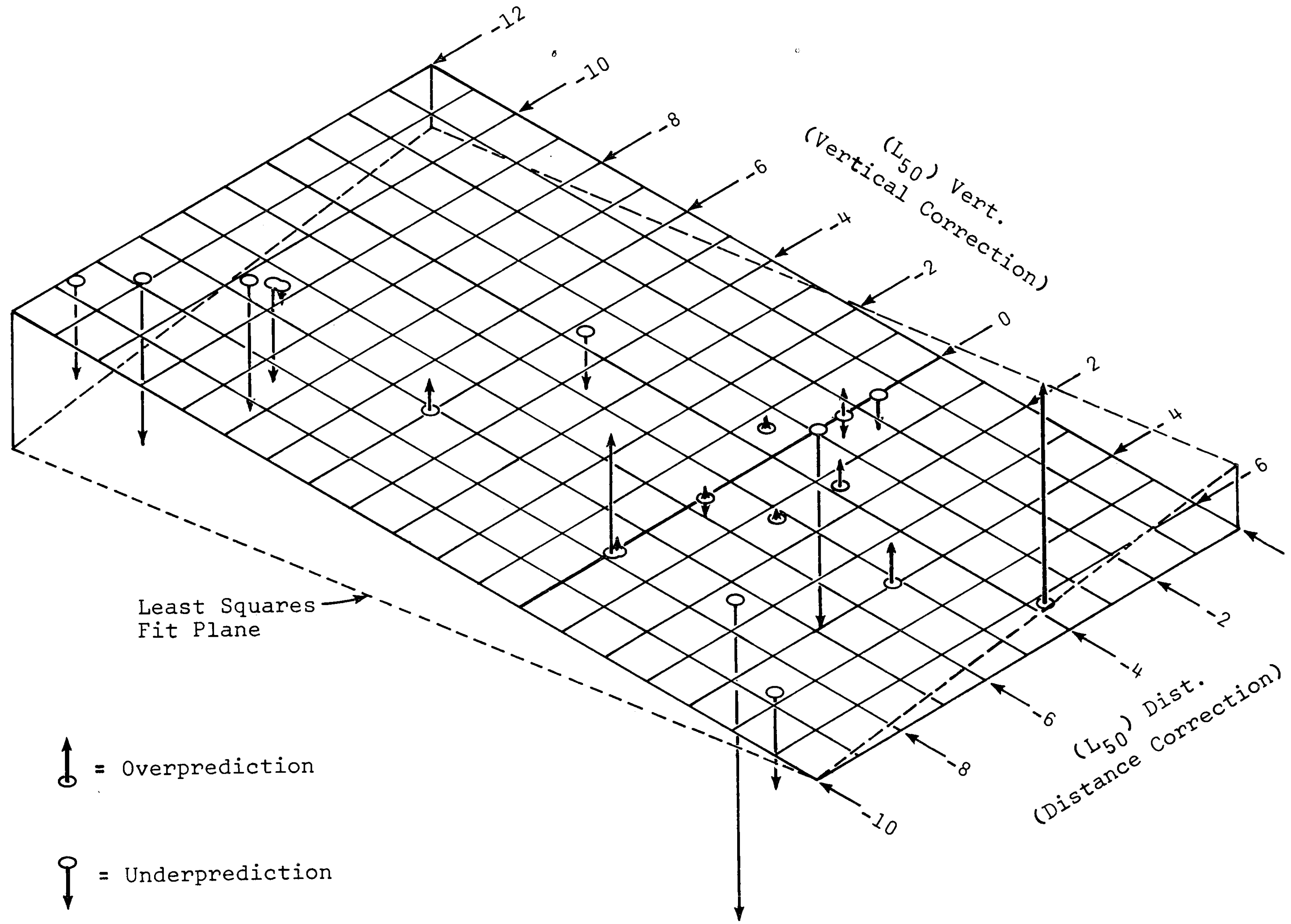


Figure 7. Correction errors in MICNOISE 5 — trucks at 8 ft. (2.4 m).

Table 4

Least Squares Fit Study

Program Version	C_o	C_{DIST}	C_{VERT}	E_{RMS} (Fit)	E_{RMS} (Original)	$\overline{E}$ (Original)
2X	-0.205	-0.0338	-0.0715	1.33	1.37	0.0636
5	0.263	0.126	0.148	2.03	2.32	-0.7136
5X	-0.256	0.128	0.077	1.55	1.99	-1.1409
5V	-0.208	0.102	-0.002	1.83	1.99	- .7591

The errors indicated in Figures 6 and 7 may be attributed to a number of causes, among which are:

1. Errors in the readings of the paired microphones.
2. Errors in the analysis of the results. (This includes failure to analyze identical lengths of magnetic tape.)
3. Inaccuracies in the prediction of distance corrections.
4. Inaccuracies in the prediction of vertical corrections.

Effects due to inaccuracies in the prediction of noise levels from the traffic should be expected to cancel out when the differences between the two microphone readings are taken; therefore these have not been included in the above list.

Of the four possible causes of error cited, the first two can be expected to lead to random errors, which could not be improved greatly when related to the least squares fit plane. However, the last two errors cited should cause systematic variations. Thus, if the least squares fit plane were to depart appreciably from the zero plane, it might indicate a need for the revision of the distance or vertical correction.

For example, suppose that the data have been taken without any reading or analysis errors. Suppose, also that the vertical correction is absolutely correct, but that the attenuation is in fact 10 dB for a tenfold increase in distance, whereas 15 dB is used in MICNOISE (see equation 12 of reference 1). Then the error would be -5 dB for $(L_{50})_{DIST}$ equal to -15 dB, so that the least squares fit plane would tilt at an angle whose tangent would be 1/3 in the $(L_{50})_{DIST}$ direction. It is quite evident from an inspection of Figures 6 and 7 that there is no such tilt, thus the 15 dB law appears to be justified by the results.

A further indication of the possible advantages to be gained from a modification of the distance and vertical corrections can be obtained from Table 4, which shows the RMS errors both relative to the least squares fit plane and as originally calculated. A comparison of the two RMS errors indicates the best improvement that could be obtained from a revision of the calculated distance and vertical corrections. The least improvement (from 1.37 to 1.33 dB) is obtained with MICNOISE 2X, which also has the lowest RMS errors, and is therefore, the best program of the four according to the results of this study. Of the others, MICNOISE 5X and 5V are somewhat better than MICNOISE 5, but both show some improvement when related to the least squares fit plane. However, both indicate a degree of unconservatism or underprediction in the prediction of corrections as evidenced by the fact that the mean errors, $\bar{E}$, are negative.

Possibly, an extension of this approach would lead to improved methods of calculating vertical corrections. However, the errors are not large in themselves; the worst RMS error in Table 4 is 2.32 dB, as compared with a maximum $(L_{50})_{MEAS}$ of 18.4 dB in Table 3. The least RMS error in Table 4 is 1.33, which is comparable with the experimental RMS error reported in the original report. (Actually, 1.16, 0.70, 5.52, 11.10 and 1.39 respectively for the five sites, as given by Table 7 of reference 2).

Thus there is little margin for improvement so that, even though the programs could be made to fit the measured data better, there is little guarantee that such improvements would hold with other data.

It is concluded that the data bank available does not justify further efforts at refining the predictions of vertical errors in the computer programs, and that, before such an effort is made, it would be advisable to plan and execute a new and more extensive program of roadside measurement. The desirability of going to such lengths must be weighed against the future need for MICNOISE, taking into consideration other computer programs which are available or under development.

It might be asked why MICNOISE 5, using a new method of calculating vertical corrections and based on the recommendations of NCHRP Report No. 144, should be less reliable than MICNOISE 2X, using earlier techniques. It would appear that MICNOISE 2X predicts noise levels of traffic at sites where tractor trailers predominate over other types of trucks with considerable accuracy. For example, examine the results for site 2 in Table 2, for which there were no vertical corrections. The vertical corrections used in MICNOISE 2X were based on early readings of the data used in the preparation of NCHRP Report No. 144. These are also shown to have led to accurate predictions. However, a degree of over-conservatism was introduced into the MICNOISE 5 program, which was based on the following recommendations in NCHRP Report No. 144.

1. A single correction should be used for elevated and depressed highways, and barriers, as suggested by Kurze and Anderson.[4,5] (This was done in MICNOISE 5.)

2. Not applicable.

3. The 5 dB reduction in the vertical correction for trucks should be cut to 3 dB or truck noise sources should be taken as eight feet (2.4 m) above the road with 0 dB reduction for trucks. (The latter was done.)

4. Possibly, the 10 dB law should be used over very flat terrain. (This was not done.)

The net effect of these recommendations appears to have been to overcompensate for acoustical barrier effects leading to a tendency to underpredict noise levels.

One further disadvantage of the MICNOISE 5 treatment of trucks is evident from a comparison of $(L_{50})_{VERT}$ values from MICNOISE 2X and 5 for site 1 in Table 3. These values indicate up to 3 dB more attenuation predicted by MICNOISE 5 compared with MICNOISE 2X, leading to an average relative underprediction of L_{50} levels of around 1 dB, as indicated by Table 2. The reason for this is that the 8-foot (2.4 m) height assumed for trucks in MICNOISE 5 is small compared with the 35-foot (10.7 m) depression of the roadway at this site, whereas there is the same 5 dB across-the-board reduction for trucks in MICNOISE 2X, regardless of the depth of the cut.

CONCLUSIONS AND RECOMMENDATIONS

In the following conclusions, due attention is paid to the fact that only MICNOISE Versions 2, 5, and 5V are available to Virginia Department of Highways and Transportation personnel at present. Actually, only Versions 2 and 5 are authorized for use by the Federal Highway Administration, however version 5V is demonstrably more conservative than 5. Because MICNOISE 2 has certain drawbacks, and is therefore not fully useable, only MICNOISE 5 and 5V can be considered.

In view of this, the following conclusions and recommendations are made.

1. In applying predictions made by MICNOISE 5, 3 dB should be added to obtain the 68% confidence level, and with Version 5V, 2 dB should be added.

2. If better accuracy is desirable, consideration should be given to making appropriate changes to MICNOISE 5, so that MICNOISE 2 or 2X methods are used in calculating vertical corrections. By doing this, the 68% and 95% confidence levels can be brought to within 2 dB and 4 dB respectively of predicted values.

3. Further attempts to improve methods of calculation beyond the level of MICNOISE 2X should not be made unless a parallel program of roadside measurements can be justified.

REFERENCES

1. Haviland, J. K., D. F. Noble, and H. L. Golub, "Verification of MICNOISE Computer Program for the Prediction of Highway Noise", Virginia Highway & Transportation Research Council, VHRC 73-R37, March 1974.

2. Gordon, C. G., W. J. Galloway, B. A. Kugler, and D. L. Nelson, "Highway Noise — A Design Guide for Highway Engineers", National Cooperative Highway Research Program — Report No. 117, Highway Research Board, Washington, D. C., 1971.

3. Kugler, B. A., and A. G. Piersol, "Highway Noise — A Field Evaluation of Traffic Noise Reduction Measures", National Cooperative Highway Research Program — Report No. 144, Highway Research Board, Washington, D. C., 1973.

4. Kurze, U., and G. S. Anderson, "Sound Attenuation by Barriers", J. Applied Acoustics, Vol. 4, No. 1, (1971), pp. 35-53.

5. Kurze, U., and L. L. Beranek, "Sound Propagation Outdoors", Chapter 7, Noise and Vibration Control, (L. L. Beranek, ed.) McGraw-Hill, (1971).

APPENDIX A

LISTING OF VERSION 5 COMPUTER PROGRAM

Input Stack

A typical input stack for the IBM 360 Job Control Language (HASP System) is shown in Figure A-1. Note that the conversion program reads input cards as File #1, writes both input (MICNOISE 2) output (MICNOISE 5) formats as File #2 (output listing), and also writes MICNOISE 5output as File #3. File #3 is set up as the temporary library MICDAT.

MICNOISE 5 then reads MICDAT as File #1, and writes final output as File #2 (output listing).

```
                  JOB CARD
// EXEC FORTGCLG
//FORT.SYSIN DD *

                  CONVERSION PROGRAM

/*
//GO.FT01F001 DD *

                  INPUT DATA FOR MICNOISE 2

/*
//GO.FT02F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//GO.FT03F001 DD UNIT=SYSDA,DSN=@@MICDAT,DISP=(NEW,PASS),
// SPACE=(800,(25,5)),DCB=(RECFM=FB,BLKSIZE=800,LRECL=80)
// EXEC FORTGCLG
//FORT.SYSIN DD *

                  MICNOISE VERSION 5 PROGRAM

/*
//GO.FT01F001 DD UNIT=SYSDA,DSN=@@MICDAT,DISP=(OLD,DELETE),
// SPACE=(800,(25,5)),DCB=(RECFM=FB,BLKSIZE=800,LRECL=80)
//GO.FT02F001 DD SYSOUT=A,DCB=(RECFM=FA,LRECL=133,BLKSIZE=133)
//
```

Figure A-1. Input stack for MICNOISE 5 run using MICNOISE 2 data.

Conversion Program

The conversion program is shown in Figure A-2. The following calculations are made.

MICNOISE 5 data		MICNOISE 2 data
Q	=	ADT * PCADT * N/100
Q = Hourly Traffic		ADT = Average Daily Traffic
		PCADT = Percentage of ADT during peak hours
		N = No. of lane groups per roadway element
HE	=	H1 - H2
HE = Roadway Elevation		H1 = Height of elevated road
		H2 = Depth of depressed road
BETA = 0		No equivalent
BETA = Barrier and angle (was not used)		

```
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           C      PROGRAM TO CONVERT MICNOISE 2 INPUT DATA TO MICNOISE 5 FORMAT
           C      OUTPUT IS ONTO UNITS 2 AND 3
 0001             WRITE(2,400)
 0002         400 FORMAT('1',10X,'MICNOISE 2 INPUT DATA CONVERTED TO MICNOISE 5
                 1FORMAT (INDICATED BY **)')
 0003          29 CONTINUE
 0004             READ(1,444) JOB,ID,NC,NRE
 0005          30 WRITE(2,445) JOB,ID,NC,NRE
 0006         444 FORMAT(2A3,I1,I8)
 0007         445 FORMAT('0',5X,2A3,I1,I8)
 0008             IF(NC.NE.0) GO TO 800
 0009             WRITE (2,446) JOB,ID,NC,NRE
 0010             WRITE(3,444) JOB,ID,NC,NRE
 0011             DO 700 INRE=1,NRE
 0012             READ(1,444) JOB,ID,NC,N
 0013             WRITE(2,445) JOB,ID,NC,N
 0014             IF(NC.NE.1) GO TO 800
 0015             WRITE(2,446) JOB,ID,NC,N
 0016         446 FORMAT(' ',' **  ',2A3,I1,I8)
 0017             WRITE(3,444) JOB,ID,NC,N
 0018             READ(1,555) JOB,ID,NC,ADT,PCADT,TMIX,ST,SA,HD,DN,RL,BL,FLO,P,
                 1DEL3,DEL5,DEL7
 0019             WRITE(2,556) JOB,ID,NC,ADT,PCADT,TMIX,ST,SA,HD,DN,RL,BL,FLO,P,
                 1DEL3,DEL5,DEL7
 0020         555 FORMAT(2A3,I1,F8.0,13F5.0)
 0021         556 FORMAT('0',5X,2A3,I1,F8.0,13F5.0)
 0022             IF(NC.NE.2) GO TO 800
 0023             Q=ADT*PCADT*N/100
 0024             READ(1,555)  JOB,ID,N3,MED,THETA,H1,DS,H2,DC,H,DB,ALPHA,HO
 0025             WRITE(2,556) JOB,ID,N3,MED,THETA,H1,DS,H2,DC,H,DB,ALPHA,HO
 0026             IF(N3.NE.3) GO TO 800
 0027             HE=H1-H2
 0028             WRITE(2,557) JOB,ID,NC,Q,TMIX,ST,SA,HE,DN,RL,BL,P,
                 1DEL3,DEL5,DEL7
 0029         557 FORMAT(' ',' **  ',2A3,I1,F8.0,13F5.0)
 0030             WRITE(3,555) JOB,ID,NC,Q,TMIX,ST,SA,HE,DN,RL,BL,P,
                 1DEL3,DEL5,DEL7
 0031             BETA=0
 0032             WRITE(2,557) JOB,ID,N3,MED,THETA,HO,DS,DC,H,DB,ALPHA,BETA
 0033             WRITE(3,555) JOB,ID,N3,MED,THETA,HO,DS,DC,H,DB,ALPHA,BETA
 0034         700 CONTINUE
 0035             GO TO 900
 0036         800 WRITE(2,801)
 0037         801 FORMAT(' ERROR IN CARD ORDER, THIS RUN HAS BEEN SKIPPED')
 0038         810 READ(1,444) JOB,ID,NC,NRE
 0039             IF(NC.EQ.0) GO TO 30
 0040             GO TO 810
 0041         900 READ(1,444) JOB,ID,NC,ICON
 0042             WRITE(2,445) JOB,ID,NC,ICON
 0043             IF(NC.NE.4) GO TO 800
 0044             WRITE(2,446) JOB,ID,NC,ICON
 0045             WRITE(3,444) JOB,ID,NC,ICON
 0046             IF(ICON) 999,29,900
 0047       999   STOP
 0048             END
```

Figure A-2. Conversion program. MICNOISE 2 format to MICNOISE 5 format.

MICNOISE 5

Figure A-3 shows the MICNOISE version 5 program, as supplied by the Data Processing Division of the Virginia Department of Highways and Transportation. Some minor changes have been made for this evaluation.

(1) The program has been fixed so that it will accept a zero percentage of truck traffic.

