WASHINGTON STATE DEPARTMENT OF TRANSPORTATION
RESEARCH PROGRAM REPORT 24.5

FIELD EVALUATION OF SINGLE BARRIERS

RESEARCH PROJECT

Y-1663

APRIL 1978

PREPARED FOR
WASHINGTON STATE TRANSPORTATION COMMISSION
IN COOPERATION WITH
U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

RENE N. FOSS

APPLIED PHYSICS LABORATORY

UNIVERSITY OF WASHINGTON

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FIELD EVALUATION OF SINGLE BARRIERS		5. Report Date June 1978
		6. Performing Organization Code
7. Author(s) Rene N. Foss		8. Performing Organization Report No. APL-UW 7812
9. Performing Organization Name and Address Applied Physics Laboratory University of Washington Seattle, Washington 98195		10. Work Unit No.
		11. Contract or Grant No. Y-1663
12. Sponsoring Agency Name and Address Washington State Highway Commission Department of Highways Highway Administration Building Olympia, Washington 98504		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code

15. Supplementary Notes

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

A series of measurements was undertaken in the summer and fall of 1977 to determine the noise radiated by a wide variety of cars and trucks, and the effect of an acoustic wall, or barrier, on suppressing the transmission of that noise. The assumption of the "correct" effective radiating height was found to be the most critical parameter in making the calculations agree with the measured results. The "best height" value varied greatly from vehicle to vehicle, and with speed, load, and throttle setting for a given vehicle. The variability of this parameter made it impossible (solely from these tests) to assess such considerations as whether Fresnel's or Maekawa's curves should be used to calculate the attenuation produced by the wall.

The most noteworthy observation from this study is that newer trucks not only are quieter (to meet noise radiation standards) but have an effective radiating height as low as 2 ft compared to as much as 11 ft for older trucks. Thus, as the newer types of trucks become predominant in the highway traffic mix, the effectiveness of walls and barriers in shielding the community from noise will increase considerably. This is good news, because wall effectiveness has been marginal at best for pre-1970 trucks because of their radiation heights.

17. Key Words Noise suppression Noise barriers Noise screens Highway acoustics Fresnel diffraction		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 109	22. Price

Form DOT F 1700.7 (8-69)
HWY FORM 341-004 6/72

TABLE OF CONTENTS

SUMMARY

A series of measurements was undertaken in the summer and fall of 1977 to determine the noise radiated by a wide variety of cars and trucks, and the effect of an acoustic wall, or barrier, on suppressing the transmission of that noise. The assumption of the "correct" effective radiating height was found to be the most critical parameter in making the calculations agree with the measured results. The "best height" value varied greatly from vehicle to vehicle, and with speed, load and throttle setting for a given vehicle. The variability of this parameter made is impossible (solely from these tests) to assess such considerations as whether Fresnel's or Maekawa's curves should be used to calculate the attenuation produced by the wall.

The most noteworthy observation from this study is that newer trucks not only are quieter (to meet noise radiation standards) but have an effective radiating height as low as 2 ft compared with as much as 11 ft for older trucks. Thus, as the newer types of trucks become predominant in the highway traffic mix, the effectiveness of walls and barriers in shielding the community from noise will increase considerably. This is good news, because wall effectiveness has been marginal at best for pre-1970 trucks because of their radiation heights.

For new trucks, it is recommended that a radiating height of 2.5 ft and a frequency of 300 Hz be used in calculating wall effectiveness. For small vehicles, a change from the currently used height and frequency does not appear warranted in view of the slight improvement that would be gained.

INTRODUCTION

Acoustic walls, or screens, are one of the few tools available to the highway designer for reducing the traffic noise that flows into adjacent communities. The amount of sound that penetrates the wall is usually negligible compared with that diffracted over the top; therefore, the latter is the main effect considered when assessing the effectiveness of a proposed wall design.

If the predominant vehicle noise were a pure tone at a fixed height above the ground, the diffractive effect could be easily calculated using Fresnel's equations. In practice, the noise radiating from cars and trucks comes from a number of sources (exhaust, engine, fan, gearbox, tires, aerodynamic flow, etc.) that are at different heights. Also, each is not a pure tone but has its own frequency spectrum. The spectral levels emitted by these sources are a function of the properties of the individual vehicle and how it is operated (e.g., engine settings, gear settings, load, etc.).

In principle, if one knew the effective height and frequency spectrum of each of these sources, the spectra could be broken down into individual frequency bins and one could calculate diffraction for each frequency and position. The acoustic energy calculated for each frequency would then be summed to yield the "received spectrum." This spectrum could then be A-weighted and integrated to yield the actual A-weighted sound level that the vehicle would produce at any location on the other side of the wall. This would be a lengthy task, even if all the information necessary for the calculation were known. Since the intensity level and frequency spectrum of each of the individual sources are unknown (and almost impossible to measure separately), such computation is not presently possible. Even if it were, it could probably not be justified economically.

To circumvent this problem, an enormous approximation is taken in highway noise calculations; namely, that a moving vehicle will produce an A-weighted sound field that everywhere will have the same intensity that would be produced by a pure tone at some appropriate height above the ground. Such an approximation may or may not be sufficiently accurate for the intended purpose. Obviously some sets of height and frequency assumptions are better than others. A goal of this study was to determine experimentally which sets most closely approximate the actual A-weighted sound fields.

The tests were carried out by driving a wide variety of vehicles past an 8-ft high wall and recording the sound pressure simultaneously at a number of points behind the wall. For comparison, the sound levels were also measured at corresponding points without a wall. These measured sound levels were then compared with the levels that would be predicted for "point-source" pure tones using Fresnel's equations.

DESCRIPTION OF TEST SITE

The test site was an unused taxiway at the Snohomish County Airport (Paine Field) near Everett, Washington (see Figure 1). This taxiway was about 1400 ft long, with over twice that length available when it was permissible to cross the end of a runway. This additional distance was needed to allow the larger trucks enough acceleration for the runs at higher speeds.

A wall 200 ft long, 8 ft high and 5 in. thick was constructed parallel to the taxiway. It was built of 5/8-in. thick plywood and filled with sand to minimize direct sound penetration. (See Figure 2.)

Two 19-ft high microphone towers were placed behind the center of the wall at distances of 50 ft and 125 ft from the road. Two others were placed at identical distances from the road at a location where there was no wall. A fifth microphone tower was located 37.5 ft from the road and behind the wall. (See Figures 3 and 4.)

Two 19-ft high anemometer towers were used to record wind effects. One (Tower G) was located at the wall, and the other (Tower H) was in the field. (See Figures 2 and 4.)

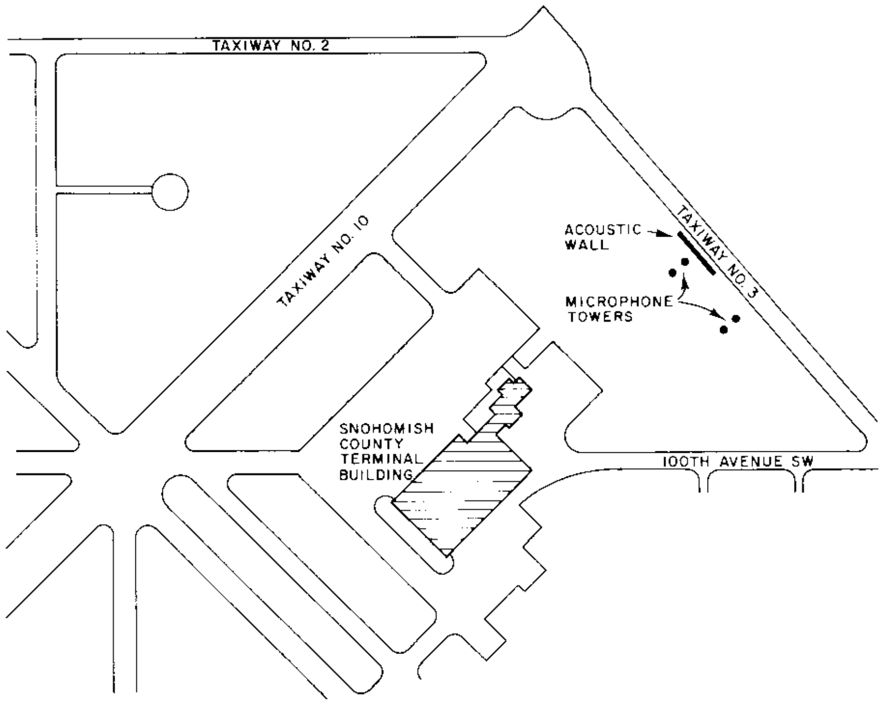


Figure 1. Paine Field test site.

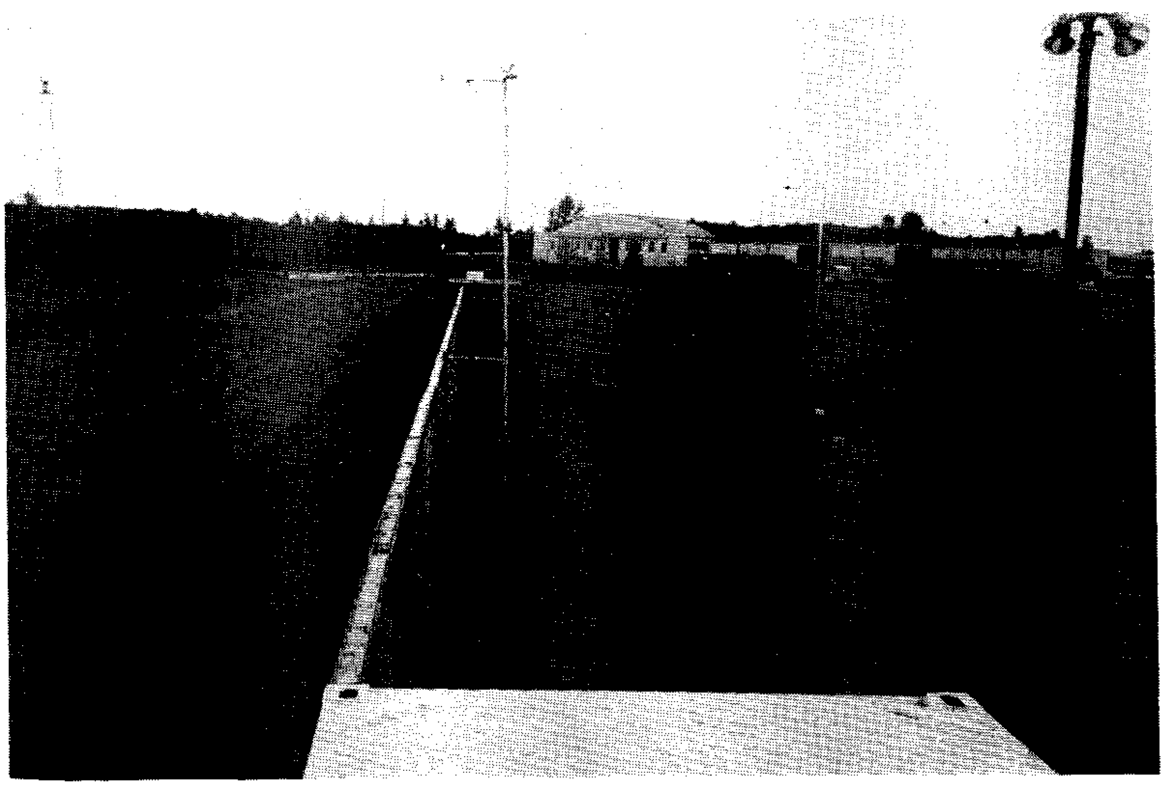


Figure 2. Top view of wall.

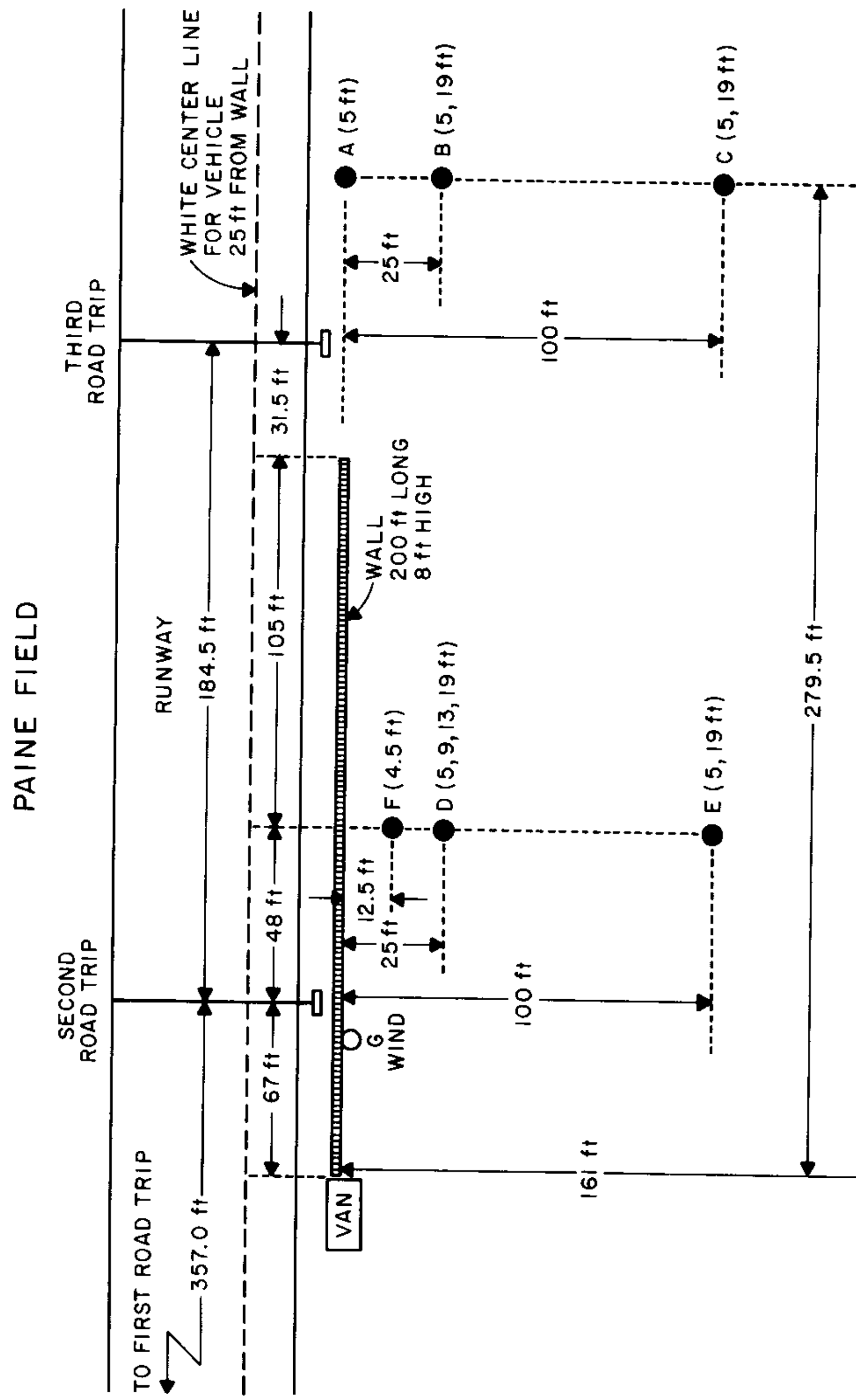


Figure 3. Diagram of test site.

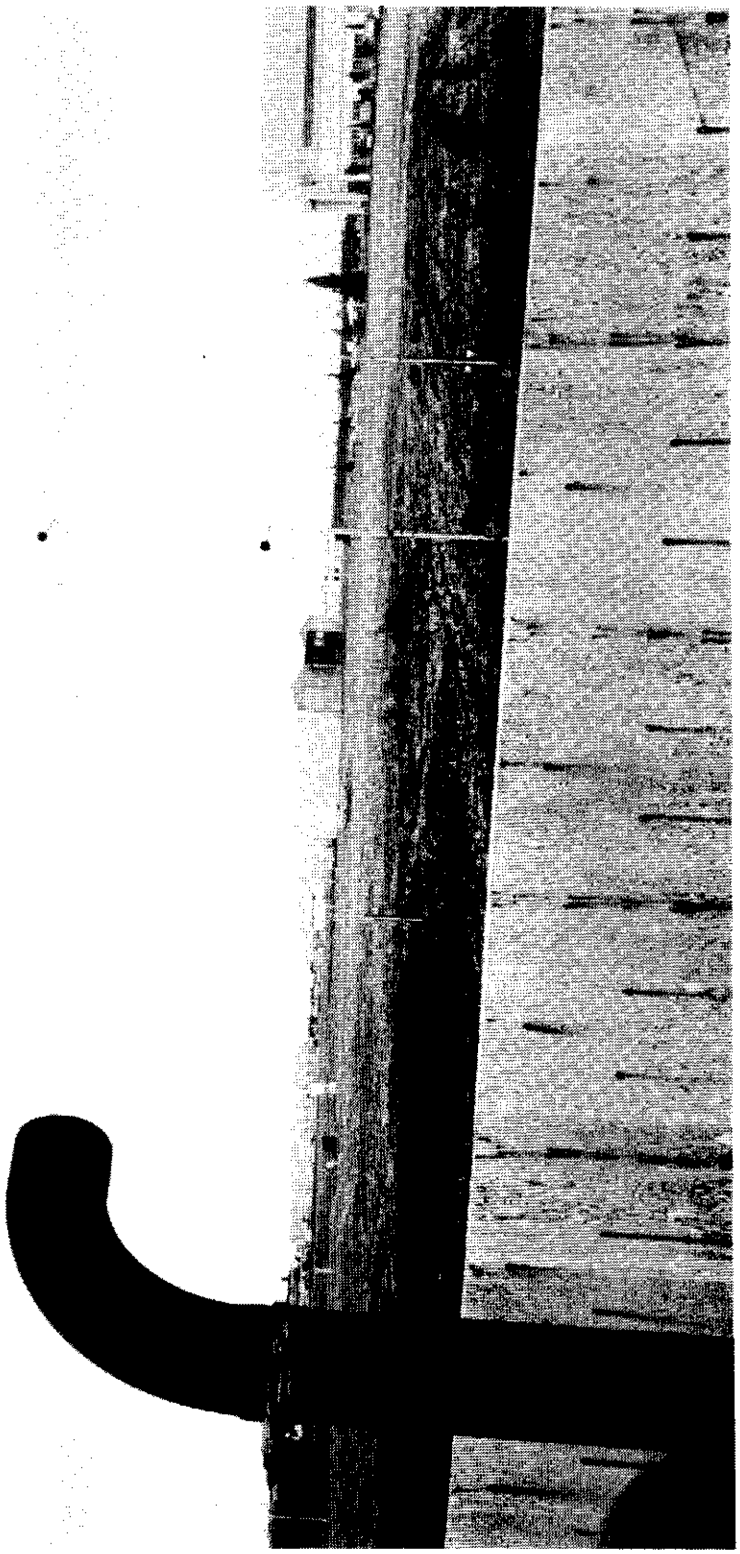


Figure 4. View looking over wall showing D and E microphone towers and H wind tower.

TYPES OF VEHICLES STUDIED

Data were taken on 32 different vehicles (some were used in more than one test series) over 708 runs. These vehicles ranged from subcompact cars to Seattle (Metro) buses and fully loaded tractor-trailers. Some of the trucks were old and others were almost new (see Table I). The vehicles were chosen to give a representative sample of the vehicles found on Washington State's highways.

MEASUREMENT PROCEDURE

The tests were conducted early in the morning, usually starting at about 4:30 a.m. and ending at 7:00 a.m. This was necessary for three reasons:

1. To obtain a good signal-to-noise ratio on all channels, background noise had to be at a minimum, especially for low-speed runs and lower microphone heights. Early in the morning there were almost no aircraft taking off or landing, and vehicular traffic in the area was at its lightest.

2. To make the higher speed runs, it was necessary to cross the end of an active runway. We had permission to do this only before the control tower opened at 7:00 a.m.

3. Calm wind and weather conditions, which were desirable for the tests, were more likely early in the morning.

DATA-GATHERING SYSTEM

Figure 5 is a block diagram of the data-recording system, showing how both the microphone and wind data were put on tape.

Eleven General Radio 0.5-in. diameter electret-condenser microphones (with B&K wind screens installed) were coupled to General Radio P-42 preamplifiers and installed on the microphone towers. The output of each microphone preamplifier was cabled directly to one of three microphone interface panels located in a 20 ft x 8 ft x 8 ft containership container placed at the beginning of the wall. (See Figure 6.) To ensure that the lowest signals of interest could be set to a level within the dynamic range of the tape recorder, the interface panels contained adjustable gain potentiometers (5-dB steps) for each channel. A 14-channel Bell & Howell model CPR 4010 tape recorder run at 15 ips in the FM mode was used for recording. A "trimming" potentiometer on the early preamplifier stage of each channel allowed additional gain adjustment to equalize any inherent sensitivity differences between the microphones. The sensitivity was equalized at the beginning of each

Table I. Test vehicles.

Vehicle No.	Vehicle Description	Times Used	No. Runs
1	1974 Ford Pinto station wagon, Lab #43	1	8
2	1976 Dodge Coronet station wagon, Lab #66	1	2
3	1976 Dodge Coronet station wagon, Lab #67	1	20
4	1976 Dodge Coronet station wagon, Lab #68	4	75
5	1975 Dodge Custom 200 pickup, Lab #87	1	16
6	1967 Ford Falcon van, Lab #91	1	14
7	1977 Chevrolet van 20, Lab #33	1	10
8	1976 Ford F-350 w/14-ft van, Int'l Rental, #355	1	13
9	1973 Ford C-700 w/22-ft van, Int'l Rental, #713	1	16
10	1976 Saab 99 2-dr automobile	5	56
11	1970 Buick Gran Sport 2-dr, bad mufflers	4	39
12	1970 Buick Gran Sport 2-dr, new mufflers	1	16
13	1970 International cabover Hogland w/flatbed	1	14
14	1970 International cabover Hogland w/van	1	20
15	1964 Peterbilt conventional Hogland w/flatbed	1	24
16	1971 Kenworth conventional Hogland w/flatbed	2	28
17	1971 Kenworth conventional Hogland w/three-axle lowboy	1	23
18	1971 Kenworth conventional Hogland w/van	2	51
19	1964 Peterbilt conventional Hogland w/flatbed	1	21
20	1967 White Freightliner cabover Hogland w/flatbed	1	16
21	1967 White Freightliner cabover Hogland w/van	1	25
22	1964 Ford cabover Hogland w/van	1	25
23	1973 Peterbilt conventional PACCAR w/tanker 3/4 full	2	34
24	1976 Kenworth conventional PACCAR w/tanker 3/4 full	2	33
25	1973 Kenworth conventional PACCAR w/flatbed 68,000 lb	1	12
26	Old 700 series G.M. bus, Metro #701	1	10
27	1976 1100 series A.M. bus, Metro #1105	1	11
28	Old Metro bus, #551	1	11
29	New Metro bus, #1154	1	1
30	1976 Kenworth PACCAR w/van	1	28
31	Old Metro bus, #704	1	18
32	New Metro bus, #1111	1	18
		TOTAL	708

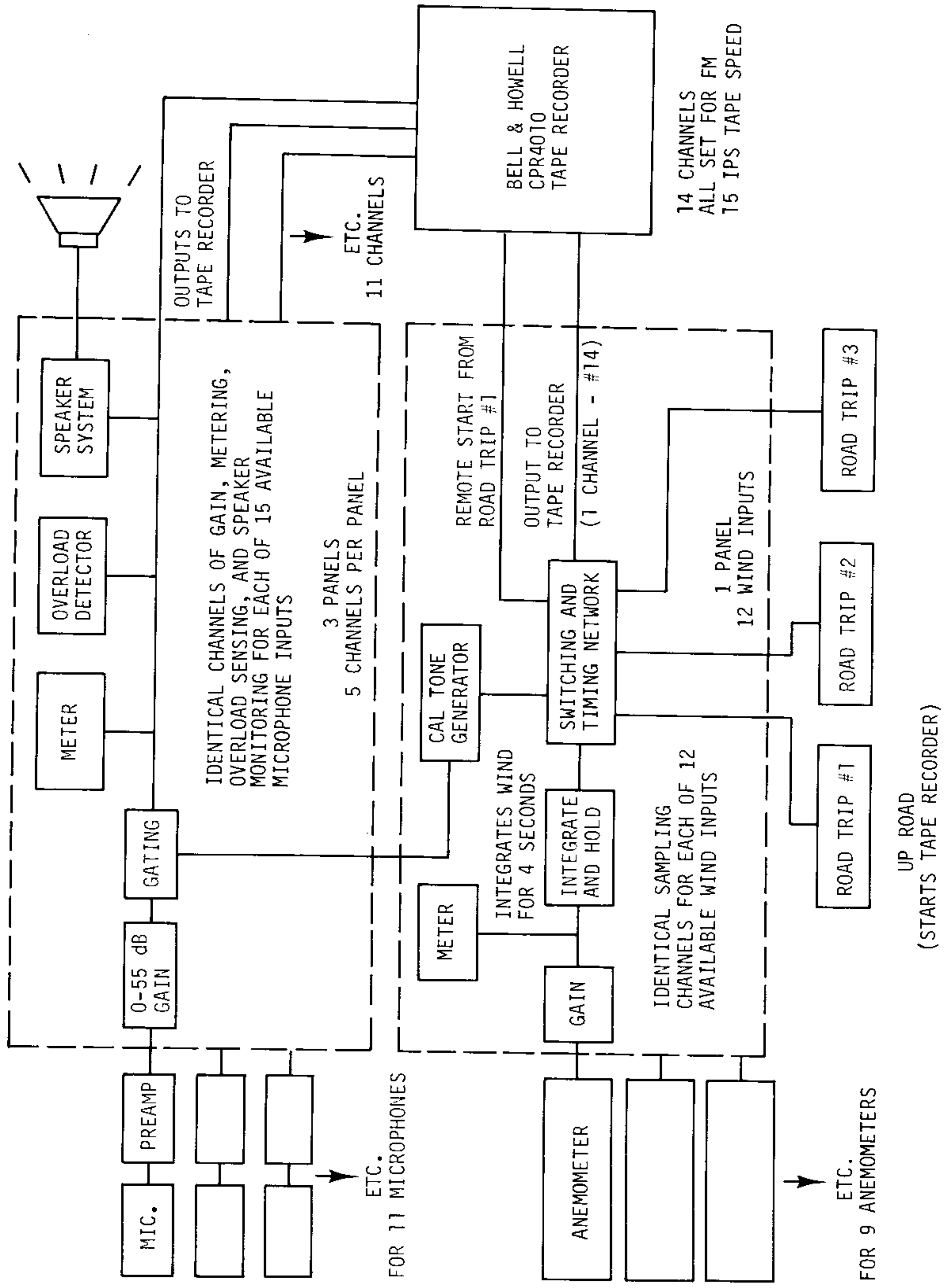
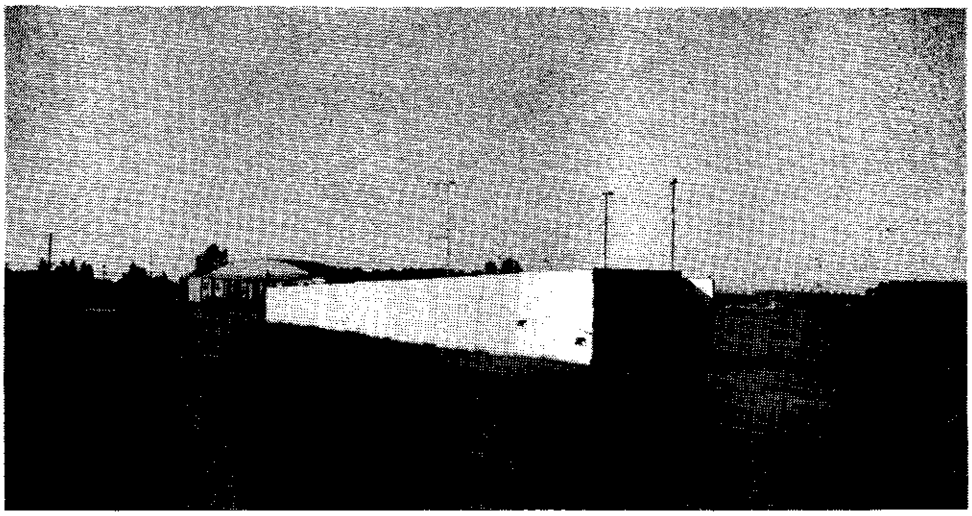


Figure 5. Data-recording system.



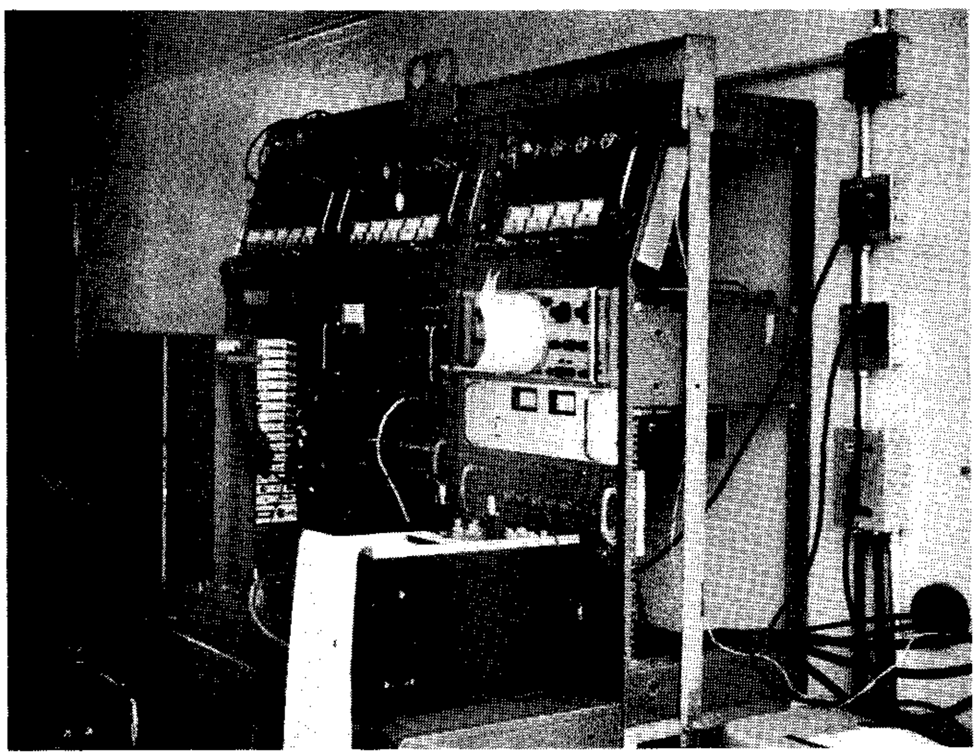


Figure 6. View of instrument van and wall (top); inside of van (bottom).

data-taking session by placing a General Radio slip-on calibrator (set to 1 kHz) on each of the microphones and adjusting each of the "trim pots," in turn, until an oscilloscope showed the same signal for each microphone. The panel contained overload lights to indicate if the signals were exceeding the dynamic range. A sound level meter on each channel allowed on-site adjustment of the 5-dB gain pots to keep each channel within the dynamic range of the tape recorder. A speaker system was included to monitor the sound being picked up by the microphones.

The system was set up to inject a calibration tone on the tape automatically at the end of each run. This tone consisted of a series of 1-kHz square waves applied, in sequence, at a 1-V peak and a 1/10-V peak. The settings were such that, when a vehicle passed, the peak signals would be in the range of at least one of these calibration levels. The presence of these calibration tones made accurate setup of the rest of the recording and processing system possible. The frequent updating of this calibration information provided increased confidence that the recorder was operating properly during both recording and playback.

Nine Gill 21281 propeller anemometers were used to measure the wind. Each anemometer responded only to the component of the wind that was parallel with its axis of rotation. When the wind was exactly perpendicular to the axis of the propeller, it would stop rotating. On the wind tower at the wall, anemometers mounted at heights of 9, 13 and 19 ft measured the wind components perpendicular to the wall. A fourth anemometer, also mounted at 19 ft, was rotated 90° to measure the wind components parallel to the wall. On the field tower, the setup was the same except that an additional anemometer was placed at a height of 5 ft to measure wind components normal to the wall. The anemometer signals were cabled to an interface panel which provided the desired gain to each channel and displayed the instantaneous output on a meter. In addition, each channel had its own 4-sec integrate-and-hold system which was controlled by the switching-and-timing network. Since nine additional recorder channels were not available, a multiplexing system was used to "write" the wind data sequentially on one channel.