(2) Output has been increased.

```
C**********************************************************************C
C*                                                                    *C
C*                                                                    *C
C*   MM      MM  III    CCCC    N     N    0000     III   SSS    EEEEEE  *C
C*   M M    M M   I    C    C   NN    N   0    0     I   S   S   E       *C
C*   M  M M  M    I   C         N N   N  0      0    I    S      E       *C
C*   M   M   M    I   C         N  N  N  0      0    I     S     EEEEE   *C
C*   M       M    I   C         N   N N  0      0    I      S    E       *C
C*   M       M    I    C    C   N    NN   0    0     I   S   S   E       *C
C*   M       M   III    CCCC    N     N    0000     III   SSS    EEEEEE  *C
C*                                                                    *C
C*                                                                    *C
C**********************************************************************C
C
C
C     INPUT VARIABLES
C
C
C     JOB = JOB NUMBER
C     ID = IDENTIFICATION NO.
C     NC = CARD IDENTIFICATION NUMBER
C     NRE = NUMBER OF ROADWAY ELEMENTS
C     N = NUMBER OF LANE GROUPS PER ROADWAY ELEMENT
C     Q = HOURLY FLOW RATE (DESIGN HOUR TRAFFIC VOLUME)
C         NO SIGN = FREE FLOW, - = INTERRUPTED
C     TMIX = PERCENT TRUCK MIX
C     ST = TRUCK SPEED (MPH)
C     SA = AUTO SPEED (MPH)
C     HE = ROADWAY ELEVATION (FEET)
C         - = DEPRESSED, 0 = AT GRADE, + = ELEVATED
C     DN = OBSERVER TO CENTER OF NEAR LANE (FEET)
C     RL = ROADWAY LENGTH TYPE
C          1 = INFINITE, 2 = SEMI-INFINITE, 3 = FINITE
C     BL = BARRIER LENGTH
C          0 = NONE, 1 = INFINITE, 2 = FINITE
C     P = NUMBER OF LANES PER LANE GROUP
C     DEL3 = GRADE CORRECTION
C            0,+2,+3,+4 DB FOR .LE. 2, 3-4, 5-6, .GE. 7%)
C     DEL5 = ROADWAY SURFACE CORRECTION
C            -5, 0, +5 DB FOR SMOOTH, NORMAL, ROUGH
C     DEL7 = STRUCTURE SHIELD CORRECTION (-4.5 1ST ROW HOUSES,
C            -1.5 OTHERS, -10 MAX.)
C     MED = MEDIAN WIDTH FOR DIVIDED HIGHWAYS (FEET) WHEN N .GT. 1
C     THETA = ROADWAY INCLUDED ANGLE (DEGREES) WHEN RL .GE. 2
C     DS = OBSERVER TO SHOULDER (FEET) WHEN HE .GT. 0
C     DC = OBSERVER TO CUT (FEET) WHEN HE .LT. 0
C     H = BARRIER HEIGHT (FEET) WHEN BL = 1 OR 2
C     DB = OBSERVER TO BARRIER (FEET) WHEN BL = 1 OR 2
C     ALPHA = BARRIER INCLUDED ANGLE (DEGREES) WHEN BL .EQ. 2
C     BETA = BARRIER END-NORMAL ANGLE (DEGREES) WHEN RL = 2 & BL = 2
C     HO = OBSERVER HEIGHT REL. TO REF. PLANE (FEET); +ABOVE, - BELOW
C     CL10 = L10 VALUE (DB), USED TO COMPUTE OBS. DIST. FOR THIS VALUE
C     ICON = END OF DATA INDICATOR ( -1 STOP PROGRAM, 0 NEW DATA,
C            2 FIND DISTANCE FOR L10, 1 CHANGE OBSERVER'S POSITION)
C
C
C**********************************************************************C
C*    METHOD APPROVED IN PPM 90-2.  READ REPORT NCHRP 117,             *C
```

Figure A-3. MICNOISE 5 listing.

Figure A-3 (cont.)

```
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               C*    PROGRAM VERSION NO. 5, 9/1/73.                                      *C
               C*                                                                        *C
               C*    ADDITIONAL REVISIONS HAVE BEEN MADED TO THIS PROGRAM                *C
               C*    BY RONALD HEISLER OF THE VIRGINIA DEPARTMENT OF HIGHWAYS            *C
               C*    TO OBTAIN RESULTS WITHOUT THE USE OF TELECOMMUNICATIONS             *C
               C************************************************************************C
               C
               C
 0001                COMMON /BLK1/H3,H4,H5,D3,D4,DE
 0002                COMMON /BLK3/RL,ALPHA,THETA
 0003                DIMENSION Q(4),TMIX(4),ST(4),SA(4),VA(4),VT(4)
 0004                REAL MED,L10D
 0005                REAL VAL(12)/13.1,12.8,12.,10.87,8.19,5.63,4.,3.,2.13,1.5,1.26,
                    11.13/
 0006                REAL ARG(12)/20.,100.,200.,300.,600.,1500.,3000.,6000.,15000.,
                    140000.,100000.,800000./
 0007                REAL    A1(5)/30.,100.,300.,1000.,3000./
 0008                REAL    A2(10)/.1,.2,.3,.4,.5,.6,.7,.8,.9,1./
 0009                REAL    A5(7)/-60.,-20.,20.,40.,60.,70.,80./
 0010                REAL    A6(7)/0.,10.,20.,40.,60.,100.,160./
 0011                REAL    D2(7)/-5.,-5.63,-6.88,-8.28,-10.62,-15.,-15./
 0012                REAL    DEL(7)/.01,.03,.1,.3,1.,4.,30./
 0013                REAL    V5(7)/-.78,-2.03,-4.06,-5.62,-7.82,-9.55,-12.66/
 0014                REAL    V6(7)/-16.25,-12.34,-9.68,-6.56,-4.68,-2.34,-.31/
 0015                REAL    V11(5)/8.,0.,-7.,-15.,-22./
 0016                REAL    V12(5)/6.5,-.5,-7.,-15.,-22./
 0017                REAL    V13(5)/6.,-.7,-7.,-15.,-22./
 0018                REAL    V14(5)/5.5,-1.,-7.,-15.,-22./
 0019                REAL    V16(5)/4.,-1.5,-7.,-15.,-22./
 0020                REAL    V18(5)/2.5,-2.,-7.5,-15.,-22./
 0021                REAL    V25(10)/0.,3*-1.,2*-2.,-3.,2*-4.,-5./
 0022                REAL    V210(10)/0.,2*-1.,-2.,2*-3.,-4.,-6.,-7.,-10./
 0023                REAL    V215(10)/0.,-1.,2*-2.,-3.,-4.,-5.,-7.,-10.,-15./
 0024                REAL*8 AUTOS/8H AUTOS  /, TRUCKS/8H TRUCKS /
 0025                ICON = 0
 0026             29 INRE = 1
 0027                ICONB = 0
 0028                C1 = .017453
 0029                C2 = 57.29578
 0030                C3 = .0087265
 0031                C4 = 114.59156
 0032                READ(1,444) JOB,ID,NC,NRE
 0033            444 FORMAT(2A3,I1,I8,F5.0)
 0034                IF(NC .NE. 0) GO TO 800
 0035             93 J = 1
 0036                DEL2 = 0.
 0037                DEL3 = 0.
 0038                DEL4 = 0.
 0039                DL4 = 0.
 0040                DEL5 = 0.
 0041                DEL6 = 0.
 0042                DEL7 = 0.
 0043                DL6 = 0.
 0044                READ(1,444) JOB,ID,NC,N
 0045                IF(NC .NE. 1) GO TO 800
 0046                WRITE (2,400) ID,JOB
 0047            400 FORMAT('1RUN = ',A3,30X,'THE MICHIGAN NOISE PREDICTOR PROGRAM',30X
                   1,'COMPUTER JOB NO. ',A3)
```

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Figure A-3 (cont.)


```
0048            70 CONTINUE
0049               WRITE(2,450)    INRE,NRE,N
0050           450 FORMAT('-',44X,'ROAD ELEMENT NO.',I2//'0TOTAL ROAD ELEMENTS =',
                  1I2,T46,'NO. OF LANE GROUPS =',I2)
0051               READ(1,555) JOB,ID,NC,Q(J),TMIX(J),ST(J),SA(J),HE,DN,RL,BL,P,DEL3,
                  1DEL5,DEL7
0052           555 FORMAT(2A3,I1,F8.0,13F5.0)
0053               IF(NC .NE. 2) GO TO 800
0054               READ(1,555) JOB,ID,NC,MED,THETA,HO,DS,DC,H,DB,ALPHA,BETA
0055               IF(NC .NE. 3) GO TO 800
             C
             C              PRINT INPUT VARIABLES
0056               WRITE(2,560) Q(J),TMIX(J),ST(J),SA(J),HE,DN,RL,BL,P,DEL3,DEL5,DEL7
0057           560 FORMAT('0DESIGN HR. VOL. =',F7.0,     ' VEH/HR.',T46,'% TRUCK MIX =
                  1',F4.0,T89,'TRUCK SPEED =',F4.0,' MPH'/'0CAR SPEED =',F4.0,' MPH',
                  2T46,'ROAD ELEV. =',F5.0,' FEET',T89,'OBS. TO ROAD =',F5.0,' FEET'/
                  3'0ROAD LENGTH TYPE =',F3.0,T46,'BARRIER LENGTH =',F3.0,T89,'NO. OF
                  4 LANES PER LANE GROUP =',F3.0/'0GRADE CORRECTION =',F3.0,' DB',T46
                  5,'ROAD SURFACE CORRECTION =',F4.0,' DB',T89,'STRUCTURE SHIELD CORR
                  6ECTION =',F3.0,' DB')
0058               WRITE(2,570) MED,THETA,HO,DS,DC,H,DB,ALPHA,BETA
0059           570 FORMAT('0MEDIAN WIDTH =',F4.0,' FEET',T46,'ROAD INCLUDED ANGLE =',
                  1F4.0,' DEGREES',T89,'OBS. HT. =',F4.0,' FEET'/'0OBS. TO SHOULDER =
                  2',F5.0,' FEET',T46,'OBS. TO CUT =',F5.0,' FEET',T89,'BARRIER HT. =
                  3',F4.0,' FEET'/'0OBS. TO BARRIER =',F5.0,' FEET',T46,'BARRIER INCL
                  4UDED ANGLE =',F4.0,' DEGREES',T89,'BARRIER END-NORMAL ANGLE =',
                  5F4.0,' DEGREES'///)
0060           590 FORMAT('0SUMMARIES FOR',A8,'IN LANE GROUP NO.',I3/'0CORRECTIONS, D
                  1EL1 TO DEL6:',6F6.2,': L50=',F6.2,' L10=',F6.2//)
0061               IF(J .EQ. 1) DN1 = DN
             C
             C     CHECK FOR INPUT ERRORS
             C
0062               IF(HE) 100,102,101
0063           100 IF(DC .GT. 0.) GO TO 103
0064               WRITE(2,200)
0065           200 FORMAT(' ** DEPRESSED ROAD - OBS. TO CUT VALUE INCORRECT')
0066               GO TO 900
0067           101 IF(DS .GT. 0.) GO TO 103
0068               WRITE(2,205)
0069           205 FORMAT(' ** ELEV. ROAD - OBS. TO SHOULDER VALUE INCORRECT')
0070               GO TO 900
0071           102 IF(DS .EQ. 0. .AND. DC .EQ. 0.) GO TO 103
0072               WRITE(2,210)
0073           210 FORMAT(' ** AT GRADE - OBS. TO SHOULDER OR CUT FIELD IS CODED')
0074               GO TO 900
0075           103 IF(RL .GE. 2.) GO TO 104
0076               IF(THETA .EQ. 0.) GO TO 105
0077               WRITE(2,215)
0078           215 FORMAT(' ** INFINITE ROAD TYPE HAS ROAD INCLUDED ANGLE')
0079               GO TO 900
0080           104 IF(THETA .NE. 0.) GO TO 105
0081               WRITE(2,220)
0082           220 FORMAT(' ** SEMI-INF. OR FINITE ROAD TYPE WITH ZERO ROAD ANGLE')
0083               GO TO 900
0084           105 IF(BL - 1.)106,108,107
0085           106 IF(H .EQ. 0. .AND. DB .EQ. 0.) GO TO 109
0086               WRITE(2,225)
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                MAIN             DATE = 75058        15/55/47             PAGE 0004

0087          225 FORMAT(' ** BARRIER HT. AND/OR OBS. TO BARRIER FIELD ARE CODED WIT
                 1H NO EXISTING BARRIER')
0088              GO TO 900
0089          107 IF(ALPHA .NE. 0.) GO TO 108
0090              WRITE(2,230)
0091          230 FORMAT(' ** FINITE BARRIER LENG. WITH INCLUDED ANGLE ZERO')
0092              GO TO 900
0093          108 IF(H .GT. 0. .AND. DB .GT. 0.) GO TO 109
0094              WRITE(2,235)
0095          235 FORMAT(' ** BARRIER LENG. IS FINITE OR INFINITE AND BARRIER HT. OR
                 1 OBS. TO BARRIER IS EQUAL/LESS THAN ZERO')
0096              GO TO 900
0097          109 IF(N .GT. 1) GO TO 111
0098              IF(MED .EQ. 0.) GO TO 112
0099              WRITE(2,245)
0100          245 FORMAT(' ** MEDIAN WIDTH FOR ONE LANE GROUP')
0101              GO TO 900
0102          111 IF(MED .GE. 0.) GO TO 112
0103              WRITE(2,250)
0104          250 FORMAT(' ** MEDIAN WIDTH IS NEGATIVE')
0105              GO TO 900
0106          112 IF(DEL3 .GE. 0. .AND. DEL3 .LE. 4.) GO TO 113
0107              WRITE(2,255)
0108          255 FORMAT(' ** GRADE CORRECTION NOT IN 0 - +4 RANGE')
0109              GO TO 900
0110          113 IF(DEL5 .GE. -5. .AND. DEL5 .LE. 5.) GO TO 114
0111              WRITE(2,260)
0112          260 FORMAT(' ** ROAD SURFACE CORR. NOT -5,0,OR +5')
0113              GO TO 900
0114          114 IF(DEL7 .LE. 0. .AND. DEL7 .GE. -10.) GO TO 98
0115              WRITE(2,265)
0116          265 FORMAT(' ** STRUCTURE CORRECTION NOT -10 TO 0 DB')
0117              GO TO 900
            C
            C     CALCULATE VEHICLE VOLUMES
0118           98 V = ABS(Q(J)) / N
0119              VT(J)=AMAX1(V*TMIX(J)*.01,1.)
0120              VA(J)=AMAX1(V-VT(J),1.)
            C
            C     DEL2   -   ELEMENT CORRECTION
0121           82 IF(RL - 2.) 42,40,41
0122           40 IF(ICON .EQ. 0 .AND. J .GT. 1 .OR. ICON .EQ. 1)
                 -CALL ANGLE(C2,C1,THETA,DN1,DNX)
0123              DEL2 = FIGB10(V5,A5,THETA,7,1)
0124              GO TO 42
0125           41 IF(ICON .EQ. 0 .AND.J .GT. 1 .OR. ICON .EQ. 1)
                 -CALL ANGLE(C4,C3,THETA,DN1,DNX)
0126              DEL2 = FIGB10(V6,A6,THETA,7,1)
            C     DE    -   EQUIVALENT LAND DISTANCE CALCULATION
0127           42 DF = DN + 12.*P -12.
0128              DE = SQRT(DN*DF)
            C     DEL1   -   DISTANCE CORRECTION
0129              IF(P - 2.) 190,191,192
0130          190 DEL1 = FIGB10(V11,A1,DN,5,0)
0131              GO TO 61
0132          191 DEL1 = FIGB10(V12,A1,DN,5,0)
0133              GO TO 61
0134          192 IF(P - 4.) 193,194,195
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                MAIN              DATE = 75058          15/55/47              PAGE 0005

         193 DEL1 = FIGB10(V13,A1,DN,5,0)
             GO TO 61
         194 DEL1 = FIGB10(V14,A1,DN,5,0)
             GO TO 61
         195 IF(P .GT. 6) GO TO 196
             DEL1 = FIGB10(V16,A1,DN,5,0)
             GO TO 61
         196 DEL1 = FIGB10(V18,A1,DN,5,0)
C            DEL4    -    VERTICAL CORRECTION
          61 IF(HE) 44,48,53
          53 IF(J .EQ. 1 .AND. ICON .EQ. 1) DS = DS + DNX
             H3 = 0.
             H4 = HE - HO
             H5 = H4
             D3 = DE - DS
             D4 = DS
             GO TO 47
          44 IF(J .EQ. 1 .AND. ICON .EQ. 1) DC = DC + DNX
             H3 = HE
             H4 = -HO
             H5 = HE - HO
             D3 = DE - DC
             D4 = DC
          47 CALL DELS(D2,DEL,DEL4,1.)
             H3 = H3 + 8.
             H5 = H5 + 8.
             CALL DELS(D2,DEL,DL4,1.)
C         DEL6 - BARRIER CORRECTION
          48 IF(BL .EQ. 0) GO TO 33
             IF(J .GT. 1 .OR. ICON .NE. 0) GO TO 117
             DBX = DB
         117 CONTINUE
             IF(J .EQ. 1 .AND. ICON .EQ. 1) DB = DB + DNX
             H3 = -H
             H4 = H - HO
             H5 = -HO
             D3 = DE-DB
             D4 = DB
             CALL DELS(D2,DEL,DEL6,1.)
             H3 = H3 + 8.
             H5 = H5 + 8.
             CALL DELS(D2,DEL,DL6,1.)
             IF(BL-2.)33,38,38
          38 IF(ICON .EQ. 2) CALL ANGLE(C4,C3,ALPHA,DB,DBX)
             CALL FINBR(V25,V210,V215,A2,DEL6)
             CALL FINBR(V25,V210,V215,A2,DL6)
          33 CONTINUE
C
C            CALCULATE   L50  AND  L10
C
             S = DEL1 + DEL2 + DEL7
             SDEL = S + AMAX1(DEL4+DEL6,-20.) + DEL5
             SDELT = S + DEL3 + AMAX1(DL4+DL6,-20.)
             YA = .119 * VA(J) / SA(J)
             UA = VA(J) * SA(J) * SA(J) * TANH(YA)
             AL50A = 10. * ALOG10(UA) - 1. + SDEL
             AA=AMAX1(VA(J)*DE/SA(J),21.)
             AT=AMAX1(VT(J)*DE/ST(J),21.)
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                MAIN            DATE = 75058         15/55/47              PAGE 0006

            AL10A = FIGB10(VAL,ARG,AA,12,0)
            OL10A = AL50A + AL10A
            YT = .119 * VT(J) / ST(J)
            UT = VT(J) * TANH(YT) / ST(J)
            AL50T = 10. * ALOG10(UT) + 65. + SDELT
            AL10T = FIGB10(VAL,ARG,AT,12,0)
            OL10T = AL50T + AL10T
            IF(Q(J) .GT. 0.) GO TO 51
            OL10A = OL10A + 2.
            OL10T = OL10T + 4.
         51 WRITE(2,590) AUTOS,J,DEL1,DEL2,DEL3,DEL4,DEL5,DEL6,AL50A,OL10A
            WRITE(2,590) TRUCKS,J,DEL1,DEL2,DEL3,DL4,DEL5,DL6,AL50T,OL10T
            AL50 = DBSUM(AL50A,AL50T)
            AL10 = DBSUM(OL10A,OL10T)
            IF(ICON .EQ. 2) GO TO 52
            WRITE(2,973) INRE,J,AL50,AL10
        973 FORMAT('0TOTALS FOR ROAD ELEMENT NO.',I4,  ', LANE GROUP',I4,  ',
          1 L50=',F6.2,', L10=',F6.2)
         52 CONTINUE
            IF(N.EQ.1) GO TO 72
            IF(J.EQ.1) GO TO 65
            AL50 = DBSUM(AL50,XX)
            AL10 = DBSUM(AL10,YY)
      C     CHECK IF ANY MORE LANE GROUPS
            IF(J.EQ.N) GO TO 72
         65 XX = AL50
            YY = AL10
            J = J + 1
            DN = DN + MED + 12. * P
            DNX = DN
            Q(J) = Q(J-1)
            TMIX(J) = TMIX(J-1)
            ST(J) = ST(J-1)
            SA(J) = SA(J-1)
            GO TO 98
      C     CHECK IF ANY MORE ROADWAY ELEMENTS
         72 IF(NRE.EQ.1) GO TO 92
            IF(INRE.EQ.1) GO TO 67
            AL50 = DBSUM(AL50,RODL5)
            AL10 = DBSUM(AL10,RODL1)
            IF(INRE.EQ.NRE) GO TO 92
         67 RODL5 = AL50
            RODL1 = AL10
            INRE = INRE + 1
            GO TO 93
      C     OUTPUT RESULTING L50 AND L10 VALUES
         92 CONTINUE
            IF(ICON .EQ. 2) GO TO 161
            WRITE(2,23) ID,AL50,AL10
         23 FORMAT(  '0RUN = ',A3,'  L50 = ',F5.2,'   L10 = ',F5.2/)
      C
      C     CHECK IF ANY MORE PROBLEMS TO BE SOLVED
      C     ICON = 2,1,0,-1 FOR ITERATE,NEW OBS. DIST.,NEW DATA,STOP
      C
            READ(1,444) JOB,ID,NC,ICON,L10D
            IF(NC .NE. 4) GO TO 800
        115 CONTINUE
            IF(ICON .EQ. 2) GO TO 187
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                  MAIN              DATE = 75058         15/55/47                 PAGE 0007

          IF(ICON)28,29,30
C                    NEW OBSERVER POSITION
       30 CONTINUE
          READ(1,555) JOB,ID,NC,DUM,DUM,DUM,DUM,DUM,DN
          IF(NC .NE. 2) GO TO 800
          WRITE(2,591) ID,DN
      591 FORMAT(' ',17('*****')/'0RUN = ',A3,5X,'OBSERVER TO ROAD =',F5.0,'
         1FEET')
          DNX = DN - DN1
          DN1 = DN
          J = 1
          INRE = 1
          GO TO 82
C
C                   ITERATE L10
      187 CONTINUE
          WRITE(2,595) L10D
      595 FORMAT('0SELECTED L10 =',F4.0,' DB')
          IF(INRE .EQ. 1 .AND. N .LE. 2) GO TO 945
          WRITE(2,940)
      940 FORMAT('0** TOO MANY ELEMENTS OR LANE GROUPS TO ITERATE L10')
      162 ICON = 0
          ICONB = 1
          GO TO 92
      945 CONTINUE
          DX = 0.
          DELDN = 100.
      161 DXN = AL10 - L10D
          IF(ABS(DXN) .LT. .1) GO TO 162
          IF(DELDN .LT. 2.) GO TO 162
          IF(DXN*DX .LT. 0.) DELDN = .5 * DELDN
          DXX = SIGN(DELDN,DXN)
          DNN = DN1 + DXX
          XXX = DNN
          IF(HE) 144,145,146
      144 DC = DC + DXX
          XXX = DC
          GO TO 145
      146 DS = DS + DXX
          XXX = DS
      145 IF(BL .EQ. 0.) GO TO 181
          DBN = DB + DXX
          XXX = DBN
      181 IF(XXX .LE. 0.) GO TO 180
          IF(RL - 2.) 151,149,150
      150 CALL ANGLE(C4,C3,THETA,DN1,DNN)
      151 IF(BL .EQ. 2.) CALL ANGLE(C4,C3,ALPHA,DB,DBN)
          GO TO 148
      149 CALL ANGLE(C2,C1,THETA,DN1,DNN)
          IF(BL .NE. 2.) GO TO 148
      198 ALB = ALPHA + BETA
          CALL ANGLE(C2,C1,ALB,DN1,DNN)
          CALL ANGLE(C2,C1,BETA,DN1,DNN)
          ALPHA = ALB - BETA
      148 DN = DNN
          DN1 = DNN
          DX = DXN
          IF(BL .NE. 0.)DB = DBN
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                MAIN            DATE = 75058        15/55/47            PAGE 0008

0292              J=1
0293              INRE=1
0294              GO TO 82
0295          180 WRITE(2,203)
0296          203 FORMAT(' TRY CLOSER L10 AFTER RESET OF SITE DATA')
0297              GO TO 162
0298          800 WRITE(2,305) NC,ICON
0299          305 FORMAT('-**** CARD HAS WRONG CARD NO., PROBABLE ERROR IS TOO MANY
                 1OR TOO FEW CARDS'/' WRONG NO. IS',I2,10X,'LAST END OF DATA INDICAT
                 2OR =',I3)
0300          900 WRITE(2,300) ID
0301          300 FORMAT('0INPUT ERROR -- CALCULATIONS WERE NOT PERFORMED FOR RUN ',
                 1A3,' --  READ NEXT SET OF DATA')
0302              NRE = 1
0303          116 IF(NC .EQ. 4) GO TO 115
0304              READ(1,444) JOB,ID,NC,ICON
0305              GO TO 116
0306           28 STOP 0001
0307              END
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                  FIGB10              DATE = 75058           15/55/47              PAGE 0001

0001                FUNCTION FIGB10(VAL,ARG,DY,K,J)
0002                DIMENSION VAL(1), ARG(1)
             C      INTERPOLATES ON EITHER A LINEAR OR SEMILOG GRID
             C      IN THE CALL, SET J = 1 FOR LINEAR, = 0 FOR SEMILOG
0003                D = AMAX1(AMIN1(DY,ARG(K)),ARG(1))
0004                IF(DY.GE.ARG(1)) GO TO 7
0005                WRITE(2,20) DY,ARG(1),ARG(K)
0006             20 FORMAT(' ** ARGUMENT LIMITED AT LOW END **    DY=',F8.2,' ARG(1)='
                   1,F8.2,' ARG(K)=',F8.2/)
0007                GO TO 8
0008              7 IF(DY.LE.ARG(K)) GO TO 8
0009                WRITE(2,21) DY,ARG(1),ARG(K)
0010             21 FORMAT(' ** ARGUMENT LIMITED AT HIGH END **    DY=',F8.2,' ARG(1)=
                   1',F8.2,' ARG(K)=',F8.2/)
0011              8 DO 1 I = 2,K
0012                IF(D.GT.ARG(I)) GO TO 1
0013                IF(J.EQ.1) GO TO 9
0014                FIGB10 = ALOG10(D) -ALOG10(ARG(I-1))
0015                F = ALOG10(ARG(I)) - ALOG10(ARG(I-1))
0016              6 FIGB10 = FIGB10*(VAL(I)-VAL(I-1))/F + VAL(I-1)
0017                RETURN
0018              9 FIGB10 = D - ARG(I-1)
0019                F = ARG(I) - ARG(I-1)
0020                GO TO 6
0021              1 CONTINUE
0022                RETURN
0023                END
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21            DBSUM            DATE = 75058       15/55/47          PAGE 0001

 0001               FUNCTION DBSUM(A,B)
              C     CALCULATES THE DB SUM OF A AND B
 0002               DBSUM = B
 0003               IF(A.LE.0.01) RETURN
 0004               DBSUM = A
 0005               IF(B.LE.0.01) RETURN
 0006               DBSUM = 10.*ALOG10(10.**(0.1*A) + 10.**(0.1*B))
 0007               RETURN
 0008               END
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21            ANGLE            DATE = 75058         15/55/47           PAGE 0001

              SUBROUTINE ANGLE(A,B,ANG,X,XN)
              IF(ANG*B .LE. 1.57077) GO TO 10
              WRITE(2,20)
           20 FORMAT('0** INPUT ANGLE GREATER THAN 180 DEGREES - CAN NOT USE')
              ANG = 180.
           10 ANG = A * ATAN(TAN(ANG*B) * X / XN)
              RETURN
              END
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                DELS                DATE = 75058          15/55/47            PAGE 0001

 0001                  SUBROUTINE DELS(D2,DEL,DELX,R)
                 C     CALCULATES SHIELDING EFFECTS
 0002                  DIMENSION D2(7),DEL(7)
 0003                  COMMON /BLK1/H3,H4,H5,D3,D4,DE
 0004                  DELX = 0.
 0005                  SB = H4/D4
 0006                  SD = H5/DE
 0007                  IF(SD .GT. SB) RETURN
 0008                  A = SQRT(H3 * H3 + D3 * D3)
 0009                  B = SQRT(H4 * H4 + D4 * D4)
 0010                  D = SQRT(H5 * H5 + DE * DE)
 0011                  DL = A + B - D
 0012                  DL=DL*R
 0013                  IF(DL .LT. .01) RETURN
 0014                  DELX = FIGB10(D2,DEL,DL,7,0)
 0015                  RETURN
 0016                  END
```

Figure A-3 (cont.)

```
FORTRAN IV G LEVEL  21                FINBR            DATE = 75058        15/55/47          PAGE 0001

 0001                  SUBROUTINE FINBR(V25,V210,V215,A2,DELX)
                 C     CALCULATES FINITE BARRIER ATTENUATION
 0002                  DIMENSION A2(10),V25(10),V210(10),V215(10)
 0003                  COMMON /BLK3/RL,ALPHA,THETA
 0004                  IF(RL-2.)74,75,76
 0005               74 A = ALPHA/180.
 0006                  GO TO 77
 0007               75 A = ALPHA/(90.-THETA)
 0008                  GO TO 77
 0009               76 A = ALPHA/THETA
 0010               77 IF(A .GE. 1.) RETURN
 0011                  IF(A .LE. .1) GO TO 89
 0012                  IF(DELX .GT. -5.) GO TO 86
 0013                  IF(DELX .GT. -10.) GO TO 87
 0014                  VU = FIGB10(V210,A2,A,10,1)
 0015                  VL = FIGB10(V215,A2,A,10,1)
 0016                  GO TO 88
 0017               89 DELX = 0.
 0018                  RETURN
 0019               86 VU = 0.
 0020                  VL = FIGB10(V25,A2,A,10,1)
 0021                  GO TO 88
 0022               87 VU = FIGB10(V25,A2,A,10,1)
 0023                  VL = FIGB10(V210,A2,A,10,1)
 0024               88 AL = .1 * AINT(10. * A)
 0025                  AU = AL + .1
 0026                  DELX = (A - AL) * (VL - VU) / (AU - AL) + VU
 0027                  RETURN
 0028                  END
```

Trial Run — Output from Conversion Program

MICNOISE 2 input for the near and far microphones of Test 1, Trial 1 was supplied, exactly as listed in Table A-1 of the original report. Both the input card format and the converted card format are shown in Figure A-4. The converted format is distinguished by the two asterisks preceding it on the same line.

Detailed formats can be inferred from reading the listing of the conversion program. However, prospective users of MICNOISE 5 are cautioned that other functions are available in the program, such as the ability to obtain contours, which were not used in this evaluation. It is suggested that prospective users contact Mr. Ronald Heisler of the Data Processing Division of the Virginia Department of Highways and Transportation for more information on preparing input decks.

```
             MICNOISE 2 INPUT DATA CONVERTED TO MICNOISE 5    FORMAT (INDICATED BY **)

        111N0      2
   **   111N0      2

        111N1      1
   **   111N1      1

        111N2   2011. 100.  21.  58.  63.   0.  56.   1.   0.   1.   3.   0.   0.   0.

        111N3     0.   0.   0.   0.   0.   0.   0.   0.   0.  13.
   **   111N2  2011.  21.  58.  63.   0.  56.   1.   0.   3.   0.   0.   0.
   **   111N3     0.   0.  13.   0.   0.   0.   0.   0.   0.

        111N1      1
   **   111N1      1

        111N2   2414. 100.  20.  59.  64.   0. 237.   1.   0.   1.   3.   0.   0.   0.

        111N3     0.   0.   0.   0.   0.   0.   0.   0.   0.  26.
   **   111N2  2414.  20.  59.  64.   0. 237.   1.   0.   3.   0.   0.   0.
   **   111N3     0.   0.  26.   0.   0.   0.   0.   0.   0.

        111N4      0
   **   111N4      0

        111F0      2
   **   111F0      2

        111F1      1
   **   111F1      1

        111F2   2011. 100.  21.  58.  63.   0. 106.   1.   0.   1.   3.   0.   0.   0.

        111F3     0.   0.   0.   0.   0.   0.   0.   0.   0.  37.
   **   111F2  2011.  21.  58.  63.   0. 106.   1.   0.   3.   0.   0.   0.
   **   111F3     0.   0.  37.   0.   0.   0.   0.   0.   0.

        111F1      1
   **   111F1      1

        111F2   2414. 100.  20.  59.  64.   0. 287.   1.   0.   1.   3.   0.   0.   0.

        111F3     0.   0.   0.   0.   0.   0.   0.   0.   0.  50.
   **   111F2  2414.  20.  59.  64.   0. 287.   1.   0.   3.   0.   0.   0.
   **   111F3     0.   0.  50.   0.   0.   0.   0.   0.   0.

        111F4     -1
   **   111F4     -1
```

Figure A-4. Trial run — output from conversion program.

Trial Run — Output from MICNOISE 5

Figure A-5 shows the output from MICNOISE 5, using the data from Figure A-4 indicated by asterisks. The data summary was extended for the purpose of this evaluation. Prospective users are referred to the cautionary comment on page A-19.

```
RUN = 11N                     THE MICHIGAN NOISE PREDICTOR PROGRAM                     COMPUTER JOB NO.   1

                                   ROAD ELEMENT NO. 1

TOTAL ROAD ELEMENTS = 2            NO. OF LANE GROUPS = 1
DESIGN HR. VOL. =  2011. VEH/HR.   % TRUCK MIX = 21.                  TRUCK SPEED = 58. MPH
CAR SPEED = 63. MPH                ROAD ELEV. =   0. FEET             OBS. TO ROAD =  56. FEET
ROAD LENGTH TYPE = 1.              BARRIER LENGTH = 0.                NO. OF LANES PER LANE GROUP = 3.
GRADE CORRECTION = 0. DB           ROAD SURFACE CORRECTION =  0. DB   STRUCTURE SHIELD CORRECTION = 0. DB
MEDIAN WIDTH =  0. FEET            ROAD INCLUDED ANGLE =  0. DEGREES  OBS. HT. = 13. FEET
OBS. TO SHOULDER =   0. FEET       OBS. TO CUT =   0. FEET            BARRIER HT. =  0. FEET
OBS. TO BARRIER =   0. FEET        BARRIER INCLUDED ANGLE =  0. DEGREES   BARRIER END-NORMAL ANGLE =  0. DEGREES


SUMMARIES FOR AUTOS  IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6:  2.53  0.0   0.0   0.0   0.0   0.0 : L50= 69.50 L10= 74.85

SUMMARIES FOR TRUCKS IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6:  2.53  0.0   0.0   0.0   0.0   0.0 : L50= 74.60 L10= 83.59

TOTALS FOR ROAD ELEMENT NO.   1, LANE GROUP   1, L50= 75.77, L10= 84.14
```

Figure A-5. Trial run — output from MICNOISE 5.