The switching-and-timing network was responsible for controlling the timing sequence, using signals from three road switches which were tripped as the vehicles passed. The first road switch was approximately 300 ft before the beginning of the wall. It was used to start the tape recorder and put a "start-of-run" calibration tone on the tape. The second road switch was approximately 50 ft before the center of the wall. When this switch was closed momentarily, it started the 4-sec intregration of the wind data. (The position of this switch was chosen so that the 4-sec sampling period would cover the time when the vehicle was passing the microphones.) Pressing this switch also put an internally generated 3.13-kHz tone of 50-msec duration on the control channel of the tape. Knowing the position of the road switch and the speed of the vehicle, we could determine the position of the vehicle for correlation with the noise level trace on the microphone channels.

The third road switch was placed approximately 50 ft before the second group of microphone towers, which had no wall in front of them. When this switch was closed momentarily, it started the multiplexing (sequential readout) of the integrated wind levels onto the control channel of the recorder. Each wind channel was analog recorded on a strip chart for 0.5 sec, in sequence, with a 0.5-sec space between each channel (see Figure 7). The third road switch also triggered a 6.25-kHz tone of 50-msec duration on the control channel of the tape. This tone was used to locate the vehicle's position.

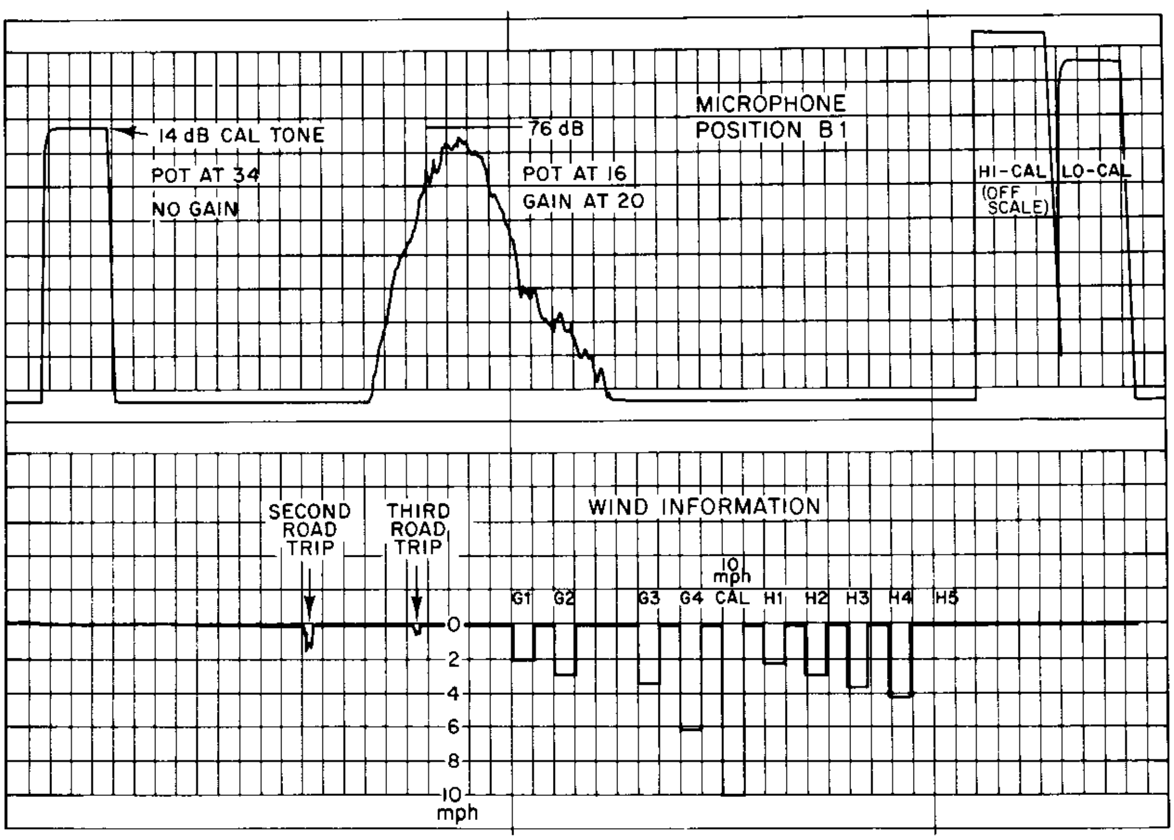


Figure 7. Sample strip chart recording for one vehicle run.

After all the wind channels had been multiplexed, the 1-kHz calibration tone discussed earlier was automatically recorded on all channels of the tape recorder.

All tape channels were FM, and there was no frequency weighting at the time the acoustic data were recorded. Since the FM channels were "flat" down to direct current, there was no low-frequency attenuation caused by the recording instrumentation itself. The low-frequency limitation was primarily due to the microphones and the microphone interface panel. The microphones were reasonably good down to 1 or 2 Hz, and the interface panel was flat down to approximately 10 Hz.

TEST PROCEDURE

Vehicle drivers were given the following test instructions:

1. Achieve the test speed before reaching the wall, and then hold the speed until well past the test area. A light will indicate when braking can begin.

2. Maintain the fixed speed without changing the throttle setting, or manifold pressure, during the run. If the speed achieved is somewhat different from that called for, this is preferable to having the throttle changed during the test. The actual speed is recorded.

3. Center the vehicle over the white line (which was 25 ft from the wall) during the data-taking part of the run. After the vehicle pass, an observer will check the accuracy with which this alignment was achieved.

As many variables as possible were recorded. In the runs with large trucks, one of the test team rode in the truck to record the speed during the pass, what gear the truck was in, the rpm, and also the manifold pressure (if available). Normally, a series of tests with a vehicle would consist of at least three runs each at 20, 30, 40, and 50 mph or whatever top speed the vehicle could manage. In the case of cars, 60 mph or higher was obtained. In addition, there were runs in which the driver was instructed to enter the system at 20-25 mph and then accelerate to the maximum while driving by the wall. For trucks, this sometimes took an adjustment in gearing. Before the truck was released, additional information was obtained, such as the height of the exhaust stack outlets and the total length of the vehicle. If there was sufficient light to do so, photographs were also taken.

A red and green light system signaled the drivers to commence their runs. An ambient noise recording was usually taken before each run series.

The runs were stopped several times each morning to inject acoustic calibration signals (from slip-on calibrators) all the way through the acoustic system. It was particularly important to obtain a calibration at the beginning of the tests, and at least once more before the sun was high enough to strike the microphones. The General Radio electret microphones were found to be somewhat sensitive to temperature. Once the sun was up, acoustic calibrations were required at frequent intervals.

MAEKAWA'S CURVE VERSUS FRESNEL DIFFRACTION

Previous work involving model studies,[1] where conditions could be fully controlled, has clearly shown that Fresnel diffraction correctly describes the reduction in sound levels produced by refraction over the top of a wall. Figures 8 and 9 show the points determined experimentally, together with the curves used by Maekawa[2] and Fresnel. There was some thought that perhaps the distinction between the Fresnel and Maekawa diffraction curves could be detected in full scale using actual vehicles as the noise source. However, the variables involved were of such magnitude that a clear-cut comparison of this sort could not be made.

If it had been possible to obtain data derived solely from a vehicle whose noise radiated overwhelmingly from a single point (at least in any one frequency bin, if spectral analysis were used for the data reduction), we could have computed the apparent height, as measured by the transducer arrays behind the wall, using both Fresnel's equations and Maekawa's curve, and seen which one came closest to yielding the known radiating height of the vehicle. However, such a point source would be extremely rare. The best source might be a poorly muffled truck that radiated strongly at the piston firing frequency at the exhaust outlet. This type of vehicle was not among the array of trucks available for the study. Even those trucks that were not well muffled did not act as a point source; the radiating height varied with speed, indicating a mixing of sources. Although the exhaust might have been the main source of noise radiation at some frequency, nowhere in our data did it clearly dominate by a sufficiently wide margin.

Even if a vehicle acting as a true point source at its exhaust outlet had been available, the radiation point would have been 10.5 to 11.5 ft above the roadway. With our 8-ft wall, which was considered the most practical for the other goals of the testing, this geometry would have caused the Fresnel numbers to be near zero or negative for most of the microphones. As can be seen in Figure 9, in this region there is little difference between the Fresnel and Maekawa curves. Another impediment was an apparent resonance of the wall that made specific spectral readings for the frequency bins around 125 Hz (where the firing frequency might typically fall) unreliable on the lower microphones. (See section entitled Overall Test of System Accuracy.)

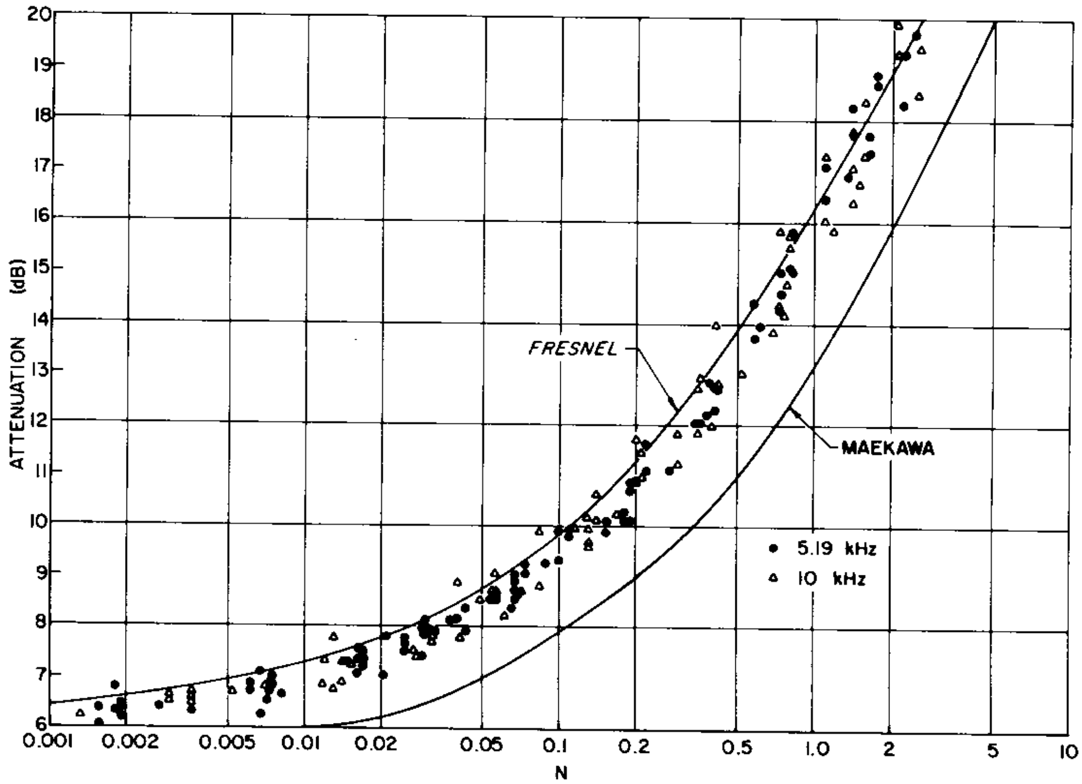


Figure 8. Comparison of experimental data with Fresnel's curve and with Maekawa's curve for conditions where the wall blocked the line of sight.

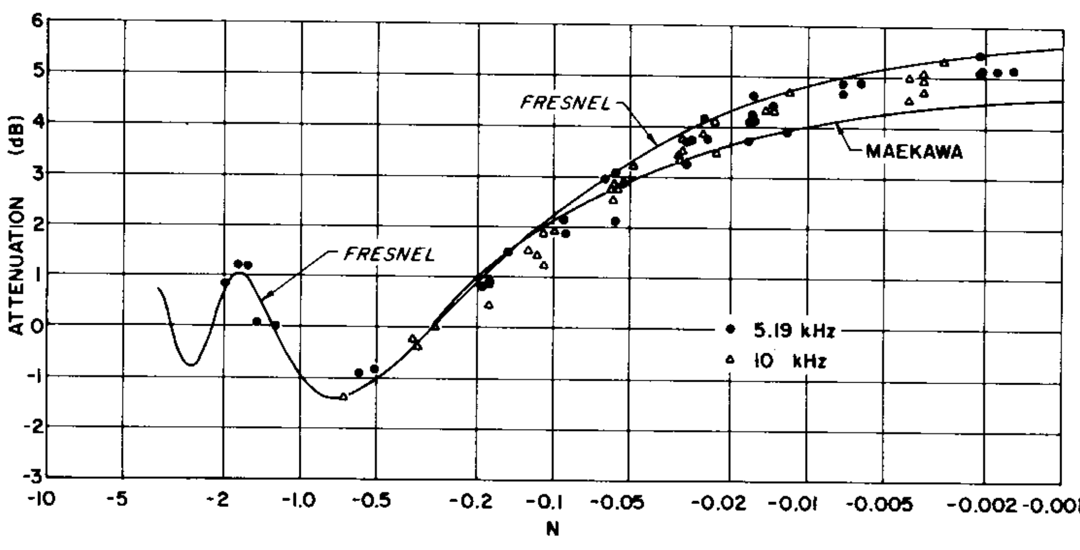


Figure 9. Comparison of experimental data with Fresnel's curve and with Maekawa's curve for conditions where the wall did not block the line of sight.

There were other factors that appeared to have much more influence on the attenuations obtained than the Fresnel-Maekawa differences. The effective radiating height of a vehicle, in particular, had a great influence on the wall's effectiveness as an acoustic barrier.

All the calculations in this report are based on Fresnel diffraction. Had the calculations used Maekawa's curve, the calculated radiating heights would have been lower than those presented. For instance, assuming the radiating frequency is 300 Hz, a calculated best fit to the experimental data that yields a radiating height of 4 ft above the ground using Fresnel diffraction would be only 2.15 ft above the ground using Maekawa's diffraction (see Appendix C).

For conditions in which the wall blocks the line of sight (see Figure 8), the general shape of the Fresnel and Maekawa curves is similar but Maekawa's curve is 2 or 3 dB lower. Therefore in this case, to a first-order approximation, one could obtain the same attenuation behind a wall when using Maekawa's curve as when using Fresnel's,* provided that a lower radiating height was assumed when using Maekawa's curve. Since it is merely necessary to use a different effective radiating height to compensate for the differences in the two diffraction curves--at least as far as first-order effects are concerned--it is impossible to detect differences between the two curves from the acoustic data. In other words, when one does not know the actual effective radiating height by independent means, but infers it from a best fit of the experimental data, one cannot then use the same experimental diffraction data to say that a distinction between the two diffraction curves has been detected.

The most important difference between Fresnel's and Maekawa's curves is the difference in magnitude; however, note from Figure 8 that there is also a slight difference in shape. In principle, it might be possible to detect the difference on the basis of the shape. This is a second-order effect, however, and many other variables--particularly, the fact that the source is not really a point source-- completely swamp any second-order effects. As can be seen in the height calculations for the various vehicles (for example, truck 18, in Figure 11), the spread in the height data caused by small differences in such parameters as gear setting, wind speed, load, etc. represents variables far in excess of the difference in the shape of the two diffraction curves.

---

* If the effective radiating height is calculated using Fresnel diffraction, Fresnel diffraction must be used in any future computations involving that radiating height. The same applies to Maekawa's curves. Noticeable errors would be introduced if the two systems were mixed.

The results of an earlier study[1] clearly show that simple Fresnel diffraction is appropriate when, as in this study, individual cars and trucks are passing by the measurement system one at a time and, to a first-order approximation, can be considered single point sources of noise. Indeed, Fresnel diffraction (or more complex formulations for which Fresnel is a simplified case) is used in all other fields where diffraction is important, such as optics, electromagnetics, sonar, and radar. Only in highway barrier work is Maekawa's diffraction used, and it is the author's opinion that this variance should be eliminated.*

For highways where many vehicles are on the road simultaneously, the appropriate formulation of the Fresnel curve will somewhat depend on the calculation method. Perhaps the best and most versatile calculation method (which is not currently implemented) would be to divide the roadway of interest into small lengths and consider each length an incoherent noise source; each segment would be short enough that it could reasonably be considered a point source. Taking into account the distance and the shape of the terrain between the segment and the "microphone," a calculation would be made for each segment and the results summed to obtain the noise level that the whole road would contribute at a particular listening position. For this method, it would be appropriate to use the Fresnel equations directly.

Other methods of calculation, such as the 117 Program,** attempt to "pre-integrate" the results. Strictly speaking, the results can only be pre-integrated for a given segment, e.g., a road that is perfectly straight in both elevation and azimuth. For this case, the pre-integrated version of the Fresnel curve would be somewhat lower than the unintegrated Fresnel curve (see lower curve in Figure 10). In practice, of course, not many roads (at least in the state of Washington) run from horizon to horizon without turning or dipping. In an attempt to circumvent this problem, the road is broken into a few straight segments and the noise components for each segment are energy summed to compute the total sound energy arriving at the "microphone." This system suffers from a number of problems. Germane to the discussion here is the fact that the shape of the pre-integrated curve that should be used for the diffraction calculation varies with the length of the line segment--varying from the lower curve in Figure 10 for the infinite straight road to the unintegrated Fresnel curve for short segments.