Figure A-5 (cont.)

```
RUN = 11N                     THE MICHIGAN NOISE PREDICTOR PROGRAM                    COMPUTER JOB NO.   1

                                  ROAD ELEMENT NO. 2

TOTAL ROAD ELEMENTS = 2           NO. OF LANE GROUPS = 1
DESIGN HR. VOL. = 2414. VEH/HR.   % TRUCK MIX = 20.                TRUCK SPEED = 59. MPH
CAR SPEED = 64. MPH               ROAD ELEV. =   0. FEET           OBS. TO ROAD = 237. FEET
ROAD LENGTH TYPE = 1.             BARRIER LENGTH = 0.              NO. OF LANES PER LANE GROUP = 3.
GRADE CORRECTION = 0. DB          ROAD SURFACE CORRECTION =  0. DB STRUCTURE SHIELD CORRECTION = 0. DB
MEDIAN WIDTH =  0. FEET           ROAD INCLUDED ANGLE =  0. DEGREES OBS. HT. = 26. FEET
OBS. TO SHOULDER =   0. FEET      OBS. TO CUT =   0. FEET          BARRIER HT. =  0. FEET
OBS. TO BARRIER =   0. FEET       BARRIER INCLUDED ANGLE =  0. DEGREES  BARRIER END-NORMAL ANGLE =  0. DEGREES


SUMMARIES FOR AUTOS  IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -5.65  0.0   0.0   0.0   0.0   0.0 : L50= 62.33 L10= 65.11

SUMMARIES FOR TRUCKS IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -5.65  0.0   0.0   0.0   0.0   0.0 : L50= 67.23 L10= 72.15

TOTALS FOR ROAD ELEMENT NO.   2, LANE GROUP   1,  L50= 68.45, L10= 72.93
RUN = 11N  L50 = 76.51   L10 = 84.45
```

Figure A-5 (cont.)

```
RUN = 11F                          THE MICHIGAN NOISE PREDICTOR PROGRAM                              COMPUTER JOB NO.   1

                                        ROAD ELEMENT NO. 1

TOTAL ROAD ELEMENTS = 2                 NO. OF LANE GROUPS = 1
DESIGN HR. VOL. =  2011. VEH/HR.        % TRUCK MIX = 21.                     TRUCK SPEED = 58. MPH
CAR SPEED = 63. MPH                     ROAD ELEV. =   0. FEET                OBS. TO ROAD = 106. FEET
ROAD LENGTH TYPE = 1.                   BARRIER LENGTH = 0.                   NO. OF LANES PER LANE GROUP = 3.
GRADE CORRECTION = 0. DB                ROAD SURFACE CORRECTION =  0. DB      STRUCTURE SHIELD CORRECTION = 0. DB
MEDIAN WIDTH =  0. FEET                 ROAD INCLUDED ANGLE =  0. DEGREES     OBS. HT. = 37. FEET
OBS. TO SHOULDER =   0. FEET            OBS. TO CUT =   0. FEET               BARRIER HT. =  0. FEET
OBS. TO BARRIER =   0. FEET             BARRIER INCLUDED ANGLE =  0. DEGREES  BARRIER END-NORMAL ANGLE =  0. DEGREES


SUMMARIES FOR AUTOS  IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -1.03  0.0   0.0   0.0   0.0   0.0 : L50= 65.94 L10= 69.97

SUMMARIES FOR TRUCKS IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -1.03  0.0   0.0   0.0   0.0   0.0 : L50= 71.04 L10= 78.24

TOTALS FOR ROAD ELEMENT NO.   1, LANE GROUP   1, L50= 72.21, L10= 78.84
```