Figure 10 shows the appropriate pre-integrated diffraction curves for three cases in which the straight line segment of interest is centered normal to the observer: ±90° (i.e., from horizon to horizon, a

---

* Also see the paper by Kurze[3] who holds the same opinion.

**The computer program in National Cooperative Highway Research Program Report 117, which is currently used by the state for highway noise prediction.

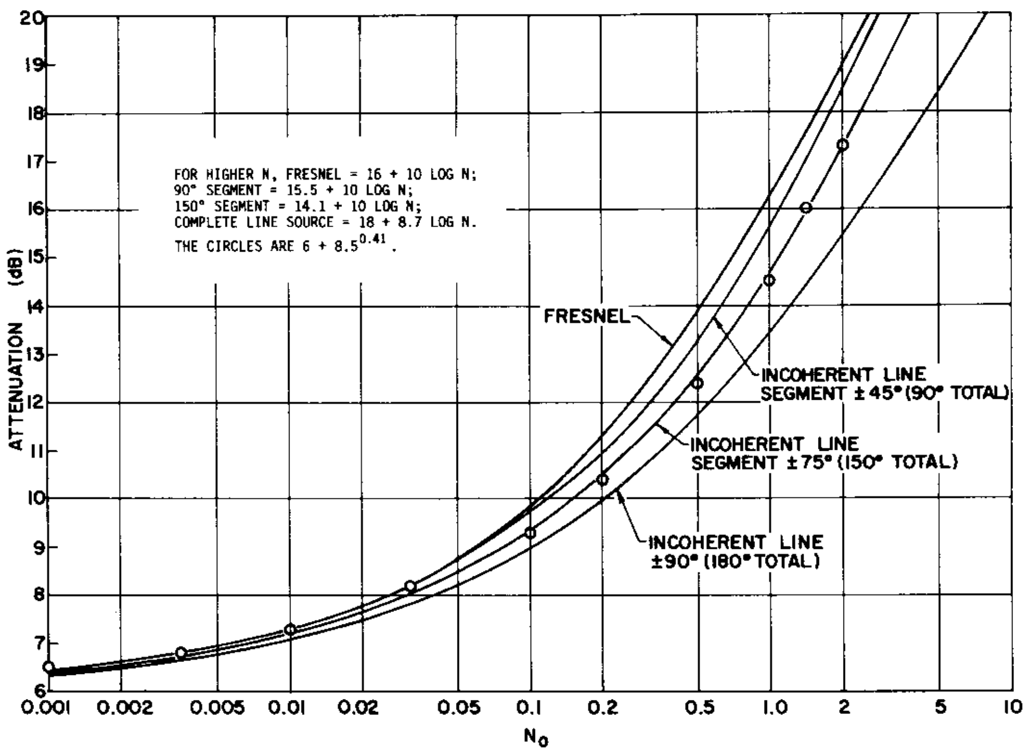


Figure 10. Plot of attenuation calculations for various incoherent line sources and Fresnel diffraction; wall blocking line of sight.

total included angle of 150°, and a total included angle of 90° (i.e., ±45°). Also shown is the appropriate curve for a point source (which is, of course, the original Fresnel curve). Most cases would involve road segments where the subtended angle for the observer is less than a total of 90°; in this instance, the appropriate pre-integrated curve is very close to simple Fresnel diffraction.

DATA ANALYSIS

The main method of data reduction was to use an A-weighted filter with readout on a strip-chart recorder. Spectral analysis with a Bruel & Kjaer 2131 frequency analyzer was also accomplished. Both methods of data reduction are diagrammed in Figure 11.

For the A-weighted data, the amplitude at each microphone (along with the wind information) was determined from the strip chart and these data were stored in an HP-2115 computer. The computer then calculated the relative levels that would be received at each microphone for a series of assumed point source heights and frequencies. The value that best fit the experimental data was called the radiating height for that run. The process was as follows:

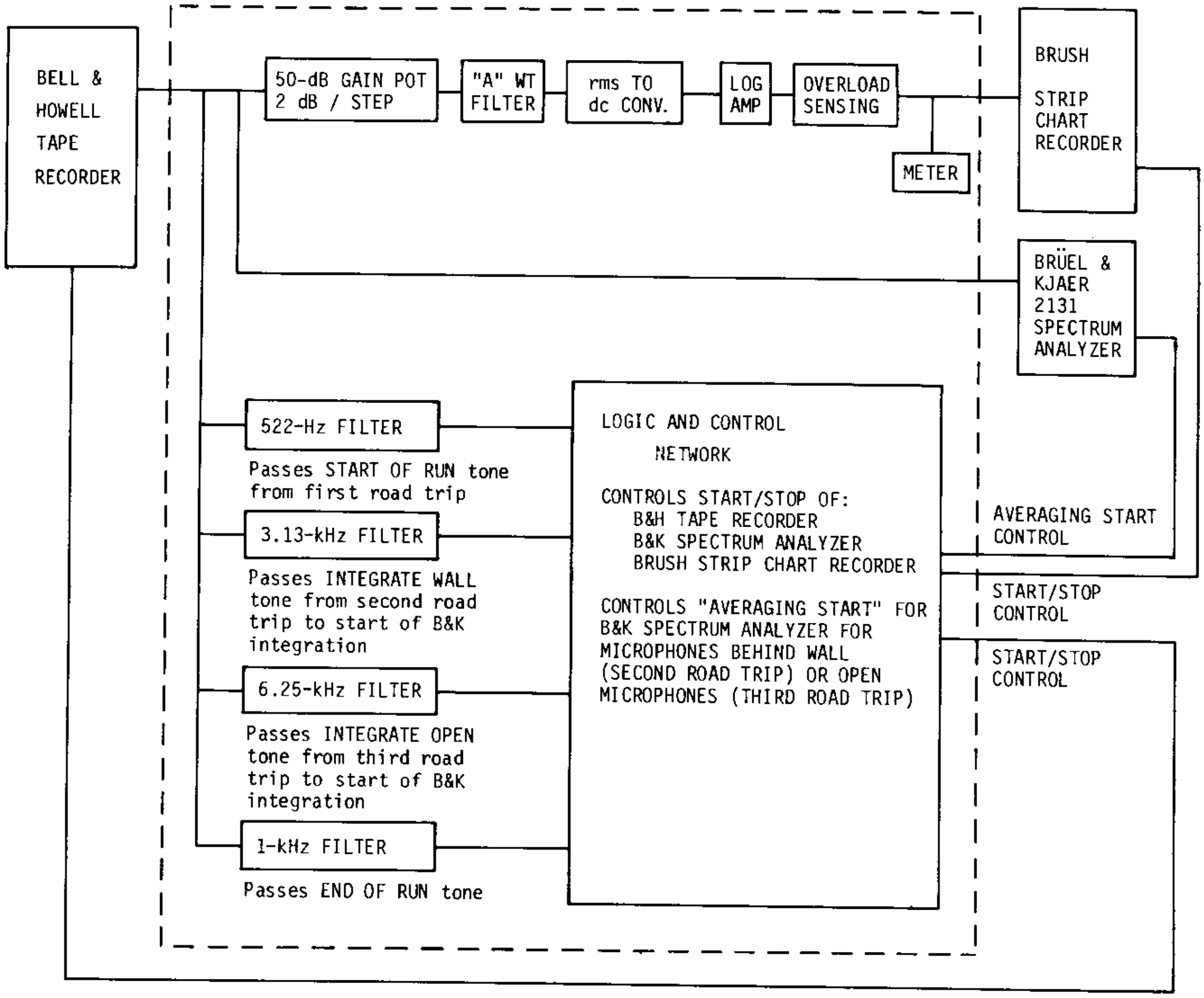


Figure 11. Data reduction and analysis.

1. It was assumed that the vehicle was a point source at some specific frequency and height; e.g., 500 Hz at 1 ft above the center of the lane in which the vehicle was traveling.

2. The top microphone on the free-field tower 50 ft from the road was used as the reference. Using the sound level recorded at this microphone, along with Fresnel's equations and the geometry involved with the assumptions of item 1 above, the computer calculated the predicted sound levels at each of the four microphones on the tower 50 ft from the road behind the wall. Spreading loss was also calculated and taken into account in the process (see Appendix D).

3. The four levels calculated from Fresnel's equations were then subtracted from the corresponding values experimentally measured on one of the vehicle passes.

4. The mean and standard deviation of the resulting values were calculated. The results indicated how well that particular height and frequency assumption predicted the results experimentally obtained for that particular vehicle.

5. To obtain a meaningful numerical value with regard both to the scatter of the data and to the mean difference between the experimental results and the calculated results, we then added the standard deviation to the absolute value of the mean. The result was a number representing the "largest likely error"* that would have accrued in this series of runs if the initial assumption had been used as the basis for computing the effectiveness of the wall against that particular vehicle using Fresnel's equations.

6. The entire process was then repeated using a different height and/or frequency assumption. With the aid of the computer, a wide range of height and frequency assumptions was investigated--specifically, from 5 ft below the pavement (due to reflections from the pavement, it is possible for a source to act as though it were below the surface) to 14 ft above the roadway, and from 100 Hz to 875 Hz. The computation was done in 0.5-ft steps and 25-Hz increments.

7. The results of all the calculations from item 6 for each vehicle run were printed by the computer. An example for one vehicle run is shown in Figure 12. The minimum value for the "largest likely error" was found on the printout and selected as the best fit for the effective radiating height and frequency. Figure 13 illustrates how the minimum values shown in the printout in Figure 12 varied with a change in frequency or radiating height. Note that an incorrect assumption of radiating height can reduce the prediction's accuracy much more severely than a "poor" choice of frequency.

---

* Assuming a Gaussian distribution, the chance that the error would exceed this value is less than 10%.

EFFECTIVE RADIATING HEIGHT (ft)	100		200		300		400		500		600		700		800	
7.5	-2.32 1.51 3.83	-2.09 1.46 3.55	-1.93 1.46 3.42	-1.79 1.58 3.37	-1.66 1.70 3.37	-1.59 1.60 3.39	-1.53 1.68 3.41	-1.49 1.93 3.42	-1.49 1.94 3.44	-1.52 1.94 3.45	-1.56 1.92 3.48	-1.65 1.88 3.53	-1.74 1.85 3.59	-1.83 1.83 3.66	-1.91 1.64 3.75	-1.98 1.88 3.85
8.0	-2.05 1.51 3.56	-1.81 1.41 3.21	-1.61 1.41 3.02	-1.44 1.48 2.92	-1.30 1.57 2.87	-1.20 1.64 2.84	-1.14 1.67 2.82	-1.12 1.66 2.80	-1.13 1.65 2.79	-1.21 1.59 2.80	-1.29 1.53 2.82	-1.38 1.50 2.88	-1.46 1.50 2.96	-1.53 1.54 3.07	-1.58 1.59 3.17	-1.60 1.66 3.27
8.5	-1.79 1.51 3.30	-1.52 1.36 2.88	-1.29 1.34 2.62	-1.09 1.38 2.47	-.94 1.43 2.37	-.83 1.45 2.29	-.76 1.45 2.22	-.81 1.38 2.16	-.87 1.29 2.16	-.94 1.23 2.17	-1.03 1.20 2.23	-1.10 1.23 2.33	-1.16 1.30 2.45	-1.19 1.38 2.57	-1.19 1.46 2.65	-1.16 1.53 2.69
9.0	-1.55 1.50 3.05	-1.23 1.32 2.55	-.96 1.27 2.23	-.74 1.27 2.02	-.58 1.28 1.66	-.49 1.25 1.74	-.50 1.16 1.65	-.54 1.05 1.59	-.61 .97 1.58	-.68 .96 1.64	-.75 1.02 1.77	-.79 1.13 1.92	-.81 1.23 2.04	-.78 1.31 2.10	-.73 1.36 2.09	-.65 1.39 2.04
9.5	-1.31 1.49 2.80	-.94 1.29 2.23	-.63 1.20 1.84	-.40 1.17 1.56	-.25 1.11 1.36	-.21 1.01 1.22	-.23 .67 1.10	-.29 .76 1.05	-.35 .78 1.13	-.41 .89 1.30	-.44 1.04 1.49	-.44 1.17 1.61	-.40 1.23 1.64	-.32 1.25 1.57	-.22 1.23 1.45	-.09 1.20 1.30
10.0	-1.07 1.50 2.57	-.65 1.27 1.92	-.31 1.15 1.46	-.06 1.06 1.12	.03 .94 .98	.05 .76 .83	.02 .65 .67	-.03 .67 .70	-.08 .84 .92	-.11 1.04 1.15	-.10 1.18 1.28	-.04 1.23 1.27	.06 1.21 1.26	.15 1.13 1.31	.32 1.03 1.36	.45 .96 1.41
10.5	-.82 1.52 2.34	-.34 1.28 1.62	.03 1.12 1.14	.23 .98 1.21	.31 .81 1.12	.32 .66 .98	.28 .67 .95	.24 .87 1.11	.21 1.10 1.31	.23 1.26 1.49	.30 1.32 1.62	.41 1.26 1.67	.56 1.13 1.68	.71 .96 1.67	.64 .61 1.65	.94 .71 1.65
11.0	-.59 1.51 2.10	-.06 1.26 1.32	.31 1.08 1.39	.49 .93 1.41	.56 .76 1.32	.56 .73 1.30	.53 .93 1.46	.51 1.20 1.70	.53 1.40 1.92	.60 1.47 2.07	.73 1.41 2.14	.69 1.24 2.14	1.06 1.04 2.10	1.20 .85 2.05	1.27 .71 1.98	1.27 .68 1.95
11.5	-.36 1.51 1.87	.21 1.24 1.45	.56 1.06 1.62	.73 .90 1.62	.79 .81 1.60	.76 .96 1.74	.76 1.25 2.02	.77 1.51 2.29	.84 1.64 2.48	.98 1.60 2.57	1.15 1.43 2.58	1.30 1.20 2.50	1.42 .98 2.41	1.49 .87 2.35	1.48 .88 2.36	1.41 1.00 2.41
12.0	-.12 1.51 1.64	.48 1.23 1.71	.79 1.07 1.66	.95 .93 1.69	1.00 .99 1.99	.99 1.27 2.26	1.00 1.59 2.59	1.06 1.79 2.84	1.17 1.80 2.97	1.32 1.64 2.96	1.48 1.41 2.89	1.61 1.20 2.81	1.68 1.10 2.79	1.67 1.15 2.82	1.59 1.32 2.90	1.46 1.55 3.01
12.5	.11 1.52 1.62	.71 1.25 1.96	1.02 1.10 2.11	1.17 1.04 2.21	1.20 1.25 2.45	1.20 1.61 2.81	1.24 1.90 3.14	1.31 1.99 3.30	1.45 1.88 3.33	1.62 1.65 3.28	1.78 1.45 3.23	1.86 1.37 3.23	1.85 1.44 3.29	1.76 1.63 3.39	1.63 1.89 3.52	1.50 2.14 3.63
13.0	.34 1.52 1.86	.92 1.29 2.21	1.23 1.16 2.39	1.37 1.22 2.58	1.39 1.55 2.94	1.40 1.93 3.33	1.43 2.14 3.57	1.55 2.11 3.67	1.73 1.92 3.66	1.91 1.72 3.63	2.02 1.63 3.65	2.02 1.71 3.73	1.93 1.92 3.85	1.79 2.20 3.99	1.66 2.46 4.13	1.59 2.65 4.24

FREQUENCY (Hz)

Figure 12. Sample computer printout.