Figure A-5 (cont.)

```
RUN = 11F                         THE MICHIGAN NOISE PREDICTOR PROGRAM                          COMPUTER JOB NO.   1

                                    ROAD ELEMENT NO. 2

TOTAL ROAD ELEMENTS = 2             NO. OF LANE GROUPS = 1
DESIGN HR. VOL. =  2414. VEH/HR.    % TRUCK MIX = 20.                     TRUCK SPEED = 59. MPH
CAR SPEED = 64. MPH                 ROAD ELEV. =   0. FEET                OBS. TO ROAD = 287. FEET
ROAD LENGTH TYPE = 1.               BARRIER LENGTH = 0.                   NO. OF LANES PER LANE GROUP = 3.
GRADE CORRECTION = 0. DB            ROAD SURFACE CORRECTION =  0. DB      STRUCTURE SHIELD CORRECTION = 0. DB
MEDIAN WIDTH =  0. FEET             ROAD INCLUDED ANGLE =  0. DEGREES     OBS. HT. = 50. FEET
OBS. TO SHOULDER =   0. FEET        OBS. TO CUT =   0. FEET               BARRIER HT. =  0. FEET
OBS. TO BARRIER =   0. FEET         BARRIER INCLUDED ANGLE =  0. DEGREES  BARRIER END-NORMAL ANGLE =  0. DEGREES

SUMMARIES FOR AUTOS  IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -6.75  0.0   0.0   0.0   0.0   0.0 : L50= 61.23 L10= 63.84

SUMMARIES FOR TRUCKS IN LANE GROUP NO.  1
CORRECTIONS, DEL1 TO DEL6: -6.75  0.0   0.0   0.0   0.0   0.0 : L50= 66.14 L10= 70.62

TOTALS FOR ROAD ELEMENT NO.   2, LANE GROUP   1,  L50= 67.35, L10= 71.45
RUN = 11F  L50 = 73.44   L10 = 79.57
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APPENDIX B

TABLE OF MEASURED AND CALCULATED VALUES USING MICNOISE VERSIONS 2X, 5, 5X and 5V

TABLE B-1

COMPARISON OF LEVELS CALCULATED BY MICNOISE 2X
WITH MEASURED LEVELS AT SITE 1 ON I-495 NEAR SPRINGFIELD

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
1	1	56 N	76.9	76.5	85.0	84.3
1	1*	106 F	78.7	73.4	84.8	79.6
1	2	56 N	77.4	77.1	85.7	84.6
1	2	206 F	63.6	64.5	67.3	69.0
1	3	56 N	76.4	76.5	85.2	84.3
1	3	306 F	58.0	58.9	62.2	63.1
2	1	56 N	77.9	76.4	84.7	83.8
2	1	206 F	64.1	62.9	68.3	67.8
2	2	56 N	77.3	76.0	83.5	83.4
2	2*	106 F	76.9	72.8	81.5	78.8
3	1	56 N	76.4	75.9	83.3	83.4
3	1*	106 F	75.4	72.9	81.3	78.8
3	2	56 N	75.9	76.6	83.7	84.1
3	2	206 F	60.7	64.4	63.8	68.8
3	3	56 N	73.5	74.4	81.7	82.4
3	3	306 F	58.0	58.6	63.2	62.8

*These values not included in statistical analysis.

TABLE B-2

COMPARISON OF LEVELS CALCULATED BY MICNOISE 2X
WITH MEASURED LEVELS AT SITE 2 ON I-495 NEAR ALEXANDRIA

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
4	1	66 N	75.9	76.2	82.2	83.5
4	1	106 F	74.1	73.9	79.8	80.1
4	2	66 N	77.0	75.7	83.0	83.2
4	2	206 F	71.8	70.1	76.4	75.0
4	3	66 N	75.9	75.1	82.3	82.7
4	3	306 F	67.9	67.4	71.7	71.6
5	1	66 N	75.5	76.2	82.1	83.4
5	1	306 F	65.3	68.4	70.5	72.4
5	2	66 N	76.4	76.4	83.5	83.6
5	2	206 F	70.5	70.8	75.8	75.5
5	3	66 N	75.5	75.3	81.4	82.8
5	3	106 F	72.8	73.1	78.6	79.4

TABLE B-3

COMPARISON OF LEVELS CALCULATED BY MICNOISE 2X
WITH MEASURED LEVELS AT SITE 3 ON I-64 NEAR FISHERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
7	1*	50 N	53.8	62.4	63.4	74.1
7	1*	100 F	51.7	60.9	59.8	71.3
7	2	50 N	56.1	57.1	63.7	66.8
7	2	200 F	54.1	56.4	60.7	63.8
7	3	50 N	55.4	54.4	65.3	65.8
7	3	300 F	53.2	51.4	61.7	59.5
7	4	100 N	49.1	51.5	59.4	62.2
7	4	400 F	49.7	48.3	58.7	56.0

*These values were not used in the statistical analysis but were used in the analysis of correction errors.

TABLE B-4

COMPARISON OF LEVELS CALCULATED BY MICNOISE 2X
WITH MEASURED LEVELS AT SITE 4 ON U. S. 29 NEAR RUCKERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
8	1	50 N	51.2	58.6	68.5	70.9
8	1	100 F	46.9	52.3	55.5	63.0
8	2	50 N	59.8	61.6	71.8	73.3
8	2	200 F	47.2	48.5	53.6	58.8
8	3	50 N	56.6	60.1	70.9	70.7
8	3	100 F	49.3	51.6	55.4	60.7
8	4	300 F	42.5	45.0	46.9	53.9

TABLE B-5

COMPARISON OF LEVELS CALCULATED BY MICNOISE 2X
WITH MEASURED LEVELS AT SITE 5 ON I-95 NEAR DOSWELL

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
9	1	85 N	61.5	63.5*	69.8	73.0*
9	1	150 F	62.6	63.9*	70.8	71.8*
9	2	150 N	64.7	64.4	73.5	72.6
9	2	200 F	63.9	63.6	70.4	70.6
9	3	150 N	65.0	63.9	74.3	72.3
9	3	300 F	62.1	61.5	69.4	67.5
9	4	150 N	62.6	64.7	73.9	72.8
9	4	400 F	58.3	60.8	67.2	65.9

*Trucks on side road ignored in these calculations.

TABLE B-6

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5 (TRUCKS AT 8 FT.) WITH MEASURED LEVELS AT SITE 1 ON I-495 NEAR SPRINGFIELD

TEST #	TRIAL #	MICR. LOCN.	L_{50}			L_{10}	
			MEAS.	CALC.	CALC.**	MEAS.	CALC.
1	1	56 N	76.9	76.5	76.5	85.0	84.5
1	1*	106 F					
1	2	56 N	77.4	77.1	77.1	85.7	84.8
1	2	206 F	63.6	61.3	70.7	67.3	65.6
1	3	56 N	76.4	76.5	76.5	85.2	84.5
1	3	306 F	58.0	56.0	67.8	62.2	60.1
2	1	56 N	77.9	76.4	76.4	84.7	84.1
2	1	206 F	64.1	60.0	69.8	68.3	64.6
2	2	56 N	77.3	76.0	76.0	83.5	83.8
2	2*	106 F					
3	1	56 N	76.4	75.9	75.9	83.3	83.7
3	1*	106 F					
3	2	56 N	75.9	76.7	76.7	83.7	84.4
3	2	206 F	60.7	61.1	70.4	63.8	63.4
3	3	56 N	73.5	74.4	74.4	81.7	82.9
3	3	306 F	58.0	55.5	66.6	63.2	59.5

*These values are not included in statistical analysis.

**Calculated without vertical correction.

TABLE B-7

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5
(TRUCKS AT 8 FT.) WITH MEASURED LEVELS AT SITE 2
ON I-495 NEAR ALEXANDRIA

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{50} CALC.*	L_{10} MEAS.	L_{10} CALC.
4	1	66 N	75.9	76.2	76.2	82.2	83.6
4	1	106 F	74.1	73.9	73.9	79.8	80.1
4	2	66 N	77.0	75.7	75.7	83.0	83.3
4	2	206 F	71.8	70.1	70.1	76.4	75.0
4	3	66 N	75.9	75.1	75.1	82.3	82.9
4	3	306 F	67.9	67.4	67.4	71.7	71.6
5	1	66 N	75.5	76.2	76.2	82.1	83.5
5	1	306 F	65.3	68.4	68.4	70.5	72.4
5	2	66 N	76.4	76.4	76.4	83.5	83.7
5	2	206 F	70.5	70.8	70.8	75.8	75.5
5	3	66 N	75.5	75.3	75.3	81.4	83.0
5	3	106 F	72.8	73.1	73.1	78.6	79.5

*Calculated without vertical correction.

TABLE B-8

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5 (TRUCKS AT 8 FT.) WITH MEASURED LEVELS AT SITE 3 ON I-64 NEAR FISHERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{50} CALC.**	L_{10} MEAS.	L_{10} CALC.
7	1*	50 N	53.8	61.3	68.4	63.4	73.6
7	1*	100 F	51.7	63.7	64.6	59.8	74.7
7	2	50 N	56.1	54.5	65.8	63.7	65.1
7	2	200 F	54.1	53.3	60.7	60.7	61.6
7	3	50 N	55.4	53.3	63.6	65.3	65.1
7	3	300 F	53.2	49.1	54.7	61.7	58.5
7	4	100 N	49.1	52.1	58.9	59.4	63.8
7	4	400 F	49.7	46.2	51.6	58.7	55.1

*These values were not used in the statistical analysis but were used in the analysis of correction errors.

**Calculated without vertical correction.

TABLE B-9

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5
(TRUCKS AT 8 FT.) WITH MEASURED LEVELS AT SITE 4
ON U. S. 29 NEAR RUCKERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{50} CALC.*	L_{10} MEAS.	L_{10} CALC.
8	1	50 N	51.2	58.6	58.6	68.5	71.0
8	1	100 F	46.9	54.4	55.1	55.5	66.2
8	2	50 N	59.8	61.6	61.6	71.8	73.8
8	2	200 F	47.2	49.5	54.6	53.6	60.4
8	3	50 N	56.6	60.1	60.1	70.9	71.4
8	3	100 F	49.3	51.6	56.5	55.4	60.9
8	4	300 N	42.5	43.8	52.3	46.9	52.8

*Calculated without vertical correction.

TABLE B-10

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5
WITH MEASURED LEVELS AT SITE 5 ON I-95 NEAR DOSWELL

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{50} CALC.**	L_{10} MEAS.	L_{10} CALC.
9	1	85 N	61.5	66.7 *	69.9*	69.8	77.3*
9	1	150 F	62.6	63.8*	67.0*	70.8	72.2*
9	2	150 N	64.7	64.1	67.4	73.5	72.7
9	2	200 F	63.9	62.6	65.9	70.4	70.1
9	3	150 N	65.0	63.7	67.0	74.3	72.5
9	3	300 F	62.1	61.3	63.2	69.4	67.6
9	4	150 N	62.6	64.5	67.3	73.9	73.0
9	4	400 F	58.3	60.4	61.9	67.2	65.8

*Trucks on side road ignored in these calculations.

**Calculated without vertical correction.

TABLE B.-11

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5X (TRUCKS AT HALF FREQUENCY) WITH MEASURED VALUES AT SITE 1 ON I-495 NEAR SPRINGFIELD

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
1	1	56 N	76.9	76.5	85.0	84.5
1	1*	106 F				
1	2	56 N	77.4	77.1	85.7	84.8
1	2	206 F	63.6	61.4	67.3	65.7
1	3	56 N	76.4	76.5	85.2	84.5
1	3	306 F	58.0	56.4	62.2	60.5
2	1	56 N	77.9	76.4	84.7	84.1
2	1	206 F	64.1	60.1	68.3	64.7
2	2	56 N	77.3	76.0	83.5	83.8
2	2*	106 F				
3	1	56 N	76.4	75.9	83.3	83.7
3	1*	106 F				
3	2	56 N	75.9	76.7	83.7	84.4
3	2	206 F	60.7	61.2	63.8	65.5
3	3	56 N	73.5	74.4	81.7	82.9
3	3	306 F	58.0	55.8	63.2	59.9

*These values not included in statistical analysis.

TABLE B-12

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5X (TRUCKS AT HALF FREQUENCY) WITH MEASURED LEVELS AT SITE 2 ON I-495 NEAR ALEXANDRIA

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
4	1	66 N	75.9	76.2	82.2	83.6
4	1	106 F	74.1	73.9	79.8	80.1
4	2	66 N	77.0	75.7	83.0	83.3
4	2	206 F	71.8	70.1	76.4	75.0
4	3	66 N	75.9	75.1	82.3	82.9
4	3	306 F	67.9	67.4	71.7	71.6
5	1	66 N	75.5	76.2	82.1	83.5
5	1	306 F	65.3	68.4	70.5	72.4
5	2	66 N	76.4	76.4	83.5	83.7
5	2	206 F	70.5	70.8	75.8	75.5
5	3	66 N	75.5	75.3	81.4	83.0
5	3	106 F	72.8	73.1	78.6	79.5

TABLE B-13

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5X (TRUCKS AT HALF FREQUENCY) WITH MEASURED LEVELS AT SITE 3 ON I-64 NEAR FISHERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
7	1*	50 N	53.8	58.7	63.4	71.0
7	1*	100 F	51.7	56.2	59.8	67.1
7	2	50 N	56.1	54.8	63.7	64.7
7	2	200 F	54.1	52.2	60.7	59.3
7	3	50 N	55.4	52.7	65.3	64.2
7	3	300 F	53.2	47.6	61.7	55.4
7	4	100 N	49.1	49.2	59.4	59.3
7	4	400 F	49.7	44.9	58.7	52.2

*These values were not used in the statistical analysis but were used in the analysis of correction errors.

TABLE B-14

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5X (TRUCKS AT HALF FREQUENCY) WITH MEASURED LEVELS AT SITE 4 ON U. S. 29 NEAR RUCKERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
8	1	50 N	51.2	58.6	68.5	71.0
8	1	100 F	46.9	51.2	55.5	61.4
8	2	50 N	59.8	61.6	71.8	73.8
8	2	200 F	47.2	45.9	53.6	56.1
8	3	50 F	56.6	60.1	70.9	71.4
8	3	100 F	49.3	51.5	55.4	60.7
8	4	300 F	42.5	42.9	46.9	51.4

TABLE B-15

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5X
(TRUCKS AT HALF FREQUENCY) WITH MEASURED LEVELS
AT SITE 5 ON I-95 NEAR DOSWELL

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{10} MEAS.	L_{10} CALC.
9	1	85 N	61.5	60.2*	69.8	69.9*
9	1	150 F	62.6	59.2*	70.8	67.2*
9	2	150 N	64.7	59.9	73.5	68.2
9	2	200 F	63.9	58.6	70.4	65.1
9	3	150 N	65.0	59.4	74.3	67.9
9	3	300 F	62.1	56.8	69.4	62.4
9	4	150 N	62.6	59.9	73.9	68.2
9	4	400 F	58.3	56.0	67.2	60.9

*Trucks on side road ignored in these calculations.

TABLE B-16

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5V (TRUCKS AT 13.5 FT.) WITH MEASURED VALUES AT SITE 1 ON I-495 NEAR SPRINGFIELD

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{10} MEAS.	L_{10} CALC.
1	1	56 N	76.9	76.5	85.0	84.5
1	1*	106 F				
1	2	56 N	77.4	77.1	85.7	84.8
1	2	206 F	63.6	62.0	67.3	66.6
1	3	56 N	76.4	76.5	85.2	84.5
1	3	306 F	58.0	57.0	62.2	61.1
2	1	56 N	77.9	76.4	84.7	84.1
2	1	206 F	64.1	60.7	68.3	65.5
2	2	56 N	77.3	76.0	83.5	83.8
2	2*	106 F				
3	1	56 N	76.4	75.9	83.3	83.7
3	1*	106 F				
3	2	56 N	75.9	76.7	83.7	84.4
3	2	206 F	60.7	61.8	63.8	66.2
3	3	56 N	73.5	74.4	81.7	82.9
3	3	306 F	58.0	56.2	63.2	60.4

*These values not included in statistical analysis.

TABLE B-17

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5V (TRUCKS AT 13.5 FT.) WITH MEASURED VALUES AT SITE 2 ON I-495 NEAR ALEXANDRIA

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{10} MEAS.	L_{10} CALC.
4	1	66 N	75.9	76.2	82.2	83.6
4	1	106 F	74.1	73.9	79.8	80.1
4	2	66 N	77.0	75.7	83.0	83.3
4	2	206 F	71.8	70.1	76.4	75.0
4	3	66 N	75.9	75.1	82.3	82.9
4	3	306 F	67.9	67.4	71.7	71.6
5	1	66 N	75.5	76.2	82.1	83.5
5	1	306 F	65.3	68.4	70.5	72.4
5	2	66 N	76.4	76.4	83.5	83.7
5	2	206 F	70.5	70.8	75.8	75.5
5	3	66 N	75.5	75.3	81.4	83.0
5	3	106 F	72.8	73.1	78.6	79.5

TABLE B-18

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5V (TRUCKS AT 13.5 FT.) WITH MEASURED VALUES AT SITE 3 ON I-64 NEAR FISHERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50}		L_{10}	
			MEAS.	CALC.	MEAS.	CALC.
7	1*	50 N	53.8	67.7	63.4	80.0
7	1*	100 F	51.7	63.7	59.8	74.7
7	2	50 N	56.1	56.9	63.7	68.5
7	2	200 F	54.1	54.3	60.7	62.3
7	3	50 N	55.4	56.7	65.3	69.2
7	3	300 F	53.2	51.6	61.7	60.6
7	4	100 N	49.1	52.2	59.4	63.9
7	4	400 F	49.7	47.2	58.7	56.4

*These values were not used in the statistical analysis but were used in the analysis of correction errors.

TABLE B-19

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5V (TRUCKS AT 13.5 FT.) WITH MEASURED VALUES AT SITE 4 ON U. S. 29 NEAR RUCKERSVILLE

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{10} MEAS.	L_{10} CALC.
8	1	50 N	51.2	58.6	68.5	71.0
8	1	100 F	46.9	54.4	55.5	66.2
8	2	50 N	59.8	61.6	71.8	73.8
8	2	200 F	47.2	51.5	53.6	63.0
8	3	50 N	56.6	60.1	70.9	71.4
8	3	100 F	49.3	51.6	55.4	60.9
8	4	300 F	42.5	47.7	46.9	58.1

TABLE B-20

COMPARISON OF LEVELS CALCULATED BY MICNOISE 5V (TRUCKS AT 13.5 FT.) WITH MEASURED VALUES AT SITE 5 ON I-95 NEAR DOSWELL

TEST #	TRIAL #	MICR. LOCN.	L_{50} MEAS.	L_{50} CALC.	L_{10} MEAS.	L_{10} CALC.
9	1	85 N	61.5	66.7*	69.8	77.3*
9	1	150 F	62.6	63.9*	70.8	72.2*
9	2	150 N	64.7	64.2	73.5	72.8
9	2	200 F	63.9	63.8	70.4	71.1
9	3	150 N	65.0	63.8	74.3	72.6
9	3	300 F	62.1	61.3	69.4	67.6
9	4	150 N	62.6	64.6	73.9	73.1
9	4	400 F	58.3	60.4	67.2	65.8

*Trucks on side road ignored in these calculations.

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FIELD EVALUATIONS OF WATERPROOF MEMBRANE SYSTEMS FOR BRIDGE DECKS 1972-1974

by

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SUMMARY

Waterproof membrane systems are being studied by many agencies from the standpoint of their effectiveness in protecting the reinforcing steel in concrete bridge decks against corrosion. Trial applications and evaluations of six such systems, including both preformed sheet and liquid membranes, were made in Virginia during the period from 1972 through 1974. These field evaluations included observations of the installation procedures and assessments of the subsequent waterproofing effectiveness of the systems through electrical resistivity measurements. While none of the systems could be considered an unqualified success, four of the systems showed promise, with modification of the application techniques used in the study, of providing the desired degree of long-term protection.

Specific details of the application techniques and performances of each of the membrane systems are presented as is an evaluation of the effectiveness of earlier epoxy resin sealcoats.

FIELD EVALUATIONS OF WATERPROOF MEMBRANE SYSTEMS FOR BRIDGE DECKS 1972-1974

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INTRODUCTION

It is generally agreed that corrosion of the top reinforcing steel in a concrete bridge deck in the presence of chloride ions that have entered the concrete through its pores or cracks is a primary cause of spalling of the deck. In many areas the correction of spalling is a major maintenance expense, and much effort is being devoted to its prevention. One of several schemes being evaluated as a means of preventing corrosion of the steel is the installation of a waterproof membrane on the top surface of the deck. Trials of bridge deck membranes are being conducted by many transportation agencies, and among these are nationwide investigations under the auspices of the Federal Highway Administration (NEEP No. 12) and the Transportation Research Board (NCHRP Project 12-11).

The emphasis on the use of waterproof membrane systems has caused a proliferation in the number of systems available to the highway engineer since 1972. Some of the new membranes are very promising; they appear to offer better protection and the potential of greater economy than earlier systems such as the coal tar epoxy sealcoat widely used in Virginia. For these reasons, a limited program of field trials of promising membrane systems was proposed by the Virginia Highway and Transportation Research Council in 1972.

PURPOSE AND SCOPE

The purpose of the subject study was to evaluate a number of new membrane systems and to compare their application procedures and subsequent performances with those of the epoxy resin sealcoats. It was initially envisioned that the study would be limited to products which showed promise of success based on their trial by other agencies, but trials of experimental membranes were later included. While the determination of an effective system was a primary goal, the research was also intended to provide the Department of Highways and Transportation with sufficient background information to allow the adoption of the findings of more extensive studies being conducted by other agencies.

The project began in July 1972, with a survey of the waterproofing systems then used by the Department, followed by evaluations of the six membrane systems listed below.

1. Heavy Duty Bituthene — 3 installations.
2. Protecto Wrap — 2 installations.
3. Witmer System — 1 installation.
4. Polytok Membrane 165 — 1 installation.
5. Chevron's System — 1 installation.
6. Two-Coat Coal Tar Epoxy Sealcoat — 1 installation.

The performances of the membranes at these nine installations were evaluated using the electrical resistivity test procedure developed by Spellman and Stratfull of California.(1) Only limited laboratory tests were performed.

THE ELECTRICAL RESISTIVITY TEST

The electrical resistivity test, reported in 1971, remains virtually the only way to evaluate the effectiveness of a membrane in place on a bridge deck. The resistance is measured in the circuit shown in Figure 1, in which an ohmeter is connected to the deck reinforcement and to a copper plate and sponge on the wetted deck surface. Water, with a wetting agent added, is applied to the surface of the overlay and given time to permeate the asphaltic concrete, and a reading is taken. If the membrane, which must be of a dielectric material, is completely waterproof, the resistance will be infinite. Holes in the membrane, which allow the passage of water, reduce the resistance. On the basis of laboratory tests Spellman and Stratfull initially established a value of 500,000 ohms per square foot (0.09 m^2) as being indicative of an effective membrane. At this writing there appears to be a widely held, but unwritten, opinion that values above 200,000 ohms per square foot (0.09 m^2) are acceptable.

Because of several factors that can cause significant errors in the readings, proper application of the electrical resistivity test requires considerable judgment. The most critical factor appears to be the size of the wetted area in the asphaltic concrete overlay. Conventionally, the wetted area is assumed to be equal to the area of the copper plate, and the resistance reading is reported in relation to the area of the plate. Obviously, however, the resistance is read over the entire wetted area, and care must be used in minimizing the spread of water on the surface of and within the asphaltic concrete layer. The overlay must be dry initially, but it is difficult to determine when this condition is met. In order to approach the desired dryness, a period of about one week without rain was allowed before the readings in this study were taken.

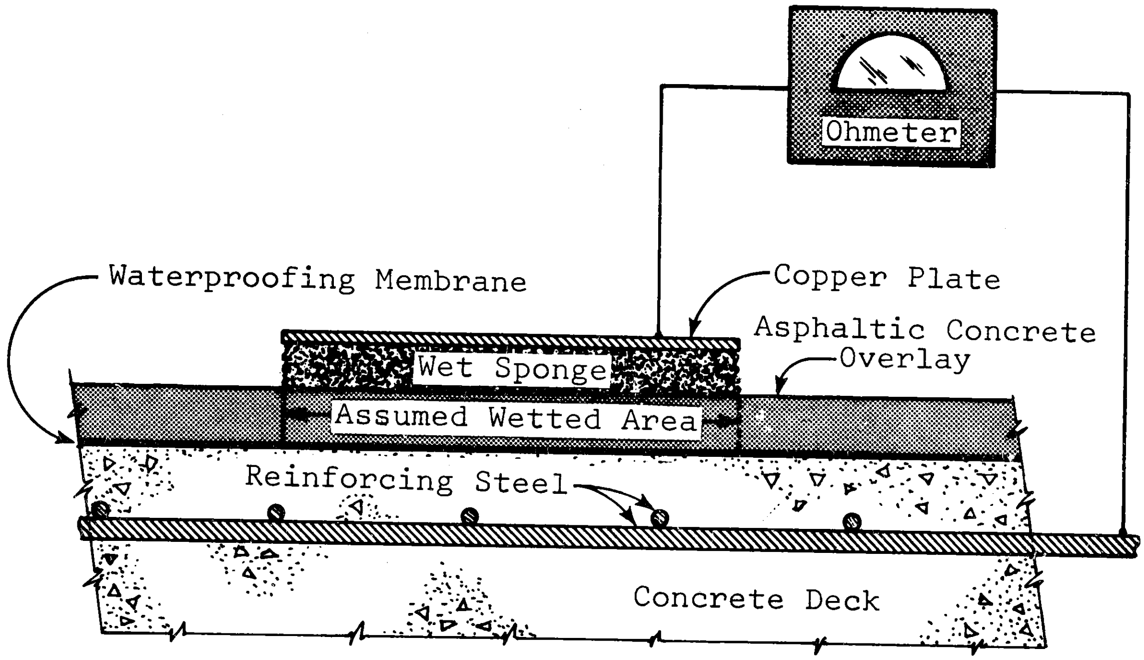

Figure 1. Assumed circuit for the electrical resistivity test.

Although difficulty is seldom encountered, care must also be exercised in selecting a proper connection to the reinforcing steel, because the connection can influence the resistivity readings. It is also important that no part of the wetted area touch bare concrete at the edge of the membrane. Several other factors that can significantly affect the reliability of the readings have been cited in a recent "Paving Information Bulletin" published by Phillips Petroleum.(2) Among these were the distance between the electrodes, the specific resistivity of the wetting agent, and the quantity of residual soluble salts in the overlay or the concrete.

The factors cited previously indicate the need for care in obtaining resistance readings. Newly placed membranes should be evaluated as soon as possible after paving, preferably before rain has fallen, to avoid the effects of moisture in the overlay. Reliable data can be obtained on new installations, but as pointed out in a recent FHWA notice, the interpretation of resistivity data taken on in-service decks requires both experience and judgment.[3] The pattern of resistance values at various points on the decks, as well as the values themselves, were found to be important in the interpretation of the data taken in this study.

EVALUATION OF MEMBRANES IN USE IN 1972

The Virginia study began with an assessment of those waterproofing systems in use in 1972. The then applicable specifications allowed two systems: Class I, a coal tar epoxy resin applied at a rate of one gallon per 30 square feet (1.36 ℓ/m^2), upon which grit was applied at a rate of 11 to 15 pounds per square yard (6.0-8.1 kg/m^2); and Class II, a built-up multilayer system consisting of three layers of fiberglass alternated with four moppings of asphalt, applied at a total rate of not less than 16 gallons per 100 square feet (6.5 ℓ/m^2), on a previously primed deck.[4] Both the Class I and Class II systems were generally protected by an asphaltic concrete overlay. A few variant systems had also been placed on an experimental basis.

Unfavorable experiences with the Class II system had resulted in an overwhelming predominance of the Class I epoxy system, to the extent that it could be considered the Virginia standard. In fact, conditions did not allow the testing of a Class II system, which in the majority of cases was used on prestressed concrete box superstructures that were not suited to the resistivity tests. The effectiveness of those systems tested during the summer of 1972 is described below; a short discussion of systems similar to the Class II system is also included.

Class I — Coal Tar Epoxy Resin Sealcoats

Twenty-three bridges waterproofed through the use of an epoxy sealcoat with grit and an asphalt wearing course were evaluated. Most of the decks were sealed with a single coat of epoxy, but some had areas with a double coating. The results of the electrical resistivity tests are shown in two forms in Figures 2 and 3.

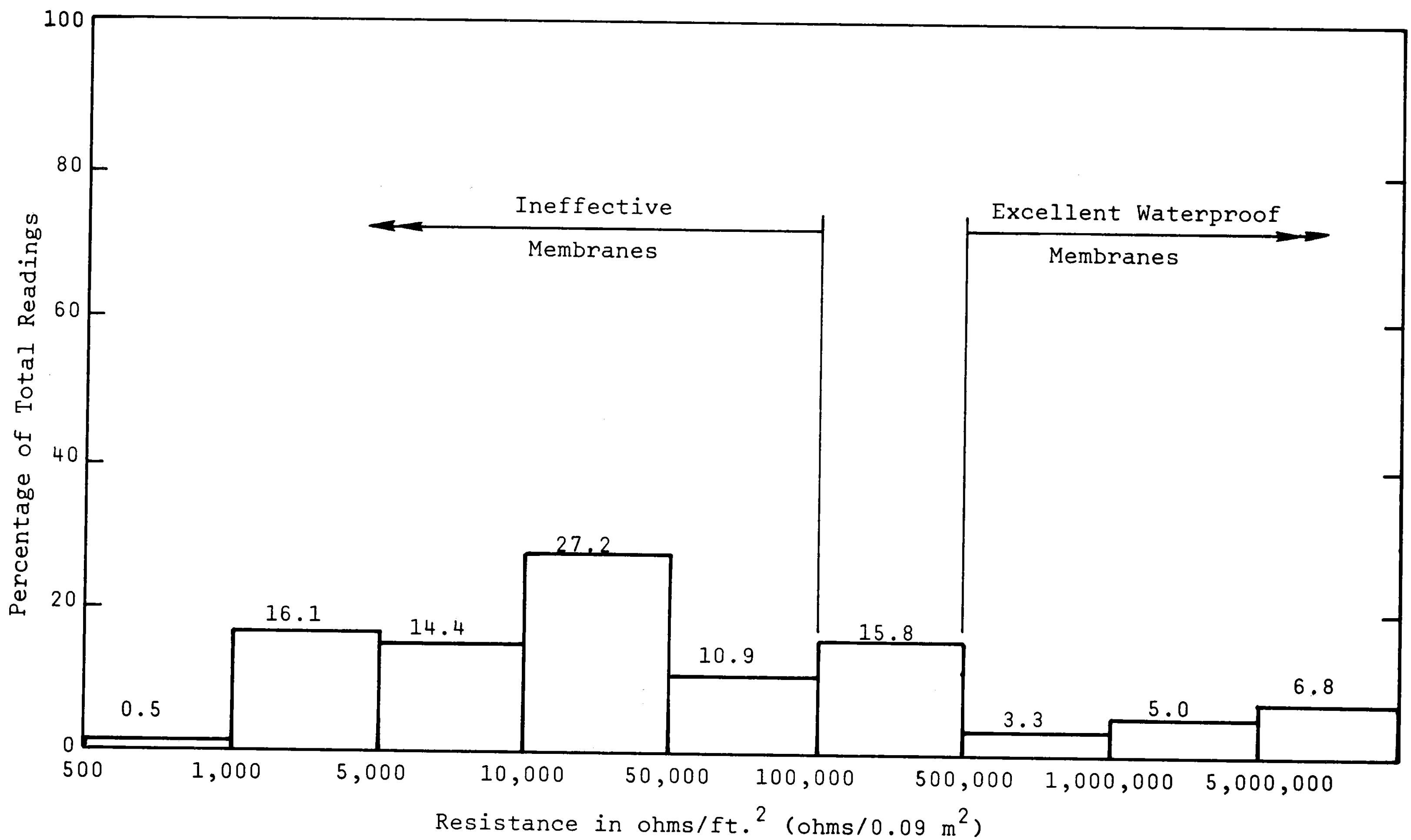

Figure 2. Distribution of resistivity readings from 23 bridges with coal tar modified epoxy resin sealcoats.

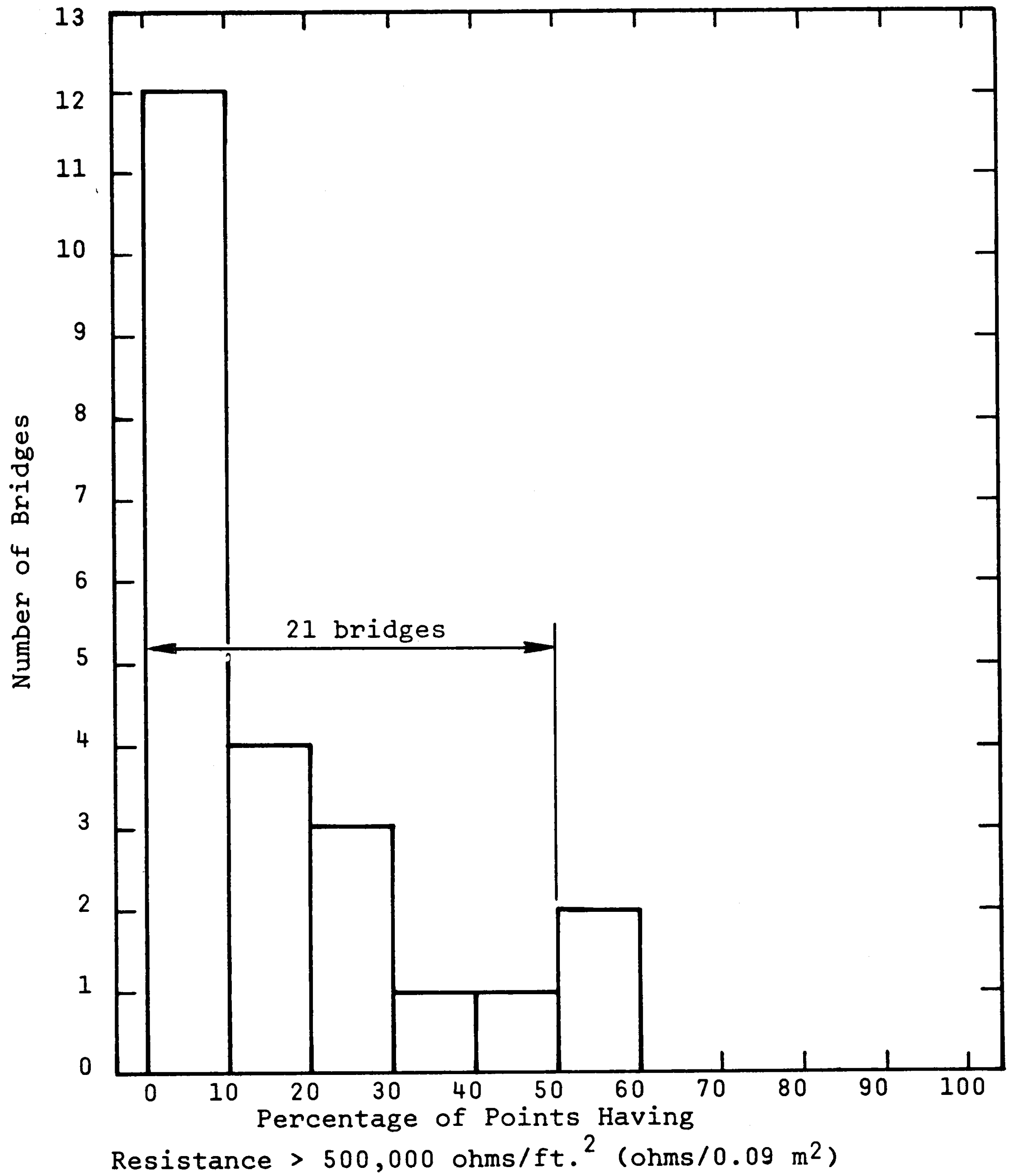

Figure 3. Percentage of points with effective waterproofing on 23 bridges with coal tar modified epoxy resin sealcoats.

Figure 2 is a plot of the percentages of all of the resistivity readings from the 23 bridges falling in several arbitrarily selected ranges of resistance in ohms per square foot. It is important to note that 69.1 percent of the readings were below 100,000 ohms per square foot (0.09 m^2), which is indicative of an ineffective waterproof membrane, while only 15.1 percent were above 500,000 ohms per square foot (0.09m^2), which is considered to be indicative of an excellent waterproofing system.(1) Thus, in general, the epoxy sealcoats did not appear to be providing satisfactory protection.

Figure 3 provides an indication of the effectiveness of the epoxy resin sealcoats on individual bridges. Here, the percentage of points at which effective waterproofing was indicated is plotted versus the number of bridges. Thus, for example 12 bridges each had 0 to 10 percent of their readings above 500,000 ohms per square foot (0.09 m^2), based on a 5-foot (1.52 m) coordinate grid system in most cases. It is important to note that of the 23 bridges tested only two had epoxy resin sealcoats that could be considered more than 50 percent effective. The best of these had only 57 percent of the readings above 500,000 ohms per square foot (0.09 m^2). Similar data, not shown, based on the failure criteria indicated that 17 bridges had 50 percent or more readings below 100,000 ohms.

Thus it appears, on the basis of electrical resistivity measurements, that a single application of an epoxy resin sealcoat does not provide effective waterproofing. Similar results were found later in the study when single coatings of an epoxy system without grit were tested, and the findings are consistent with those of a nationwide survey conducted by the Federal Highway Administration.(5) Those deck areas with double coatings of epoxy, while not uniformly satisfactory, yielded higher resistance readings.

Coal Tar Emulsion Sealcoats

Sealcoats consisting of a single coating of a coal tar emulsion were tried in a few instances prior to the summer of 1972 in an attempt to find an economical waterproofing system. Resistivity tests on two structures with such membranes gave unimpressive results. The great majority of the readings were below 100,000 ohms per square foot (0.09 m^2), and use of the system has been discontinued.

Class II — Asphalt-Fiberglass Multilayer Membrane

The Class II waterproofing system has not been popular in Virginia because of application difficulties and the possibility of the membrane sliding under traffic. No representative installation was found for testing, but the results of studies of similar systems by other agencies are available.

A report from the Federal Highway Administration's National Experimental and Evaluation Program Project Number 12 stated that the performance of a similar coal tar-fiberglass layered system "varies between good and bad depending on construction practice."(5) Tests of similar systems using hot mopped asphalt and coal tar emulsion performed in Vermont indicated that the membranes were not waterproof before paving, but the pavement and membrane systems initially were waterproof in both cases.(6) However, neither system was recommended for further use as a bridge deck membrane, possibly because neither exhibited good flexibility and elongation at low temperatures.

Summation

There is ample evidence that a single layer epoxy membrane cannot be considered waterproof, and that the coal tar emulsion system appears similarly weak. Further testing of a double layer epoxy system in which the first layer was applied without grit will be described in more detail later, but this system also failed. The poor electrical resistivity results plus the inherent expense of the epoxy systems argue strongly for trials of the newer membranes described later. While no firm data on the Class II layered system are available, the national consensus cannot be considered promising.

TESTS OF NEW MEMBRANE SYSTEMS

Heavy Duty Bituthene (W. R. Grace & Co.)

Installations

1. Route 340 over Harners Run, Augusta County, Deck area 2,535 s.f. (235.5 m^2), September 1972.

2. Route 19 over Little River, Tazewell County, Deck area 6,525 s.f. (606.2 m^2), August 1973.

3. (a) Route 64 (EBL) over Burcher Road, City of Newport News, Deck area 7,560 s.f. (702.4 m^2), July 1974.

   (b) Route 64 (WBL) over Burcher Road, City of Newport News, Deck area 7,560 s.f. (702.4 m^2), August 1974.

Description

Heavy Duty Bituthene is a prefabricated sheet membrane consisting of a woven mesh sandwiched between a layer of adhesive grade rubberized asphalt and a layer of non-tacky bituminous compound, and has a total thickness of 65 mils (1.7 mm). It is produced in rolls 3 feet (0.9 m) wide by 60 feet (18.3 m) long interwound with a release paper.

Application Procedure

The steps in a typical application of the Bituthene system are shown in Figures 4-8. The deck surface (Figure 4) was cleaned of all soil, loose debris, and accumulations of oil or grease. This required only a light brush sandblasting, after which the deck was blown clean. Bituthene primer was then applied to the decks and the faces of the wheel guards (Figure 5) and allowed to cure to a non-tacky state. Application of the sheet membrane began with the placement of short strips at the wheel guards (Figure 6) in order to provide a shingling of subsequent laps toward the low points of the deck. The membrane was extended up the face of the wheel guards for a distance equal to the depth of the overlay. Subsequent strips of the membrane were unrolled by pulling the release paper (Figure 7). After placement of the membrane its free edges were sealed with mastic and it was rolled lightly with a garden roller to ensure proper contact with the deck surface (Figure 8). Finally a 1½-inch (3.8 cm) thick asphaltic concrete overlay meeting the requirements of Table 1 was placed directly on the membrane. The treatment of the filled expansion joints in the deck consisted of placing 8-12 inch (20-30 cm) strips of the membrane along their lengths, covering them with the uncut deck membrane, and paving continuously across them.

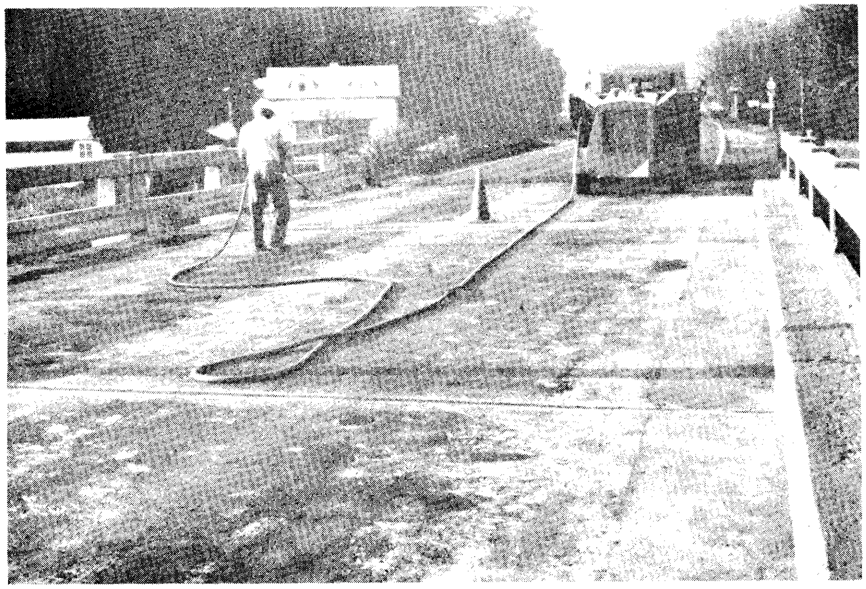

Figure 4. Deck surface prepared for application of Bituthene membrane.

Figure 5. Application of Bituthene primer.

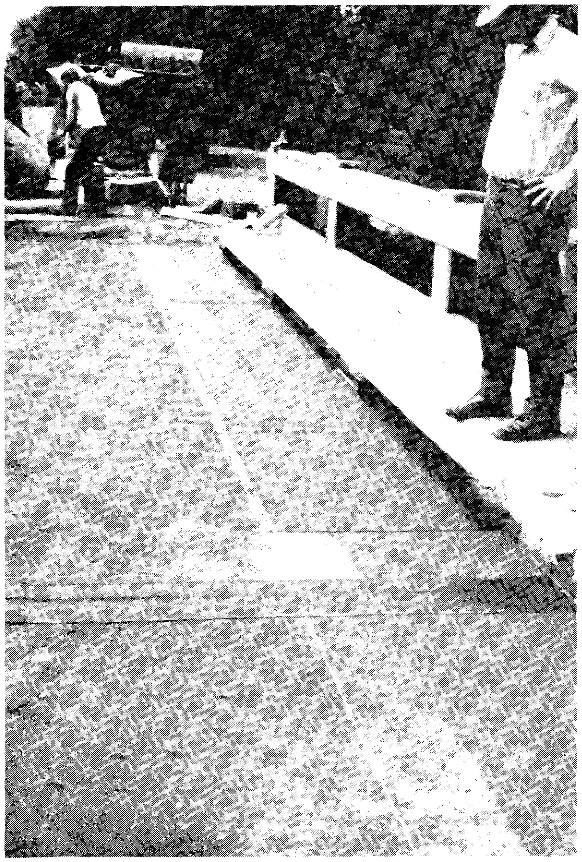

Figure 6. Placement of short strips of Bituthene membrane along curb.

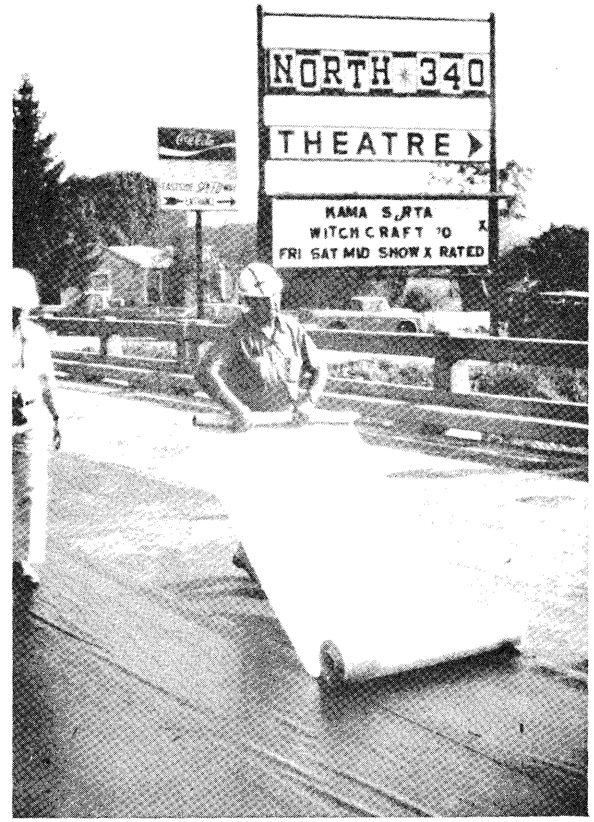

Figure 7. Unrolling of sheet membrane by pulling release paper.

Table 1

Specification Requirements for Type S-5
Bituminous Concrete Mixture Used to Overlay
Bridge Deck Membrane Systems(4)

PERCENTAGE BY WEIGHT PASSING SQUARE MESH SIEVES*						
1/2 in.	3/8 in.	No. 4	No. 8	No. 30	No. 50	No. 200
12.7 mm	9.5 mm	6.4 mm	3.2 mm	0.8 mm	0.5 mm	0.1 mm
100	80-100		35-55	15-30	7-22	2-10
PERCENT BITUMINOUS MATERIALS: 5.0 - 8.5						
MIX TEMPERATURE (AT PLANT): 225 - 300°F 107 - 149°C						

*Numbered sieves are those of the U. S. Standard Sieve Series.

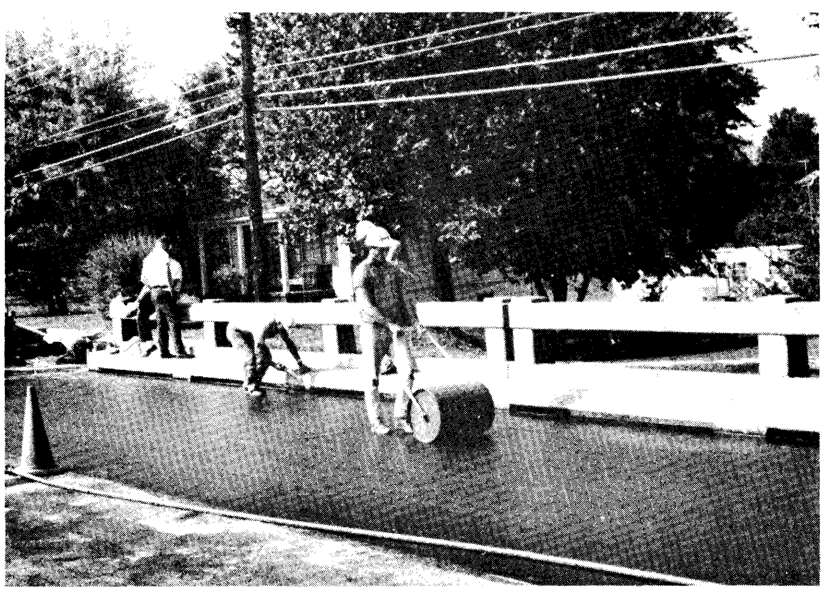

Figure 8. Rolling of the membrane to assure contact with the deck.

Evaluation

The application of a Heavy Duty Bituthene membrane, while more difficult than that of other systems because of its strong adhesion, is relatively easy to master. Pieces of the material must not be allowed to double over and care must be used in unrolling the material since it cannot easily be removed from the deck. In spite of the obvious need for careful placement of the membrane, each of the four installations was completed in one day by inexperienced personnel with the guidance of representatives of the manufacturer.

Hot weather can render the application more difficult as the adhesion of the membrane to the backing paper is increased. Sizeable blisters are also formed beneath the membrane during warm weather, but no distress resulting from the blisters has been noted. Paving has proved to be the most critical phase in the placement of any of the newer membrane systems. The asphaltic concrete overlay must be placed before the bridge is opened to traffic, but the quantity of material required is not large. Coordination of the paving operation is, therefore, difficult, but care must be exercised to avoid damaging the membrane.

With proper care, good initial results can be attained. The Route 340 bridge over Harners Run was first tested on October 2, 1972, at which time only 4 out of 120 points on a 5 x 5 foot (1.5 x 1.5 m) grid had resistivity readings below 500,000 ohms per square foot (0.09 m^2). Two of these initial readings occurred in an area at which the asphalt overlay was thin. However, resistivity readings taken on August 31, 1973, approximately one year after installation,had the pattern shown in Table 2. It can be seen that while the readings remain generally high in the shoulder areas, they have dropped to unsatisfactory levels in the wheel path areas. The readings at the centerline, while somewhat higher, are also unsatisfactory. The structure was considered dry at the time of testing; there was good provision for drainage and no rain had fallen for ten days.