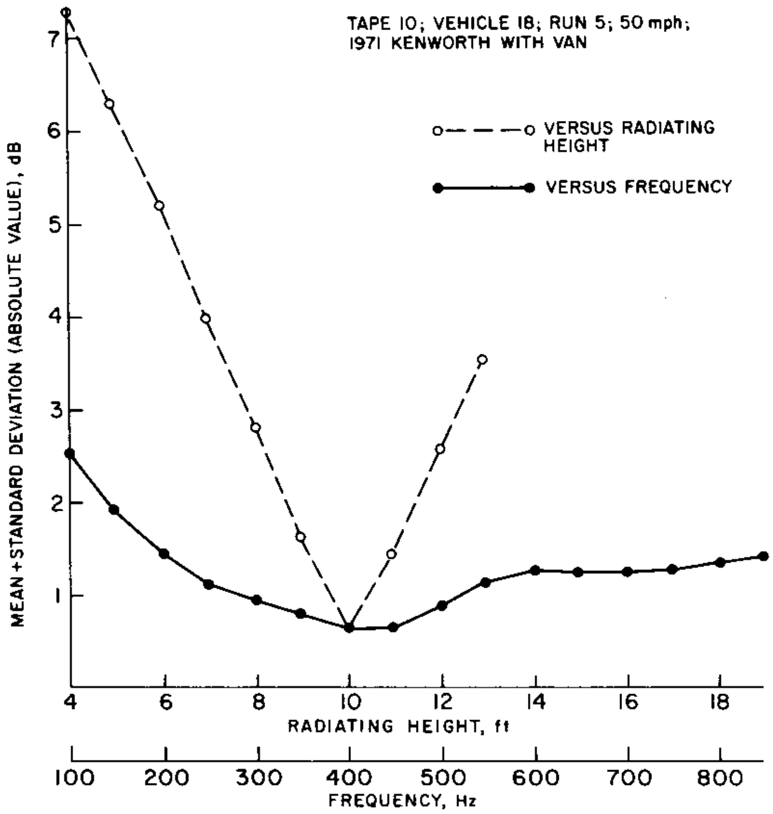


Figure 13. Average value as a function of radiating height and frequency.

OVERALL TEST OF SYSTEM ACCURACY

To test the overall accuracy of the measurement system, a series of tests was conducted with noise sources of a known position and height. These consisted of three Cobraflex horns with I-60 drivers mounted side by side at the same height and about a yard apart. These horns were positioned 25 ft from the wall, with the bell of the horn above the white line which the vehicles attempted to straddle during the test runs. Each horn was driven by a pseudorandom noise generator. The three generators were not correlated. The set of horns was placed at various heights above the roadway and the sound levels resulting at the microphones behind the wall were analyzed to determine the perceived effective radiating height. Figure 14 compares the results of the A-weighted measurements and the actual heights of the horns for four heights above the blacktop. The dashed lines on the figure represent the actual heights of the top and bottom of the bell of the horns. The run numbers at the bottom indicate different trials. Note that the "perceived"

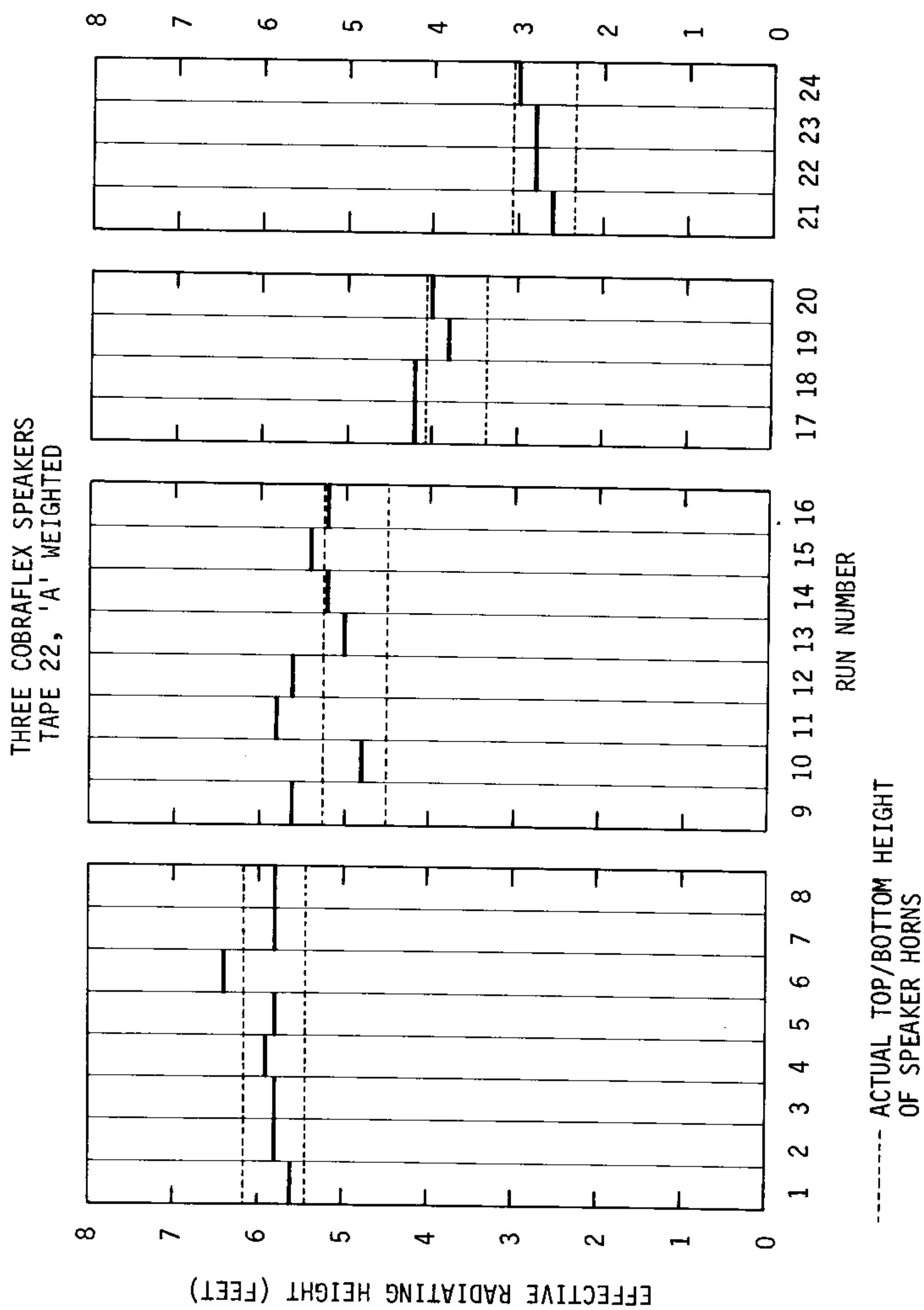


Figure 14. Test runs using Cobraflex horn sets.

radiating height falls within the bounds of the actual height for most of the measurements. In the case of the 5-ft horns, the perceived height is somewhat high, but in general the agreement is remarkably good considering all the possible variables involved. These data give us confidence that the effective radiating heights calculated from the A-weighted results are valid and that the measurements are meaningful. This confidence is particularly important because some of the results are startling: some of the newer trucks have an apparent radiating height as low as 1.5 ft.

The data from the horn tests were also analyzed on a B&K 2131 third-octave spectrum analyzer. Typical results are shown in Figure 15. Note that the "acoustic height" is substantially the same as the actual height for frequencies of 1 kHz and above. However, for frequencies below that, the acoustic height oscillates above and below the real height by as much as several feet. This effect is not present in the A-weighted results because A-weighting is a relatively wide-band measurement which tends to average out the high and low bins; also, the frequency weighting of the "A" filter reduces the effect of low frequencies.

The poorer accuracy of the spectral analysis at lower frequencies precluded certain interpretations that we had hoped to make, particularly on the trucks. We had hoped to separate the effective radiating heights of some of the various sources by associating them with the frequency bin that they dominated. For example, a frequency bin at about 125 Hz might be dominated by tailpipe exhaust noise, another frequency by the air inlet, etc. At the engine "firing" frequency, the spectral analysis did show radiating heights at or somewhat above the measured tailpipe height. Radiating heights around 5.5 ft for frequencies that might be associated with the air inlet system were also found, in good correspondence with the actual inlet height. Various other correlations of this sort would be interesting, but in view of the results shown in Figure 12 further analysis of this sort did not appear to be warranted.

Considerable effort was spent on calculating possible ground reflections in an attempt to explain the oscillations in the data (see Appendix B). This analysis did not bring the curve to a reasonable fit with the known radiating height, however, and a complete explanation of this effect is not at present known. We suspect that, even though the wall was filled with sand, there were nonetheless resonances or other transmission modes through the wall itself that were frequency sensitive and capable of creating the effects shown in Figure 15.

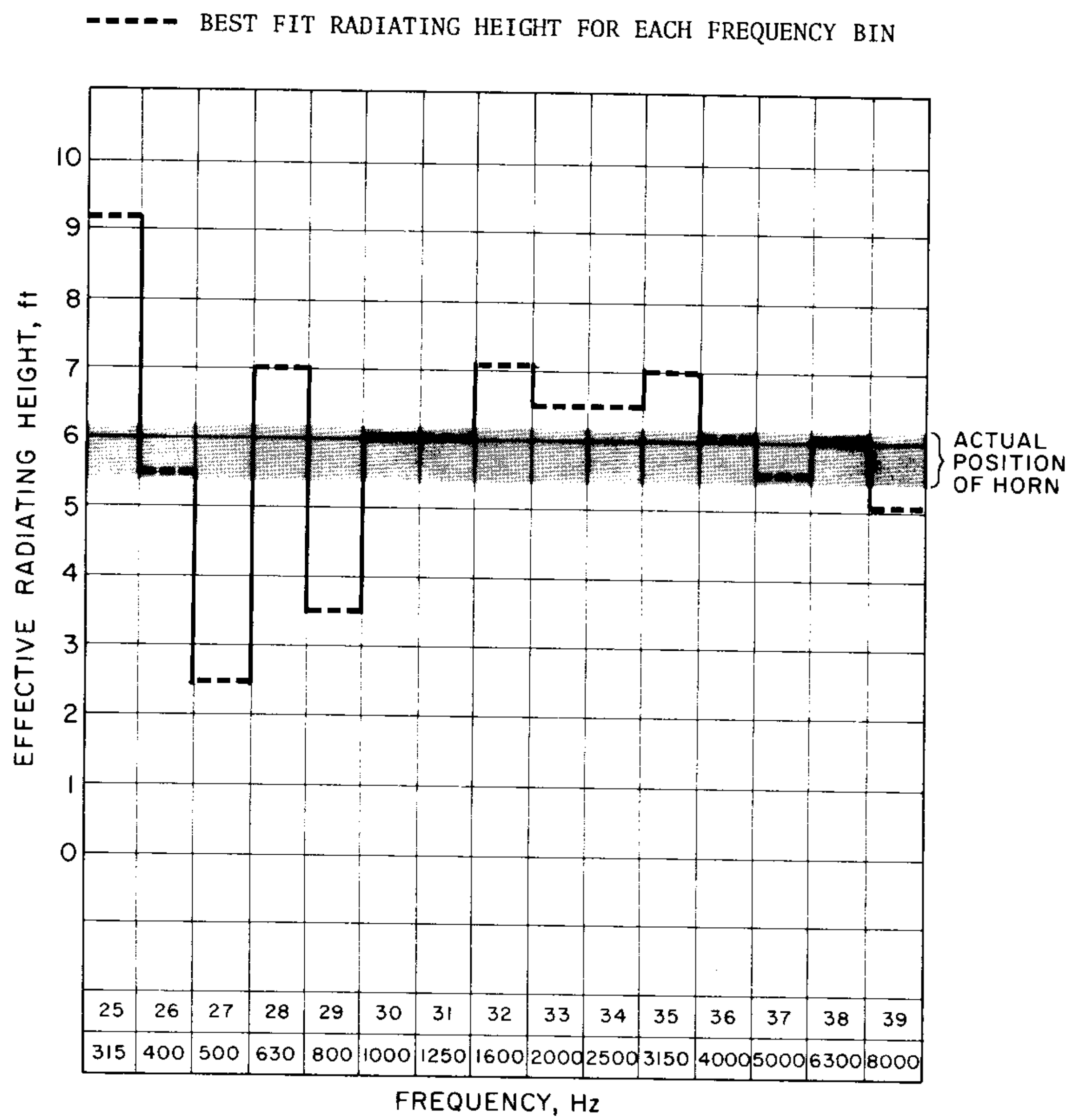


Figure 15. Effective radiating heights obtained for tests with one speaker using the B&K 2131 third octave analyzer.

RESULTS

Figure 16 is a plot of the "best" effective radiating height (regardless of what "best" frequency would be paired with it) vs speed for tests on a compact car. That is, this figure shows the height that (using Fresnel diffraction) yielded the actual A-weighted sound levels measured at the microphones. As can be seen, the data points have some scatter, varying from about -1 ft to +1.5 ft. Figure 17 is a similar plot, but for an older, large diesel truck. The effective radiating heights are considerably higher here, varying from about 5 ft to 13 ft above the ground.

To keep the size of this report manageable, it is impractical to show scatter diagrams for all the vehicles tested. Therefore, a "least-squares" fit to a linear curve was made for all of the vehicles. These curves are plotted in Figure 18 for cars and small trucks, and in Figure 19 for large trucks and buses.

All of the vehicles in Figure 18 were gasoline powered, with tail pipes at the rear and low to the ground. Note that the effective radiating height of all of these vehicles decreases somewhat as the speed increases. It is believed that this effect is due to the fact that radiation from the tailpipe increased with respect to other types of noise, lowering the effective radiating height. In any event, the effect is not pronounced. The curves are relatively flat, and the scatter diagrams from which the curves were obtained (e.g., Figure 16) also indicate that the radiating height did not change greatly as a function of speed. The radiating height for cars tended to be around 0 to 1 ft. The radiating height for the larger gasoline-powered trucks was around 3 ft (see No. 8 and No. 9, which had a 14-ft van and a 22-ft van, respectively).

Figure 19 shows radiating height vs speed for large trucks and buses. As noted on the figure, all except one vehicle (a Metro bus) had tailpipes between 10.5 ft and 11.5 ft above the ground. Note that almost all of these vehicles show an <u>increase</u> in effective radiating height with speed. Again, this is believed to be due to the fact that the higher speed required more power, which caused more radiation to come from the high tailpipe. The two exceptions to this positive slope were vehicle No. 25, a 1973 Kenworth truck, and, to a slight degree, vehicle No. 24, which was the latest (1976) and quietest Kenworth tested. (Because of a scheduling problem, we were unable to test the very latest, and quietest, of the Kenworth truck line.) The difference in effective radiating height between trucks No. 17 or No. 18 (which used the same 1971 Kenworth tractor but were pulling different loads) and No. 24 (the 1976 Kenworth) is dramatic. The curve for the 1971 model has a positive slope and shows a rather high effective radiating height, varying from 7 to almost 12 ft above the road surface. Contrast this with the 1976

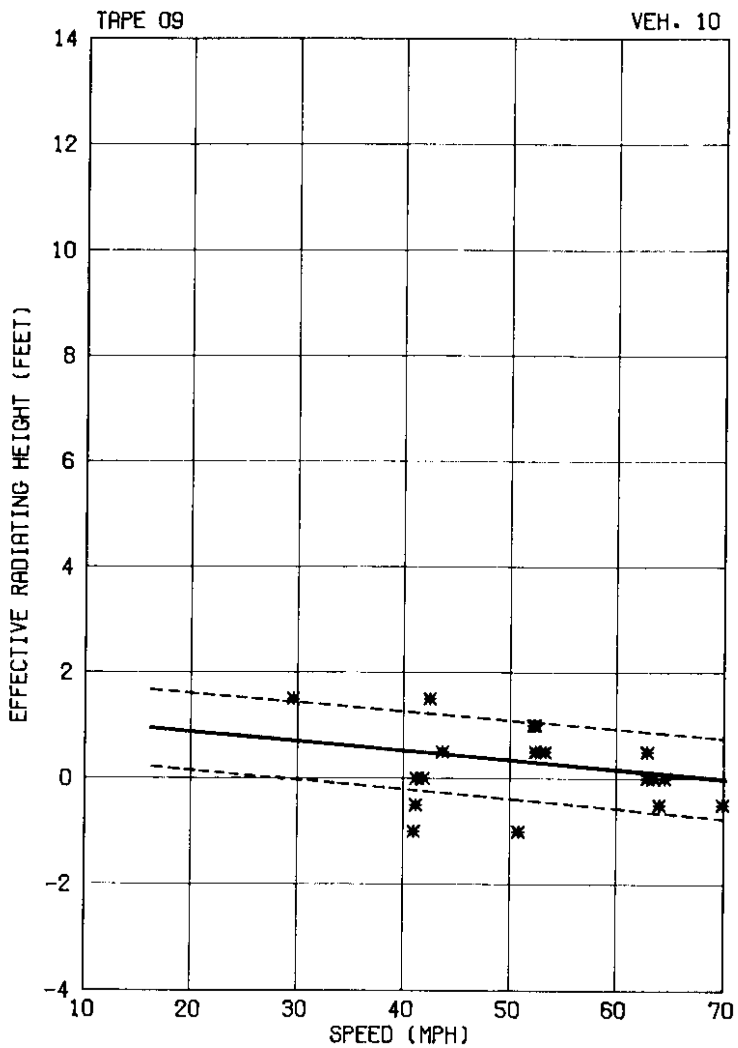


Figure 16. Best effective radiating height calculated for tests on 1976 Saab 2-door (—— least-squares fit; --- one standard deviation from least-squares fit).

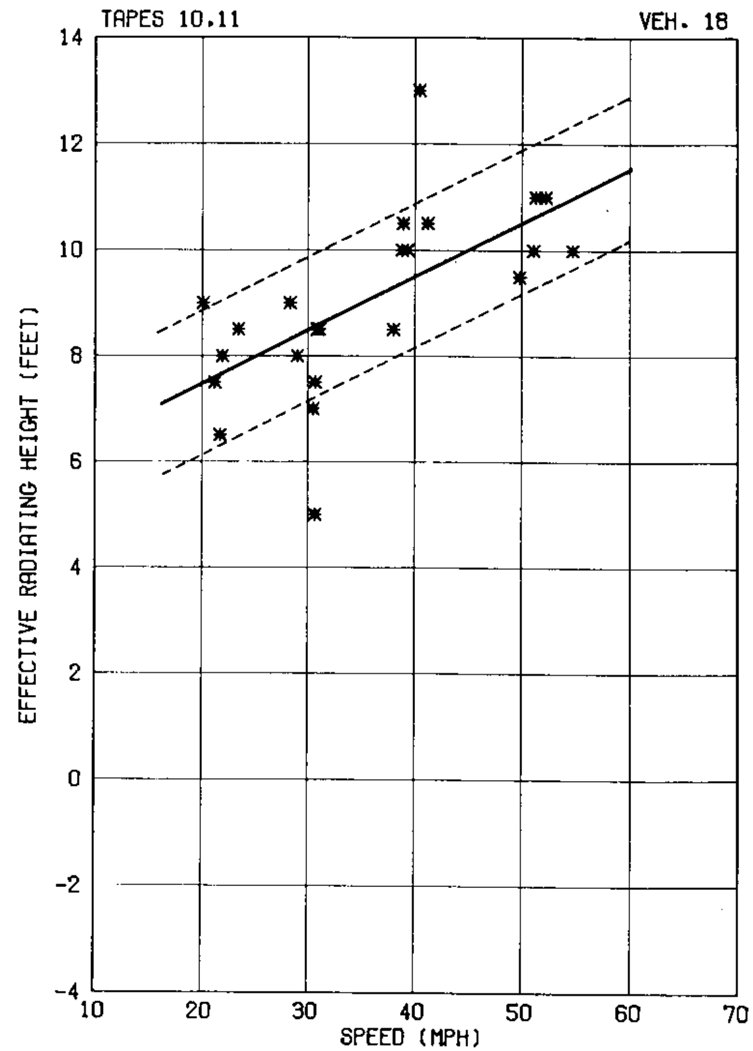


Figure 17. Best effective radiating height for tests on 1971 Kenworth with van (—— least-squares fit; --- one standard deviation from least-squares fit).

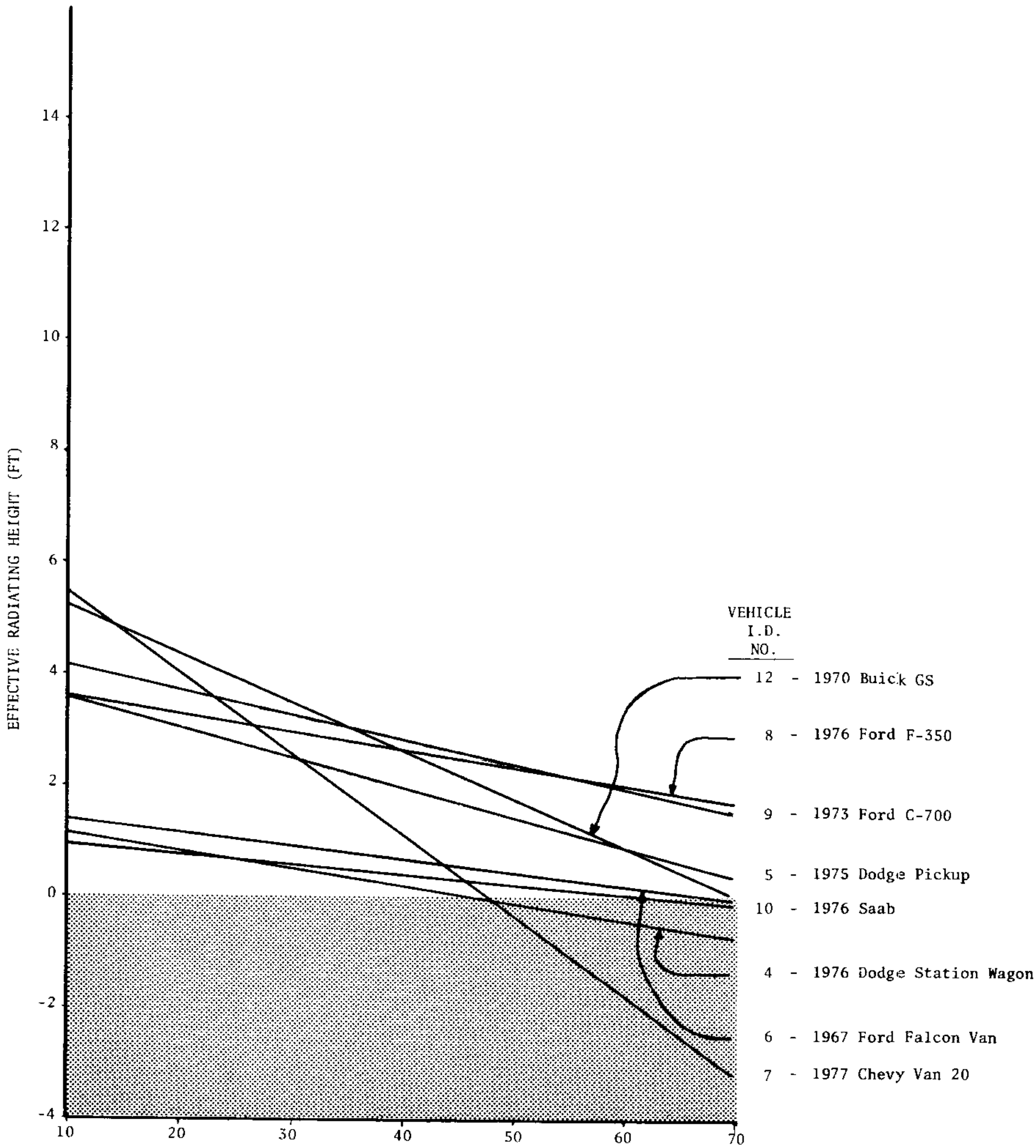


Figure 18. Effective radiating height vs speed for cars and pickup. All vehicles had low tailpipes (about 1 ft off the ground).

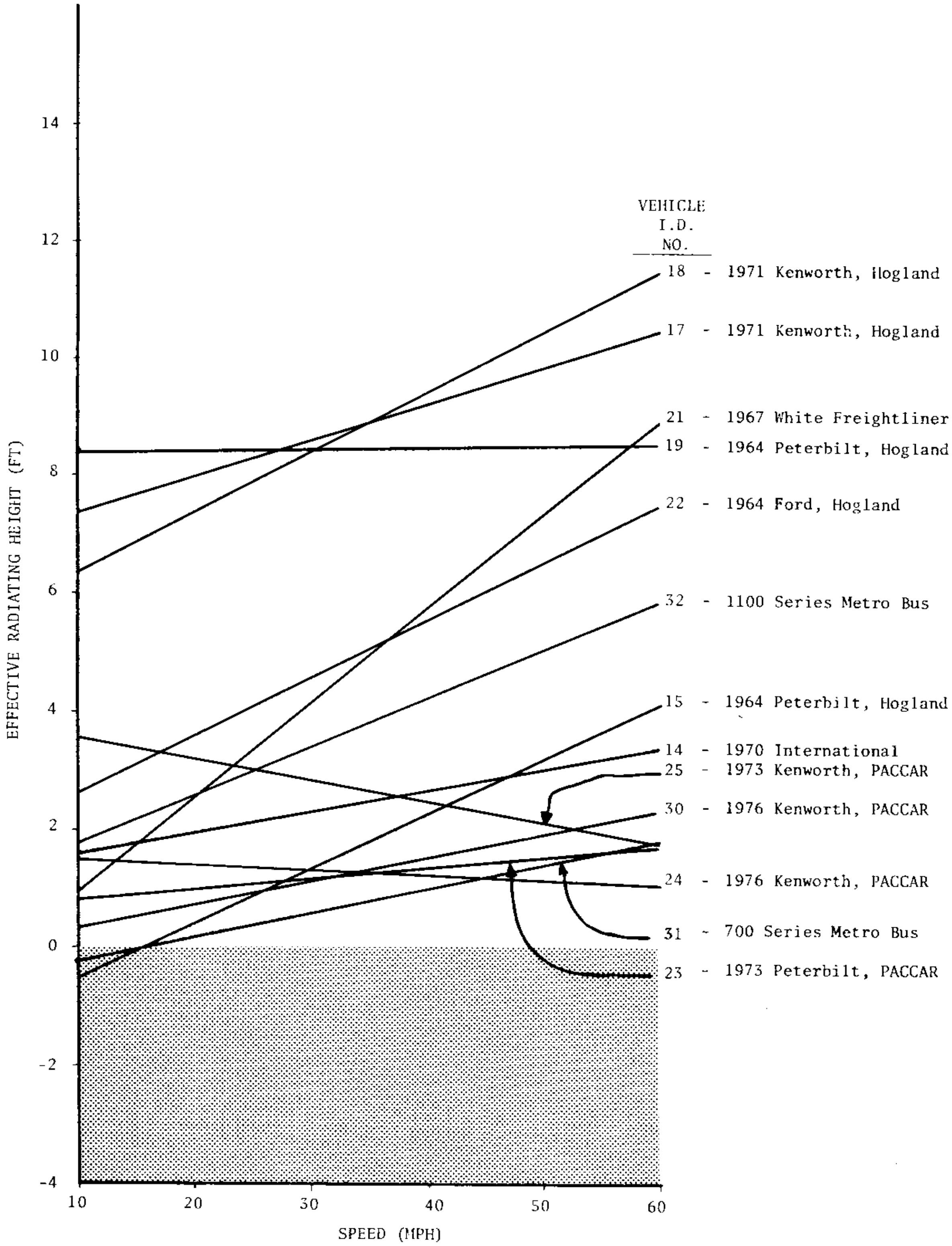


Figure 19. Effective radiating height vs speed for trucks and buses. All but vehicle No. 31 (Metro bus #704) had tailpipes between 10.5 and 11.5 ft above the ground.

Kenworth, for which the effective radiating height is fairly independent of speed and is only about 1.5 ft above the road surface. The effectiveness of a wall would be noticeably better "against" the 1976 version than the 1971 version. The current assumption of an 8-ft radiating height would be reasonable for the 1971 Kenworth (although it would tend to give the wall credit for more than it was really doing). The 8-ft assumption would not be reasonable for computations involving the 1976 Kenworth.

The plots in Figures 18 and 19 simply take the least-squares fit of the best effective radiating heights, ignoring the frequency that is paired with each point (fortunately, the frequency range for a given truck is not great). As noted earlier in this report, the accuracy of the calculation is not nearly as dependent on choice of frequency as it is on choice of radiating height. Figure 20 is a plot of effective radiating height vs frequency for data taken near 40 mph. The best radiating frequency varies from a low of 150 Hz to a high of about 450 Hz.

Table II gives considerable additional information on each of the vehicles, again for 40 mph. The first two columns identify the vehicle involved. The third column gives the level measured, in A-weighted decibels, at microphone B1. This microphone was located 50 ft from the center of the lane in which the vehicle was driven and 5 ft above the ground level; therefore, the values in this column represent the "official" noise level for that particular vehicle for 40 mph. Column 4 lists the difference at this microphone, in A-weighted decibels, that would be caused by doubling the speed; these values vary from a low of 4.8 dB to a high of 12.2 dB. As a point of reference, a 6-dB value in this column would mean that the noise power was varying with the square of the vehicle's speed; 9 dB would mean it was varying with the cube of the vehicle's speed; and 12 dB would indicate that it was varying with the fourth power of vehicle speed. Most of the cars tend to have values around 10 to 12 dB, indicating that the noise power varies between the cube and the fourth power of speed. The trucks, on the other hand, tend to have values between 5 and 9 dB, indicating a power dependence between the square and cube.

Column 5 gives the difference between microphones B1 and D1. Both these microphones were located 5 ft above ground level and 50 ft from the center of the road; one was in the open and the other was 25 ft behind the wall. Therefore, the difference between these microphones is a direct measure of the actual attenuation created by the wall at a point 5 ft above the ground. For automobiles, this value varies from about 11.5 to 13.5 dB, a noticeable reduction. The newer trucks, which have a very low effective radiating height (1 or 2 ft), have similar values, and so do many of the Metro buses. For older diesel trucks (such as vehicle No. 18) with a relatively high radiating height, the measured A-weighted reduction was only about 7.5 dB.

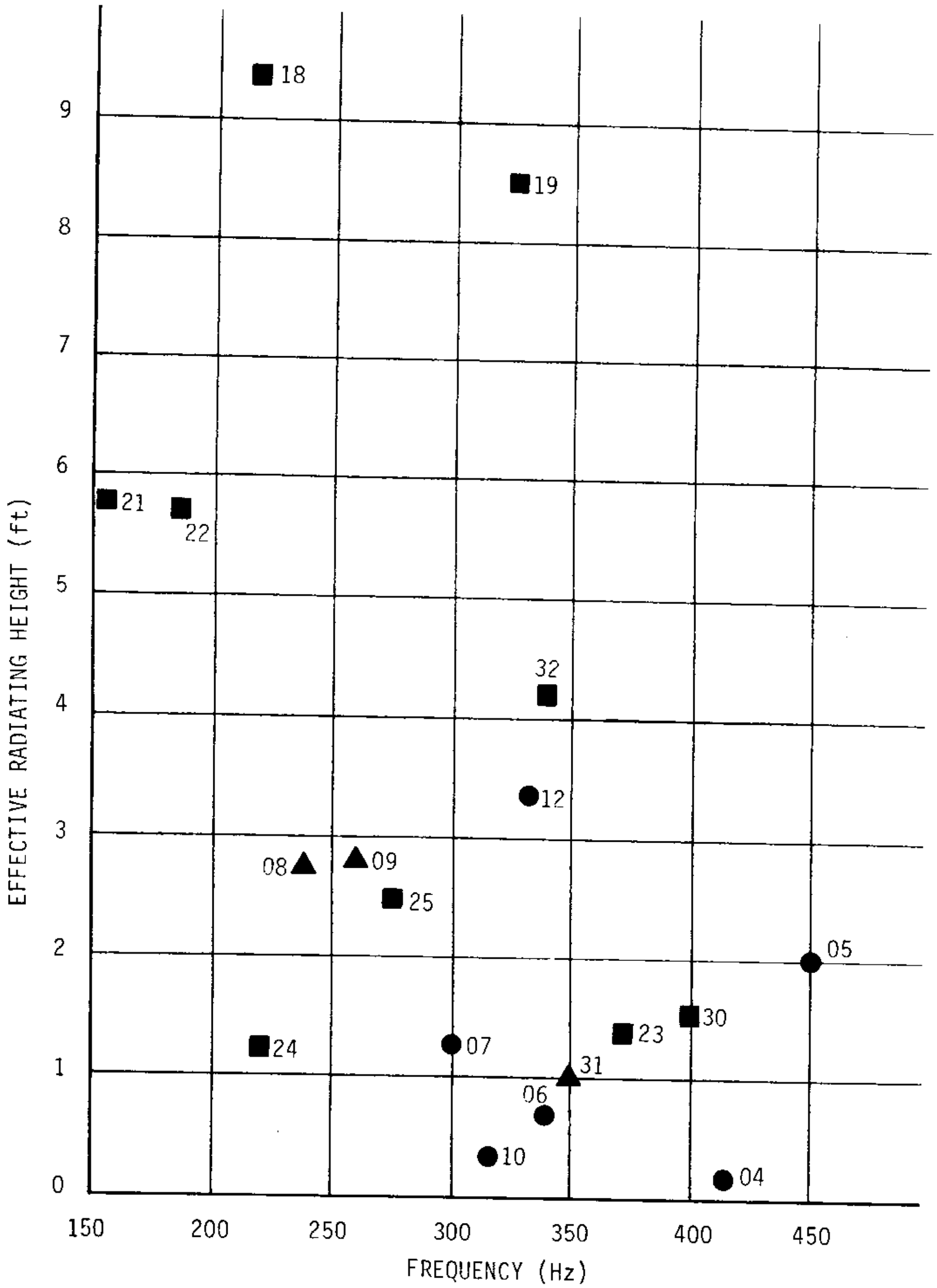


Figure 20. Effective radiating height vs frequency; all data taken at 40 mph (● = cars; ▲ = medium-to-large trucks & buses with low tailpipe/exhaust systems; ■ = trucks & buses with high tailpipe/exhaust systems).