This characteristic pattern of low resistivity readings in the traffic lanes was noted on all of the other applications and it was apparent, though not as severe, in the case of the Burcher Road bridges approximately two months after installation. The cause of the deterioration has not been determined with certainty. Attempts to remove the overlay from the Little River bridge were hampered by the excellent bond of the asphalt to the membrane. It did appear, however, that some of the membrane constituents had migrated into the rather coarse asphalt overlay. Similar problems were noted in the case of the two Protecto-Wrap installations described in the next section of this report.

Table 2

Array of Resistivity Readings, ohms x 10^{-3} Per Square Foot (0.09 m^2) Taken on a 5 x 5 ft. (1.5 x 1.5 m) Grid, Rte. 340 Bridge Over Harners Run, 8/31/73

	Curb	Wheelpath	Wheelpath	℄	Wheelpath	Between Wheelpaths	Curb
	1	2	3	4	5	6	7
1	1.80	0.012	0.01	2.00	0.07	0.02	20.00
2	4.00	0.02	0.03	2.00	0.06	0.02	20.00
3	.30	0.03	0.05	0.70	0.02	0.02	20.00
4	1.08	0.02	0.08	0.07	0.02	0.02	20.00
5	.30	0.03	0.03	0.14	0.03	0.04	0.65
6	5.00	0.02	0.02	0.19	0.07	0.03	20.00
7	1.10	0.02	0.05	0.12	0.03	0.05	20.00
8	.80	0.02	0.03	0.11	0.03	0.02	1.50
9	.40	0.02	0.03	0.13	0.06	0.03	0.70
10	.64	0.04	0.06	0.18	0.22	0.04	3.00
11	20.00	0.05	0.03	0.28	0.06	0.04	1.20
12	20.00	0.04	0.02	0.03	0.07	0.04	20.00
13	5.00	0.04	0.02	0.11	0.05	0.02	1.25
14	10.00	0.03	0.02	0.12	0.05	0.03	0.46
15	.28	0.02	0.04	0.06	0.05	0.35	0.82
16	1.50	0.03	0.02	0.03	0.05	20.00	0.35
17	20.00	0.04	0.04	0.10	0.02	20.00	0.71
18	20.00	0.03	0.06	0.11	0.10	20.00	0.32
19	.80	0.03	0.08	0.04	20.00	20.00	1.25
20	.60	0.04	0.05	0.09	20.00	0.22	0.69

The rather simple treatment of the deck expansion joints worked well on the short, rigid concrete beam spans of the Harners Run Bridge, in which little movement would be expected. However, cracking and raveling of the overlay has occurred over the joints between the longer spans of the Burcher Road Bridges. Additional consideration will have to be given to the treatment of the joints in all but the shortest spans if Bituthene and, possibly, other newer membrane systems are used.

Costs

The recent costs of installing the Bituthene membranes with 165 pound (74.8 kg) asphalt overlays on the two Burcher Road bridges, including materials, equipment and labor, were $1.04 per square foot (0.09 m^2) for the eastbound lane structure and $0.97 per square foot (0.09 m^2) for the westbound lane structure. Both installations were made by state maintenance forces.

Protecto Wrap M-400

Applications

(1) Route 81 (SBL) over Route 260, Shenandoah County, Deck area 8,232 s.f. (764.8 m^2), October 1972.

(2) Route 19 over Indian Creek, Tazewell County, Deck area 6,020 s.f. (559.3 m^2), August 1972.

Description

Protecto Wrap M-400 is a prefabricated sheet membrane composed of a non-woven synthetic fiber between layers of coal tar modified with synthetic resins, with a total thickness of approximately 70 mils (1.8 mm). It is generally available in rolls 30 inches (0.7 m) and 60 inches (1.5 m) in width and 50 feet (15.2 m) long. One side of the membrane has a polyethlene separator sheet which is removed after placement.

Application Procedure

The application of a Protecto Wrap membrane, shown in Figures 9-12, was similar to that for the Bituthene membrane described previously. The deck, which had been cleaned of all loose material, and the faces of the wheel guard were primed with Protecto Wrap No. 80 primer (Figure 9), and allowed to dry to a tack-free condition.

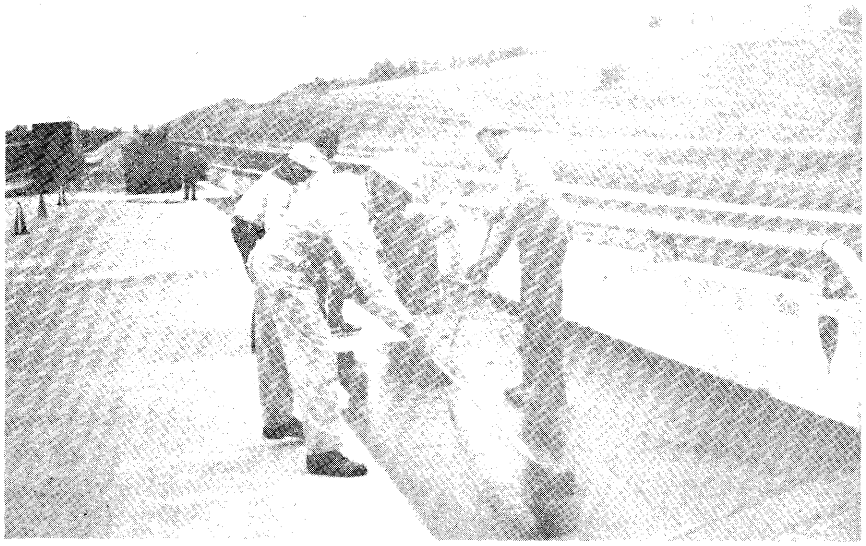

Figure 9. Application of Protecto-Wrap membrane.

Figure 10. Unrolling of Protecto-Wrap membrane.

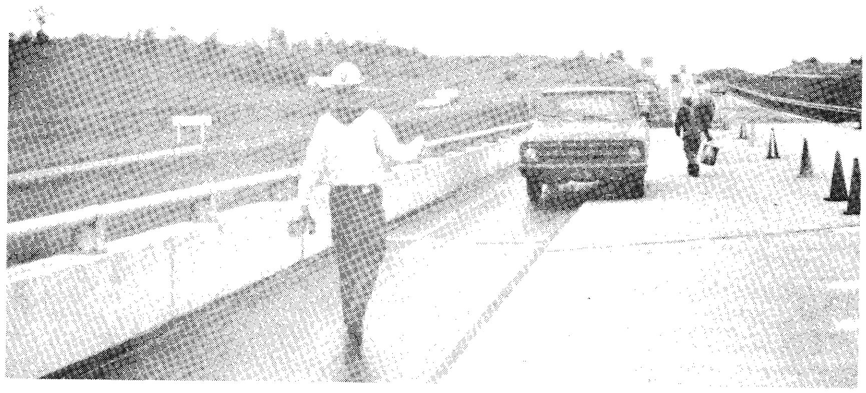

Figure 11. Rolling with light truck to set the laps between adjacent membrane sheets.

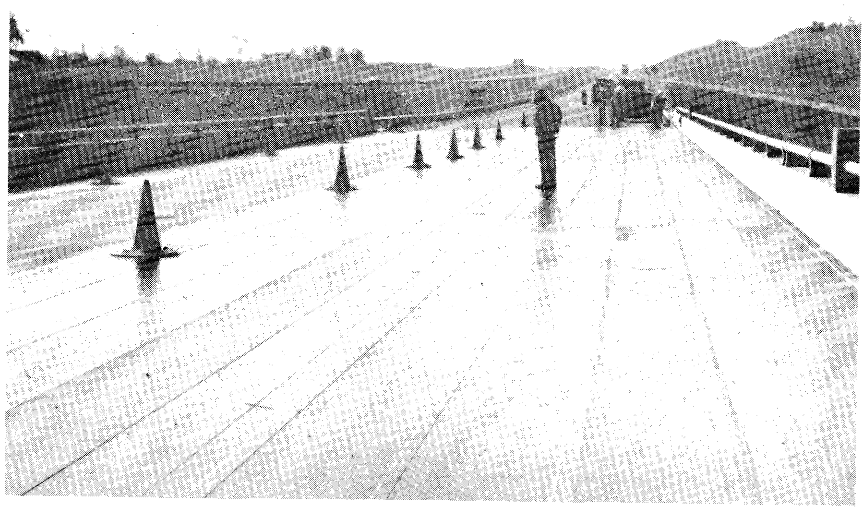

Figure 12. View of completed Protecto-Wrap membrane before paving.

Placement of the membrane began at the curb and at the low end of the bridge. The sheets were unrolled as shown in Figure 10 and lapped a minimum of 3 inches (7.62 cm) at the sides and ends of the preceding strips. A light truck was used to set the laps between rolls (Figure 11). Expansion joints were coated with mastic and the membrane was cut over the joint after placement. Finally the polyethylene separator sheet was removed (Figure 12) and the membrane was paved.

Evaluation

The Protecto Wrap membrane is easily applied. Because the membrane is not of an extremely adhesive nature, it can be adjusted once it has been placed. Some difficulty was noted in unrolling the 5-foot (1.5 m) wide rolls used on the Tazewell County bridge, but this may have been a temporary defect in the materials. Although more personnel were required, in that case, to unroll the material, the work proceeded with efficiency. The placement of the Protecto Wrap membrane is easily mastered.

Placement of the asphaltic concrete overlay requires care to avoid damage to the Protecto Wrap membrane, as with other systems. Some damage was noted during the paving operations on the Route 19 bridge. This difficulty could have been avoided had the paving operations proceeded more slowly, but the bridge overlay was only a small part of a large resurfacing contract on Route 19. It should be noted that only a tracked paver was available rather than a rubber tired machine recommended by the manufacturer.

Weather conditions did not allow the obtaining of initial readings on either bridge, and poor drainage of the deck of the Route 81 bridge prevented any meaningful resistivity evaluations. Resistivity measurements made on the Route 19 membrane about one year after placement showed a pattern similar to that described previously for the Bituthene membrane; the readings were low in the traffic areas and higher at the edges of the roadway.

Raveling of the asphaltic concrete overlay over the filled expansion joints (Figure 13) was noted in both installations. An attempt to attain better protection of the deck by leaving the membrane intact over the joint failed through raveling within two months, and this practice should be discontinued. Loss of the overlay was subsequently noted in areas where the membrane had been cut over the joint in accordance with the manufacturer's recommendations. The adhesion of the overlay to the membrane is not strong enough to prevent raveling, so treatment of the overlay at the joints should receive consideration.

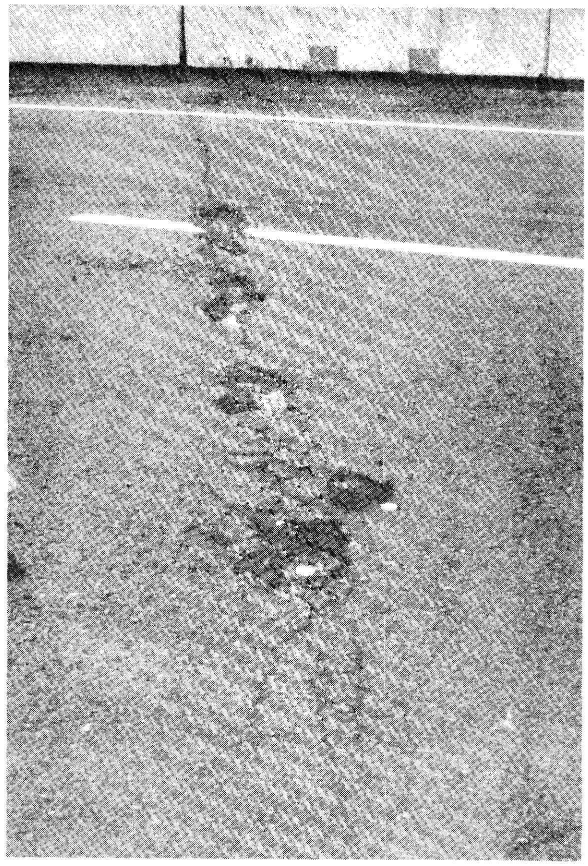

Figure 13. Raveling of asphaltic concrete overlay over deck expansion joints.

Cost

The cost of the installation on the Route 81 bridge was \$1.12 per square foot (0.09 m^2), including materials, equipment and labor.

Witmer Bridge Decking Membrane System (Witco Chemical)

Applications

(1) Route 250 over C & O Railroad, Albemarle County, Deck area 5,965 s.f. (554.2 m^2), June-July 1974.

Description

The Witmer Bridge Decking Membrane System is a two-component, bitumen extended, polyurethane elastomer, applied cold in liquid form in two coats to attain a minimum total thickness of 60 mils (1.5 mm).

Application Procedure

Both coats of the Witmer membrane were applied by squeegees.

The deck, which was surface dry and free of dust, dirt, grease or oil, was primed by squeegee with a mixture of 1 part of each of the two components and 1 part of solvent (Figure 14). After the prime coat had cured sufficiently to permit access, approximately three hours later, the second coat, composed of one part of each of the two components, with sufficient solvent for proper flow, was applied. The second application was allowed to cure for 24 hours before paving. No protective board or roofing sheet was applied to the membrane before paving, although the manufacturer's literature stated that "ideally" a layer of protection board was recommended.

Evaluation

Installation of the Witmer membrane is basically a simple process, although attention must be given to maintaining the proper rate of application. The only difficulty encountered in placing the liquid was the formation of a great many bubbles (Figure 15) in the first coat. These were probably due to the hot weather, temperatures over 90° F (32° C), and, possibly, the presence of air entrapped in the liquid during mixing. Unfortunately, it was impossible to compact the asphaltic concrete overlay because of poor bond between it and the membrane. As a result, the overlay failed quickly under traffic (Figure 16). Attempts to achieve bond through the use of a cutback asphalt tack coat and, later, the dusting of the tacky membrane with sand, were to no avail. Laboratory tests in which the specified overlay material and the membrane were placed on concrete cylinders and compacted in a Marshall mold disclosed no significant bond unless a piece of roofing sheet was placed on the tacky membrane. It appears that use of some sort of protective layer, placed while the membrane is still tacky, is mandatory to provide bond between the courses.

Figure 14. Application of Witmer liquid membrane with squeegees.

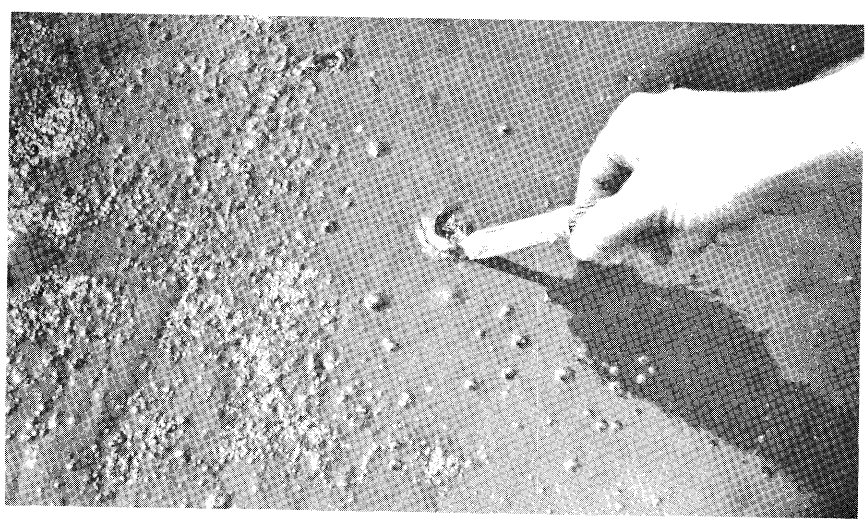

Figure 15. Bubbles in first coat of Witmer membrane.

Figure 16. Failure of asphaltic concrete overlay on Witmer membrane.

Resistivity tests taken on the membrane after the application of the second coat, but before paving, indicated that a waterproof barrier existed; all readings were above 500,000 ohms per square foot (0.09 m^2). Slight damage to the membrane in the truck wheelpaths was seen during paving, but subsequent resistivity readings were below 500,000 ohms per square foot (0.09 m^2) in many areas across the deck. Some of the loss in effectiveness may have been due to the effect of bubbles in the membrane.

Further use of the Witmer membrane without a proper protective layer on the membrane is not recommended. Such a layer, which might possibly be only a compatible roofing sheet, would, most importantly, provide sufficient bond to allow successful paving, but it might also improve the system as a waterproof barrier.

Because of the paving problems the Witmer membrane was removed and the two-coat coal tar modified epoxy system described in the next section was substituted for it.

Costs

The application of the Witco membrane installed by a contractor was initially bid at \$1.78 per square foot (0.09 m^2). Additional work caused by the paving difficulties was negotiated on a work order basis.

Two-Coat Coal Tar Modified Epoxy Resin Membrane

Applications

(1) Route 250 over C & O Railroad, Albemarle County, Deck area 5,965 s.f. (554.2 m^2), July 1974. (Replaced previously described Witmer membrane.)

Description

Coal tar modified epoxy resin sealcoats have been widely used in Virginia for several years. As described previously, resistivity tests have indicated that these sealcoats, most of which were composed of a single application of epoxy with sand cast on the surface, were inadequate as waterproof barriers. It was desired to test a two-coat application in which sand is cast only on the second coat. The average rate of application, including both coats, was 0.5 gallon per square yard (0.7 ℓ/m^2), or 1.67 gallons per 30 square feet, (2.3 ℓ/m^2), as opposed to the rate of 1 gallon per 30 square feet (1.4 ℓ/m^2) specified for a single-coat application.

Application Procedure

Application of the epoxy membrane was routine. The surface of the deck was scarified to remove the preceding membrane, sandblasted, and blown clean, and the epoxy was applied with squeegees. Sufficient time, about three hours, was allowed for curing of the first coat before placement of the second. Sand was applied only to the surface of the second coat.

Evaluation

A large number of bubbles (Figure 17) were apparent in the first coating of epoxy, which was applied early in the day during hot weather, with temperatures approaching 90° F (32° C). The bubbles were covered by the second coat, and resistivity measurements taken before paving indicated that the double coating was completely waterproof. Resistivity readings taken after paving showed a drop in effectiveness; approximately half of the readings were below 200,000 ohms per square foot (0.09 m^2). The drop in resistivity readings was probably caused by bursting of the bubbles in the membrane under the heat of the overlay asphalt. The extent of the bubbles might have been lessened, and the performance of the overlay improved, had the first coat of epoxy been applied late in the day, during a falling temperature cycle.

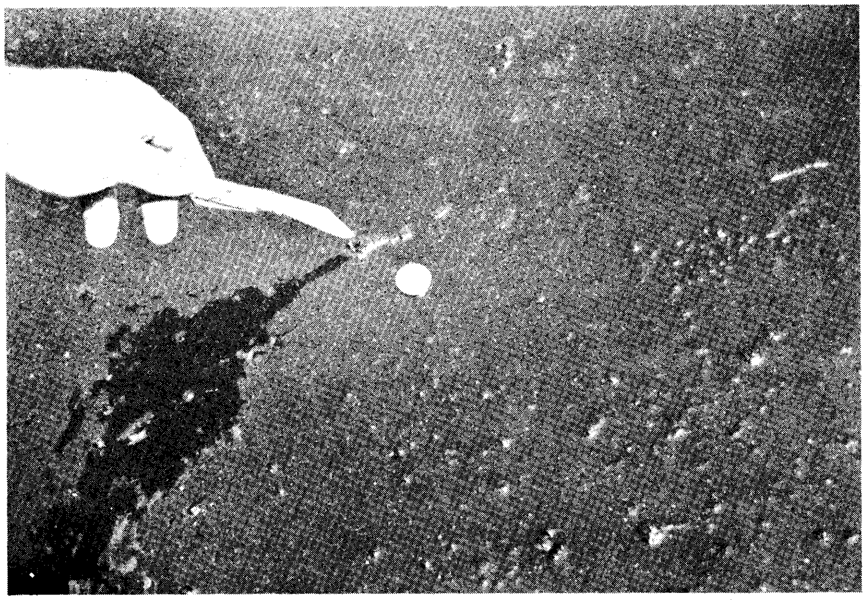

Figure 17. Bubbles in first coat of coal tar epoxy sealcoat.

Costs

No reliable cost data were developed for the membrane on the C & O bridge, because the price was negotiated through a work order. However, a similar application by the same contractor on a 11,655 square foot (1,082.8 m^2) deck in Northern Virginia was bid at \$1.78 per square foot (0.09 m^2).

Polytok Membrane 165 (Carboline Company)

Applications

(1) Route 250 over Rivanna River, Albemarle County, Deck area 11,455 s.f. (1,064.2 m^2), September 1974.

Description

Polytok Membrane 165 is a two-component, modified polyurethane elastomer, applied cold in liquid form by spray or squeegee at a 40 mil (1.0 mm) film thickness, topped by 50 pound (23 kg) asphalt impregnated roofing sheet. Solvent can be added if required for easier application.

Application Procedure

Figures 18 and 19 show the application of the Polytok membrane. The liquid membrane was applied as a single coat by spray (Figure 18) and in two coatings by squeegee when the spray equipment malfunctioned. The membrane was allowed to dry to a tacky condition, usually in about one full hour, after which the roofing sheet was placed (Figure 19) and rolled with a garden roller to ensure firm contact with the membrane. Adjacent strips of the roofing sheet were butted together at their edges. The joints at the ends of the continuous spans of the bridge were raised to the level of the top of the overlay.

Evaluation

Although the application of the Polytok membrane is relatively simple, in itself, the waterproofing of the Rivanna River bridge extended over a period of weeks, primarily because of equipment malfunctions. The spray equipment required that the polyurethane and catalyst be mixed using an electric drill before pumping, so there was little time savings over a squeegee application. Air was entrapped in the liquid during mixing, and blisters were noted in the wet membrane. No detrimental effects of the blisters were apparent in the final system, however.

Considerable difficulties were encountered in the paving operation. Although it was not clearly expressed, the manufacturer preferred a tracked paver to the rubber tired paver that was available. During the initial paving operation it was noted that the asphalt roofing sheet was shearing at the edge of the main paver wheels (Figure 20), and at times, possibly when the asphalt delivery truck drivers braked their vehicles, the membrane was torn from the deck. The damaging of the membrane was finally averted by loading the hopper of the paver only half full of asphalt and having the delivery truck pull off.