Table II. Data at or near 40 mph without acceleration.

1	2	3	4	5	6	7	8	9	10	11	12	13
VEHICLE NUMBER	VEHICLE DESCRIPTION	MICROPHONE B1 5 FT HIGH, 50 FT FROM ROAD NO WALL	ΔB1 - CHANGE PER DOUBLING OF SPEED	MICROPHONE B1 MINUS MICROPHONE D1. MEASURED ATTENUATION 50 FT FROM ROAD (5 FT HIGH, WITH AND WITHOUT WALL).	MICROPHONE C1 MINUS MICROPHONE E1. MEASURED ATTENUATION 125 FT FROM ROAD (5 FT HIGH, WITH AND WITHOUT WALL).	MEAN EFFECTIVE RADIATING HEIGHT	BEST FIT RADIATING FREQUENCY	MAXIMUM LIKELY ERROR USING COLUMNS 7 AND 8	BEST EFFECTIVE RADIATING HEIGHT @ 500 Hz	MAXIMUM LIKELY ERROR FOR COLUMN 10	MAXIMUM LIKELY ERROR TRUCKS: 8 FT RADIATING HT, 500 Hz CARS: 0 FT RADIATING HT, 500 Hz	MAXIMUM LIKELY ERROR TRUCKS: 3.5 FT RADIATING HT, 300 Hz CARS: 0 FT RADIATING HT, 300 Hz
	Units	dBA	dB	dB	dB	ft	Hz	dB	ft	dB	dB	dB
4	'76 Dodge Station Wagon	63.8	11.3	13.5	6.8	0.20	425	0.51	0.36	0.92	1.29	2.03
10	'76 Saab 2-dr	63.8	9.7	13.0	8.0	0.40	325	0.90	0.83	1.50	2.15	1.64
6	'67 Ford Falcon Van	65.0	10.7	11.8	5.8	0.70	350	0.72	0.90	1.17	2.08	1.73
7	'77 Chevy Van	61.5	12.2	12.7	4.3	1.27	300	0.57	1.50	1.44	2.60	1.08
5	'75 Dodge Custom 200 Pickup	63.0	11.5	11.5	3.8	2.00	450	0.53	1.50	0.80	1.80	1.54
12	'70 Buick Gran Sport	62.6	11.9	11.5	4.2	3.40	325	0.67	1.67	1.43	2.71	1.33
31	700 Series Bus #704	76.6	6.5	12.9	---	1.00	350	0.63	1.25	1.11	8.19	7.43
24	'76 Kenworth Paccar w/ Tanker	82.9	7.1	11.4	8.5	1.23	225	0.50	2.10	2.10	6.80	5.89
23	'73 Peterbilt Paccar w/ Tanker	82.3	6.8	12.8	9.4	1.36	375	0.58	1.57	1.12	7.18	6.67
30	'76 Kenworth Paccar w/ Van	79.8	4.8	12.9	---	1.56	400	0.56	1.63	0.89	7.20	6.73
25	'73 Kenworth Paccar w/ Flatbed	79.3	5.5	10.3	7.3	2.50	275	0.41	3.13	1.48	5.90	5.10
8	'76 Ford Truck F-350 w/ 14 ft Van	66.0	9.9	9.6	2.9	2.76	250	0.62	2.88	1.72	5.77	5.01
9	'73 Ford Truck C-700 w/ 22 ft Van	70.4	---	---	8.3	2.85	250	1.15	2.90	1.73	5.20	4.98
32	1100 Series Bus #1111	74.9	9.8	10.5	---	4.22	350	0.54	5.10	1.00	4.00	3.44
22	'64 Ford Cabover w/ Van	---	---	---	---	5.71	175	0.93	4.14	2.26	4.77	4.28
21	'69 White Freight-liner Cabover w/ Van	---	---	---	5.6	5.80	150	0.76	5.72	2.13	3.24	2.53
18	'71 Kenworth w/ Van	84.8	6.9	7.5	2.4	9.40	225	1.10	9.75	1.52	2.96	2.84

Column 6 is similar to the previous column, except in this case the microphone pairs (one behind the wall and one not) are located 125 ft from the center of the road. There is considerably less attenuation here and also more variability. It should be noted that the effect of wind shear can be very perturbing at this distance. Nonetheless, the measured attenuation runs from approximately 4 to 8 dB, indicating that the wall still has an ameliorating effect on the noise level. Column 7 lists the single-tone effective radiating height that is the best match with the measured A-weighted value obtained for that particular vehicle. Column 8 lists the effective radiating frequency that should be used concurrently. This pair represents the best choice of height/frequency values for computing the acoustics of that particular vehicle as measured by the microphones at various heights on Tower D.* Column 9 shows the "maximum likely error" if the values in Columns 7 and 8 are used for calculation. The values in this column were derived by taking the difference between what was measured and what would be calculated from Columns 7 and 8, calculating the mean and standard deviation of these differences for each microphone position, and then adding the mean difference to its standard deviation to obtain a numerical value for the maximum likely error. For the most part, the maximum likely error is between 0.5 and 1 dB.

The current "standard" for highway noise calculations is to assume a radiating frequency of 500 Hz. Column 10 shows the best radiating height for that frequency. This height is slightly higher than if the best radiating frequency is used. Column 11 lists the maximum error that would be likely if the combination of 500 Hz and the best radiating height were used.

Column 12 gives the "maximum likely error" if the older standards are used (namely, a radiating frequency of 500 Hz for both cars and trucks, an 8-ft radiating height for trucks, and a 0-ft radiating height for cars). For cars, the error is moderate; for the newer trucks, the error can be as much as 7 or 8 dB.

RECOMMENDATIONS

Figure 18 shows that the effective radiating height for small vehicles (i.e., vehicles that have gasoline-powered motors, weigh less than 8,000 lb, and have tailpipes near the ground) is relatively low. Table III shows the maximum error that would occur by assuming various radiating heights, on a vehicle by vehicle basis, for a speed of 40 mph and a frequency of 300 Hz. Figure 15 and Table III indicate that a

* These values represent the best overall fit to the readings on all the D-tower microphones.

Table III. Calculated error in decibels for chosen radiating height. All vehicles at 300 Hz and 40 mph.

VEHICLE NUMBER	DESCRIPTION	RADIATING HEIGHT (ft) -2	-1	0	1	2	3	4	5
4	'76 Dodge Stn. Wgn.	1.76	1.33	1.46	2.03	2.80	3.65	4.47	5.36
5	'75 Dodge Pickup	2.93	2.17	1.44	1.54	1.98	2.79	3.61	4.54
6	'67 Ford Falcon Van	2.38	1.81	1.54	1.73	2.22	3.02	3.87	4.76
7	'77 Chevy Van	2.55	1.83	1.23	1.08	1.52	2.36	3.17	3.94
10	'76 Saab 99 2-door	2.26	1.54	1.37	1.64	2.26	3.06	3.82	4.48
12	'70 Buick Gran Sport	2.93	2.21	1.57	1.33	1.45	2.35	3.19	4.06

good average value for small vehicles would be a source 0.5 to 1 ft above the road surface radiating at a frequency of 400 Hz. The current practice in highway noise work is to use 500 Hz (the state of Washington uses 566 Hz) and a height of 0 ft. This study shows that the current practice gives the wall credit for slightly more effectiveness than it has. However, the difference is not great compared to the variability in the whole process, and there appears to be no strong reason for a change. The results of these tests do indicate that an effective height of 0.5 ft and a frequency of 400 Hz would be a better choice.

Because of the wide disparity in their effective radiating heights, the results for large diesel trucks are not nearly so simple. The trucks in the sampling can be divided into approximately two classes: those built in 1973 or later and those built prior to 1973. The study does not represent a large enough number, statistically, to show that 1973 is a breaking point for the truck population as a whole. It does, however, indicate the difference between recently constructed trucks vis-à-vis older trucks. Note in Figure 19 that most of the pre-1973 trucks tend to have high radiating heights. Some show low-speed radiating heights of only a few feet, while others at higher speed show radiating heights of as much as 12 ft. For older trucks, there appears to be no good reason to change from the present accepted practice of assuming a radiating height of 8 ft--although, of course, this assumption can be badly in error for any individual older truck.

All of the trucks in our sample built in 1973 or later* showed radiating heights between 1 and 3 ft. It is important not only that these trucks are quieter, but that their radiating heights are lower. In general, their radiated noise spectrum is also higher in frequency; i.e., they tend to whine rather than roar. It appears that much of the noise is coming from beneath the truck and is being reflected from the pavement, producing the equivalent of a low effective radiating height, and that the noise levels of many of the higher (i.e., taller) emitters have been significantly reduced on these trucks. Table IV shows the maximum error that would be achieved by assuming various radiating heights between 0.5 ft and 8.5 ft above the roadway, on a truck by truck basis, for a speed of 40 mph and a radiating frequency of 300 Hz. The table indicates that the best overall results for new trucks would be obtained by assuming a height of 1.5 to 2.5 ft above the road. It is our recommendation that a radiating height of 2.5 ft be used for new trucks, with an effective frequency of 300 Hz.

Since roads currently contain a mixture of both new and old vehicles, it would be hard to judge the best radiating height to use unless one had a statistical sampling of the age and type of trucks used in the area. Even then the results would only lead to statistical averages--a relatively low wall would not give much protection when a higher-than-average radiator was going by. On the other hand, by 1990 or later most trucks would probably meet the lower noise requirements, and would also probably exhibit the lower radiating height. It would therefore seem reasonable that walls designed for that time frame be based on the considerably lower effective radiating height found for the newer trucks.

* All of these trucks were provided by PACCAR, the parent organization for Kenworth and Peterbilt.

Table IV. Calculated error, in decibels, for chosen radiating height. All vehicles at 300 Hz and 40 mph.

VEHICLE NUMBER	DESCRIPTION	RADIATING HEIGHT (ft)										
		0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5
8	'76 Ford 14 ft Van	2.24	1.47	1.15	1.55	2.20	2.86	3.64	4.54	5.50	---	---
9	'73 Ford 22 ft Van	2.74	1.93	1.37	1.95	2.55	3.15	3.83	4.57	5.42	---	---
23	'73 Peterbilt Paccar w/ Tanker	1.08	1.15	1.84	2.62	3.42	4.30	5.28	6.27	7.29	---	---
24	'76 Kenworth Paccar w/ Tanker	1.91	1.95	2.17	2.63	3.23	3.89	4.67	5.47	6.31	---	---
25	'73 Kenworth Paccar w/ Flatbed	2.11	1.38	1.00	1.27	1.85	2.68	3.64	4.61	5.60	---	---
30	'76 Kenworth Paccar w/ Van	1.25	1.06	1.76	2.40	3.30	4.20	5.21	6.22	7.25	---	---
31	700 Series Metro Bus #704	0.73	1.22	2.14	3.02	3.88	4.79	5.77	6.75	7.76	---	---
32	1100 Series Metro Bus #1111	4.09	3.29	2.43	1.59	1.08	1.50	2.42	3.38	4.38	---	---
18	'71 Kenworth w/ Van	9.31	8.59	7.81	7.03	6.15	5.21	4.19	3.21	2.49	2.13	1.86
21	'69 White Freightliner Cabover w/ Van	5.54	4.81	4.02	3.24	2.37	1.81	1.96	2.34	2.79	3.36	---
22	'64 Ford Cabover w/ Van	4.20	3.45	2.77	2.20	2.17	2.60	3.27	3.95	4.62	---	---
19	'64 Peterbilt w/ Flatbed	7.02	6.19	5.26	4.37	3.49	2.57	1.61	0.73	0.60	1.51	2.58

REFERENCES

1. "Noise Barrier Screen Measurements--Single Barriers," by R.N. Foss, Washington State Highway Department Research Program Report 24.1, dated June 1975 (also documented as APL-UW 7509).

2. Z. Maekawa, "Noise reduction by screens," Applied Acoustics, 1:157-173 (1968).

3. U.J. Kurze, "Noise reduction by barriers," J. Acoust. Soc. Am., 55(3):504-518 (1974).

APPENDIX A

A REPRESENTATIVE SAMPLE OF INDIVIDUAL VEHICLE DATA

Vehicle No. 01

Vehicle Information: Laboratory Pinto Station Wagon #43

Engine: HP ______ Make ______ Cylinders 4

Ht. to Mid Engine 2 ft Ht. to Top of Vehicle 4 ft 3 in

Length of Vehicle 14'-6" Width of Vehicle 5'-8" License # B12943

Tires: Size BR78-13 Front 2 Ribbed Back 2 Ribbed

	6/ 28	/	/	/	/	1977
Speed	Tape No. 1	Tape No.	Tape No.	Tape No.	Tape No.	Total
30	2					2
40	1					1
50	4					4
55	1					1
					TOTAL	8

Vehicle No. 02

Vehicle Information: 1976 Dodge Coronet Station Wagon #66

Engine: HP ______ Make 360 Cylinders 8

Ht. to Mid Engine 2'-2" Ht. to Top of Vehicle 4'-9"

Length of Vehicle 17'-10" Width of Vehicle 5'-10" License # B13666

Tires: Size HR78-15 Front 2 Ribbed Back 2 Ribbed

Speed	Tape No. 8 (7/20)	Tape No. (/)	Tape No. (/)	Tape No. (/)	Tape No. (/)	1977 Total
	2					2

Vehicle No. 03

Vehicle Information: 1976 Dodge Coronet Station Wagon #67

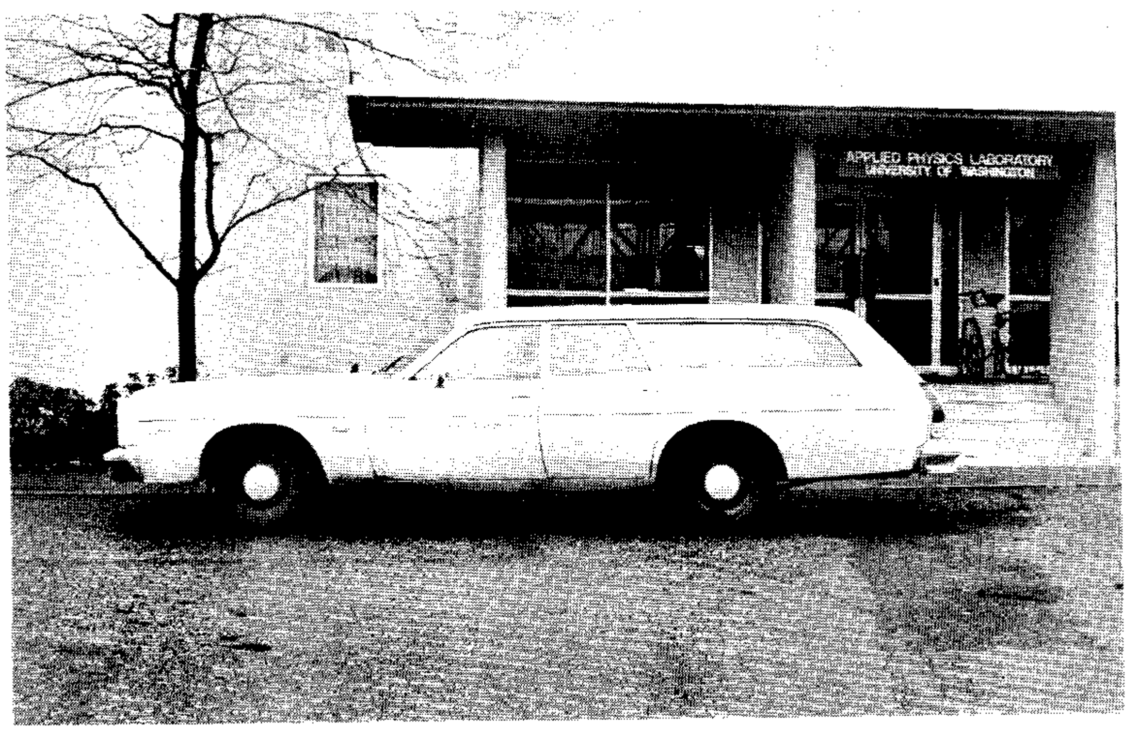
Engine: HP ______ Make 360 Cylinders 8

Ht. to Mid Engine 2'-2" Ht. to Top of Vehicle 4'-9"