Initial resistivity readings recorded after the previously described precautions were taken were well above 500,000 ohms per square foot (0.09 m^2) at all but one of 47 points, indicating that, with due care, satisfactory results can be attained. Long-term evaluations are, of course, not yet available.

Costs

Placement of the Polytok Membrane 165 on the deck of the Rivanna River Bridge by a contractor cost $1.78 per square foot (0.09 m^2). The price may be too high to be representative, as only one bid was received, and the contractor had had no previous experience with the material.

Figure 18. Spray application of Polytok liquid membrane.

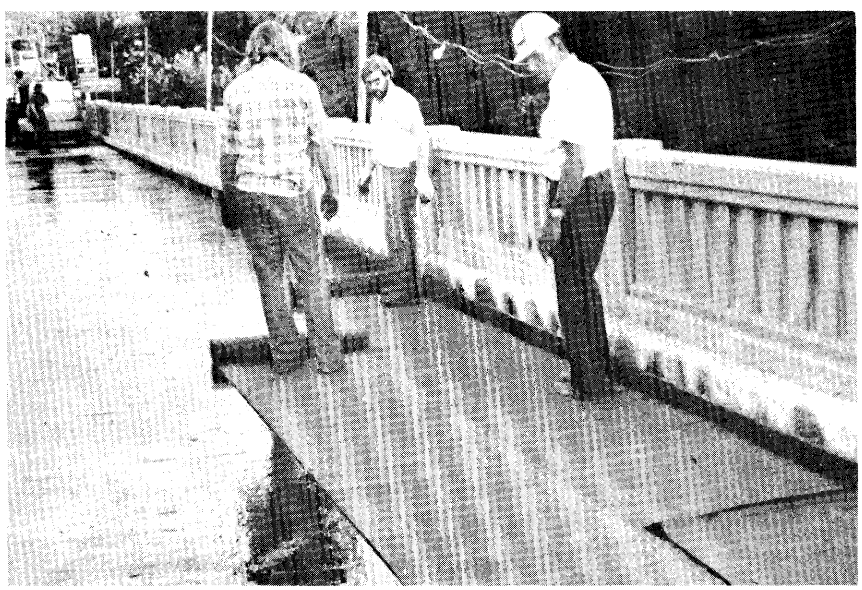

Figure 19. Placement of roofing sheet on Polytok membrane.

Figure 20. Shearing of roofing sheet under main paver wheels.

Chevron's Bridge Deck Membrane System (Chevron Asphalt Company)

Applications

(1) Route 58 over Route 95, Greensville County, Deck area 10,800 s.f. (1,003.4 m^2), September 1974.

Description

Chevron's Bridge Deck Membrane System is a two-component asphalt-urethane elastomer applied cold in liquid form. It is sprayed on the deck to an average thickness of 100 mils (2.5 mm); the minimum specified thickness is 80 mils (2.0 mm).

Application Procedure

Figures 21 and 22 show the application of the Chevron system to the Route 58 bridge. The deck, which was sound and cleaned of all loose debris, was heated to a temperature at least 30° F (17° C) above ambient using a propane fired infrared heater (Figure 21).

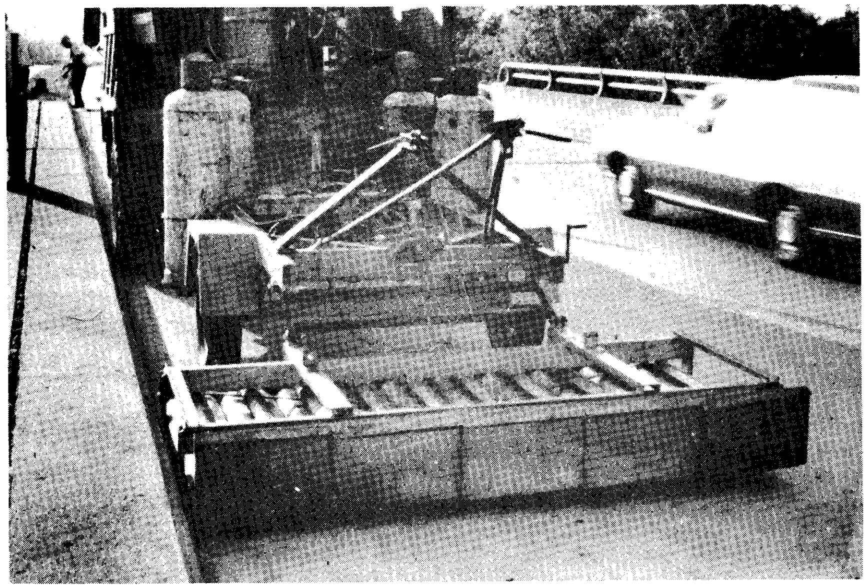

Figure 21. Infrared heater and truck mounted spray equipment used in applying Chevron's membrane system.

Figure 22. Spray application of Chevron's membrane system.

Truck mounted spray equipment developed by Chevron mixed the two components of the membrane which was applied to the deck within five minutes after heating. The rate of application of the spray equipment was coordinated with the rate of forward movement of the heater to ensure the proper rate of application of the liquid membrane. Boards placed at the side of the lane (Figure 22) were moved forward in stages with the heater to mark the area to be sprayed for the workmen and to keep them a fixed distance behind the heater. The spray operator continued to spray the given area until the heater moved forward, at which time the last board was moved. The membrane was allowed to cure overnight, primed with an uncut liquid asphalt, and paved.

Evaluation

Application of the Chevron system was somewhat more involved than those of the other liquid systems because of the heating and spraying requirements, but these operations were found to yield a blister-free membrane. The heating of the deck allows placement of the membrane under falling temperatures, which minimizes the effect of vapor pressure in the deck, and the mixing of the components in the lines avoids the entrapment of air. Blisters were noted only when small patches of sand, which held moisture, were accidentally left on the deck and when the liquid membrane was mixed in a pail and applied by squeegee. Based on the one experimental application, spreading of the premixed material by squeegee on a heated deck would not seem advisable.

Difficulties were encountered in maintaining operation of the spray equipment, which had been developed for laboratory use, but these should be remedied eventually. Unfortunately, failure of the bond of the asphaltic concrete overlay to the membrane occurred in portions of two of the four traffic lanes within five months after installation. It appears that proper bond has not been attained at the interface of the asphaltic concrete and the comparatively smooth surface of the cured urethane elastomer.

Initial resistivity readings, taken after the membrane and overlay had been open to traffic only one day, were excellent. The readings taken at points on an 8 x 8 foot (2.4 x 2.4 m) grid in one lane ranged from three million ohms per square foot (0.09 m^2) to infinity, the majority being infinity. The excellent performance of the Chevron system in this regard indicates that further study of the previously cited problem of bonding the asphaltic overlay to the membrane would be worthwhile.

Cracking of the overlays was noted over the expansion joints, but no raveling of the asphaltic concrete has been noted.

Costs

The cost of the Chevron membrane application by state forces, including materials, equipment and labor, was \$1.25 per square foot (0.09 m^2).

DISCUSSION

The trials of six membrane systems have shown that with due care four of the systems, Bituthene, Protecto Wrap, Polytok and Chevron, can be installed and paved over with no initial loss of waterproofing effectiveness. None of the epoxy systems have shown similarly good results after paving, nor did the Witmer membrane. The drop in resistance readings after paving would appear to be due to the bursting of bubbles in these liquid systems when the hot asphalt overlay is applied. Field observations showed a strong tendency to the formation of bubbles in liquid systems in which the components were stirred together, possibly due to the entrapment of air. The formation of bubbles was nearly eliminated in the case of the Chevron system, but poor adhesion of the asphaltic concrete overlay has emerged as a problem. The good initial performance of the Bituthene and Protecto Wrap systems and the poor performance of the epoxy sealcoats is in line with the experience of other states.[5,6] Long-term evaluations are available only on the two sheet membrane systems.

Unfortunately, the two sheet membrane systems, Bituthene and Protecto Wrap, appear to require an additional protective layer over the membrane to provide long-term stability and, possibly, to prevent penetration by aggregate in the overlay. The cause of the drop in resistivity values over a period of one year or less from those taken just after paving is difficult to ascertain, but it would seem to be related to the effect of traffic. A pattern of high readings at the low shoulder areas and low readings in the wheel paths would not be expected if the asphaltic concrete overlay were moist. Attempts to remove the overlay from atop the membrane were inconclusive, but it appeared that some of the components of the membrane may have migrated into the overlay. At this writing the addition of a protective layer between the membrane and the overlay seems advisable. Such added protection would also aid in preventing damage to the membrane during paving.

A small variety of protective layer materials have been used by states other than Virginia. Among these are the use of a 1/2 inch (13 mm) layer of sand asphalt, asphalt board, and 65 pound (30.4 kg) roofing sheet.[5,7,8] An additional protective layer, P-100 Protection Sheet, is also being marketed by the Protecto Wrap Company. Of these, the 65 pound (30.4 kg) roofing sheet, presently required on a limited basis in Virginia, may be the simplest alternative.[9] Its use on future sheet membrane applications is recommended.

The four initially effective membrane systems were relatively easily applied, and all required less effort in surface preparation than do the more rigid epoxy systems. This fact, coupled with the good initial resistivity evaluations, indicates the need for continued trials of membrane systems to find one that offers long-term effectiveness.

Other methods of deck protection are available, including epoxy coated or galvanized reinforcing steel, construction of the deck in two courses to ensure a proper cover of high quality concrete over the steel, and the provision of cathodic protection for the steel. Trials of these techniques, which are suitable for use at the time of construction, would provide an alternative to the use of membranes. Virginia's policy of using membranes in maintenance operations should be viewed realistically. The permanence of a completely effective membrane is assured only if the concrete does not contain sufficient salt to support corrosion. Application of a membrane to a deck in which spalling has occurred and been patched is probably, in fact, only "buying time".

The critical phase of the membrane application has proven to be the placement of the asphaltic concrete overlay. Proper care in and control of the paving operation is essential to prevent damage to the membrane and assure satisfactory performance of the overlay itself. Coordination with a paving contractor is often difficult because only a small quantity of material is required, sometimes at an isolated location.

All of the new membrane systems can be damaged by abuse during paving. As much as possible, the manufacturer's recommendations should be followed as to procedures and the type of paving machine, wheel or track, to be used. Unfortunately a selection of the type of paver is not always possible in rural areas, and, in such a case, great care is required in the use of available equipment. Damage to the membrane can be averted by requiring that the hopper of the paver be loaded only approximately half-full and having the dump truck pull away. While this is a departure from normal paving operations, it is not considered a difficult requirement because of the relatively small material quantities involved.

Control of the paving operation must not be abandoned. The asphaltic concrete should meet the requirements of Table 1, and the manufacturer's recommended application temperatures, most of which are more limited than those shown in the table. Proper compaction of a bridge overlay may also require a delay between the passes of the roller. The thickness of the overlay should be at least 1½ inches (38 mm) before the roadway is open to traffic.

A final consideration in the design of a membrane system is the treatment of the expansion joints in the deck. While epoxy sealcoats can be paved over at the joints with cracking but no loss of the overlay, this is not the case with some of the newer systems. The best solution would be to raise the joints to the level of the top of the overlay, but this is expensive and time-consuming. A simpler, but untried, solution might be to saw the overlay over the joint to provide crack control.

FUTURE WORK

The initial field tests covered in this report left several important questions unanswered. While much of the needed information should become available through the work of other agencies, continued trials of new and modified membrane systems should be continued by the Virginia Department of Highways and Transportation, and long-term data should be obtained on the more recent applications covered in this report. Research personnel will assist in these evaluations and report the findings.

CONCLUSIONS

The following conclusions are based on the field evaluations described previously. Qualifications, if any, are also noted.

1. Epoxy sealcoats, designated as Class I waterproofing in the Virginia Specifications,[10] do not appear to be effective on the basis of electrical resistivity tests.

2. Four relatively new membrane systems, Bituthene, Protecto Wrap, Polytok 165, and Chevron's system, provide good initial protection, if due care is used in installation. Long-term evaluations have not been made of the latter two of these products. The further qualifications shown in conclusions 3 and 4, below, should also be noted.

3. The two prefabricated sheet membrane systems, Bituthene and Protecto Wrap, appear to require an additional compatible protective layer over the membrane for long-term stability, based on interpretation of electrical resistivity results. Such a protective layer would also provide a desirable degree of protection during paving operations.

4. Modification of the application procedure used in conjunction with Chevron's membrane system will apparently be required to improve the adhesion between the asphaltic concrete overlay and the membrane. The excellent initial effectiveness shown by Chevron's system warrants further study of the adhesion problem.

5. Further use of the Witmer membrane system without a protective layer is not advisable, because of difficulties resulting from poor bond between the membrane and the asphaltic concrete overlay. The elimination of the adverse effect of bubbles in the liquid membrane on its initial effectiveness must also be considered.

6. Placement of the 1½ inch (38 mm) asphaltic concrete overlay, a required part of the waterproofing systems evaluated, is the critical operation in the application procedure. Care in and control of the paving operation is essential to the satisfactory overall performance of the system.

7. Treatment of the expansion joints in bridge decks must receive consideration if the membrane systems considered in this study are used, in order to prevent possible loss of the asphalt overlay through raveling. Raising the joints to the level of the top of the membrane is an ideal solution; sawing a groove over the length of the joint may suffice for structures in less than critical locations.

8. Premixing of two-component liquid systems through the use of a paddle appears to entrap air which forms bubbles in the membrane to the detriment of its effectiveness. The use of a pump system in which the components are mixed in the lines is preferable.

RECOMMENDATIONS

The field evaluations conducted by the Virginia Department of Highways and Transportation have not fully resolved the problem of effectively protecting bridge decks through the use of waterproofing membranes. Questions such as the long-term effectiveness of those systems evaluated and the measures required to obtain high quality remain unanswered. However, some information has been developed, and the following recommendations are offered as a result of the work to date.

1. The Virginia Department of Highways and Transportation should begin using the newer membrane systems in lieu of the currently specified epoxy sealcoats. Electrical resistivity data taken in this study indicate that the epoxy sealcoats do not provide a waterproof barrier.

2. While it is acknowledged that the long-term effectiveness of the systems evaluated must be determined, the four systems listed below now appear to warrant further use, based on their good initial performance.

   (1) Heavy Duty Bituthene — Future applications should include a protective layer acceptable to the Department and the manufacturer for protection during paving and for long-term stability.

   (2) Protecto Wrap — The use of a protective layer, cited previously, should be included, for the same reasons.

   (3) Polytok 165 — The long-term effectiveness of this system has not yet been evaluated.

   (4) Chevron's System — The further use of this system must include modifications to improve the bond between the membrane and the asphaltic concrete overlay.

3. Further trials of new systems and long-term evaluations of those systems shown above should be performed.

4. Any bridge deck membrane application should be viewed as a whole system, no part of which can be neglected. Due care must be provided in the application of the membrane, in the control of the placement of the asphaltic concrete overlay, which must be of sufficient thickness, and in the treatment of the expansion joints to ensure an effective installation.

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