Length of Vehicle 17'-10" Width of Vehicle 5'-10" License # B13667

Tires: Size HR78-15 Front 2 Ribbed Back 2 Ribbed

Speed	6/29 & 30 Tape No. 2	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
30	2					2
40	12					12
50	6					6
					TOTAL	20



Vehicle No. 04

Vehicle Information: 1976 Dodge Coronet Station Wagon #68

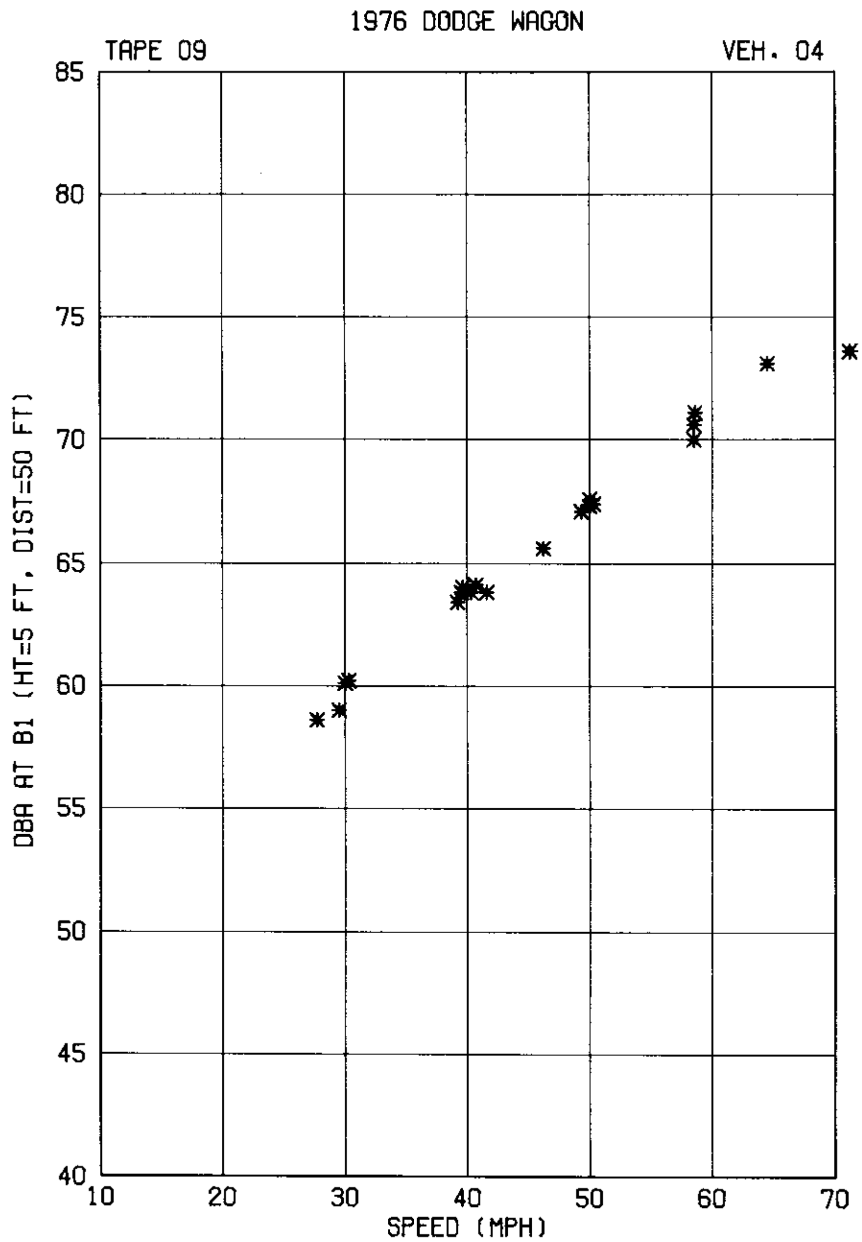
Engine: HP ______ Make 360 Cylinders 8

Ht. to Mid Engine 2'-2" Ht. to Top of Vehicle 4'-9"

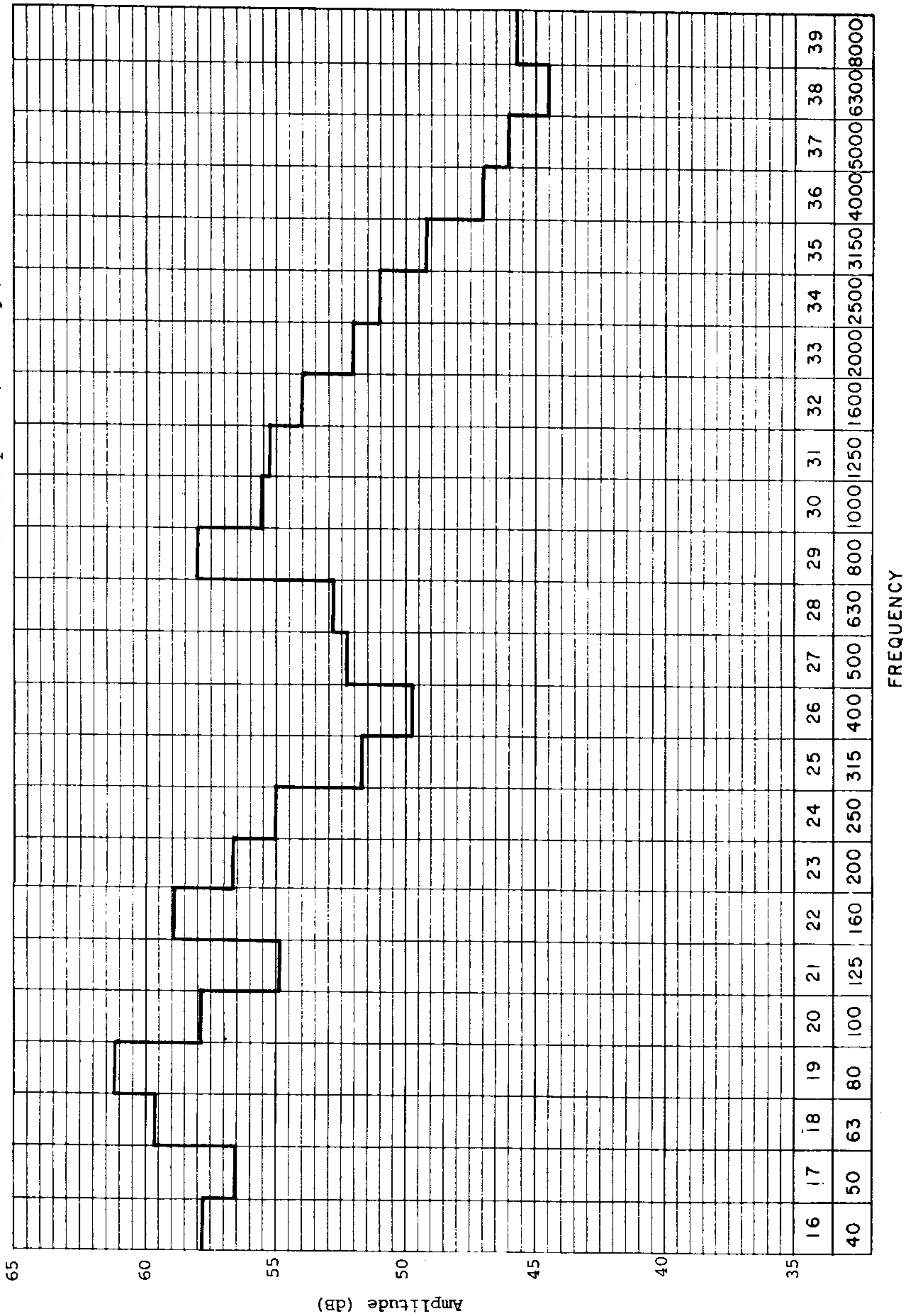
Length of Vehicle 17'-10" Width of Vehicle 5'-10" License # B13668

Tires: Size HR78-15 Front 2 Ribbed Back 2 Ribbed

Speed	6/28 Tape No. 1	7/6 Tape No. 4	7/6 & 7 Tape No. 5	7/21 Tape No. 9	/ Tape No.	1977 Total
20	2	1				3
30	4	2	2	4		12
40	7	5	4	6		22
50	13	5	3	5		26
55	2		2			4
60			2	3		5
65				1		1
70				2		2
					TOTAL	75


1976 DODGE WAGON
TAPE 09
VEH. 04
DBA AT B1 (HT=5 FT, DIST=50 FT)
85
80
75
70
65
60
55
50
45
40
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle 04, Tape 9-37, 40 mph
B1 Microphone (5 ft high, 50 ft from road)



Vehicle No. 05

Vehicle Information: 1975 Dodge Custom 200 Pickup #87

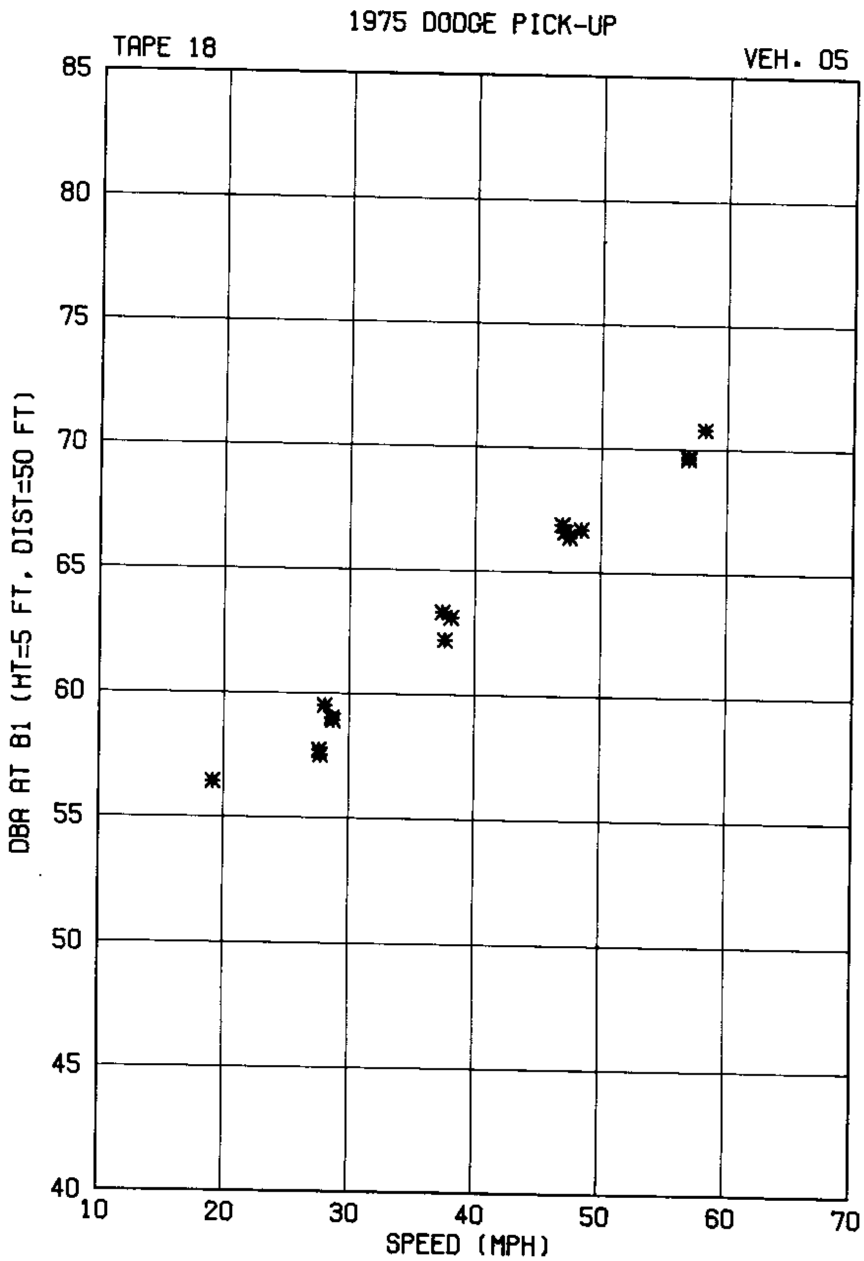
Engine: HP ______ Make ______ Cylinders ______

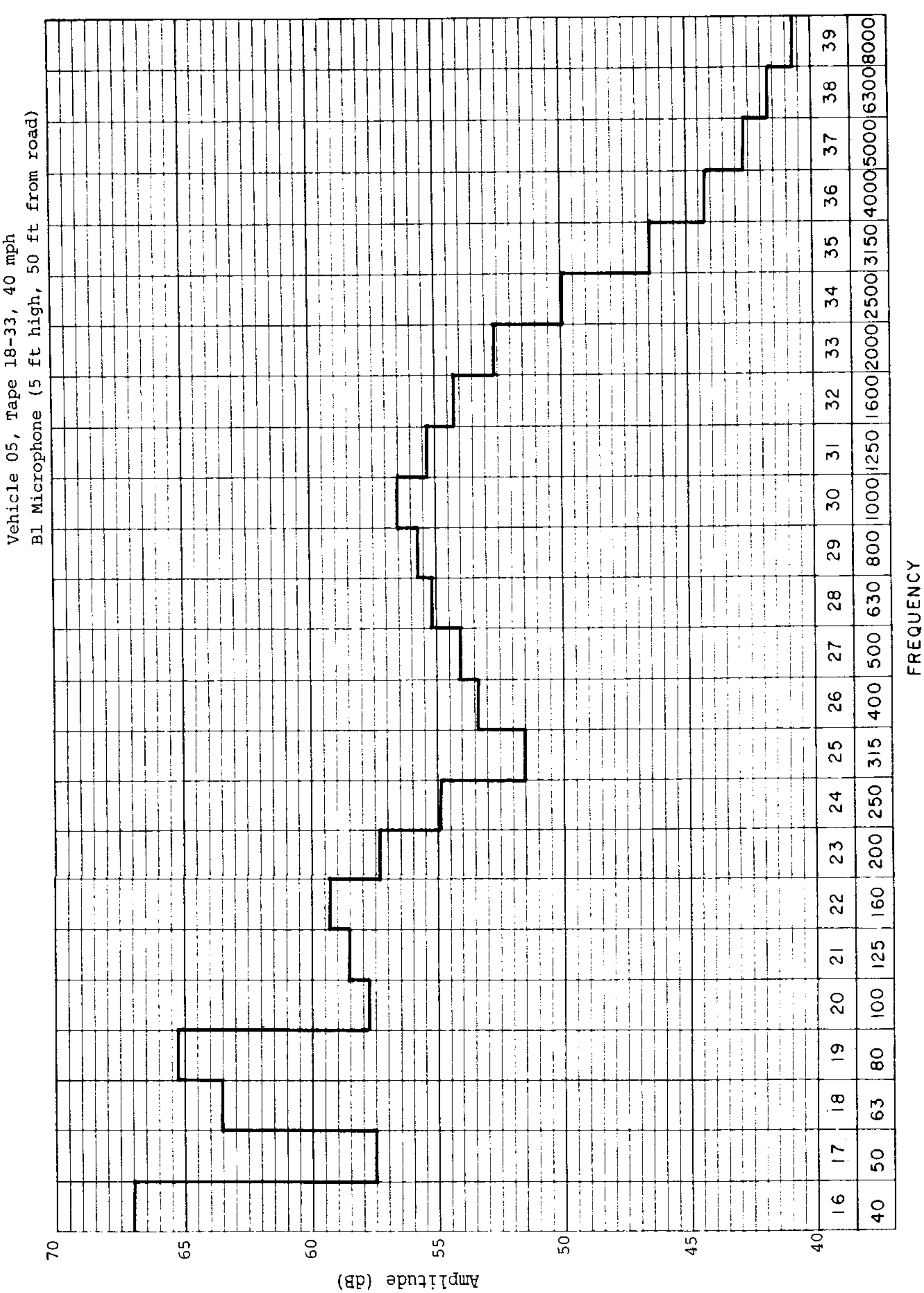
Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

Length of Vehicle ______ Width of Vehicle ______ License # ______

Tires: Size ______ Front ______ Back ______

Speed	9/7 Tape No.18	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	1					1
30	5					5
40	3					3
50	4					4
60	3					3
					TOTAL	16


1975 DODGE PICK-UP
TAPE 18
VEH. 05
DBA AT B1 (HT=5 FT, DIST=50 FT)
85
80
75
70
65
60
55
50
45
40
10
20
30
40
50
60
70
SPEED (MPH)



Vehicle 05, Tape 18-33, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
70
65
60
55
50
45
40
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

Vehicle No. 06

Vehicle Information: 1967 Ford Falcon Van #91

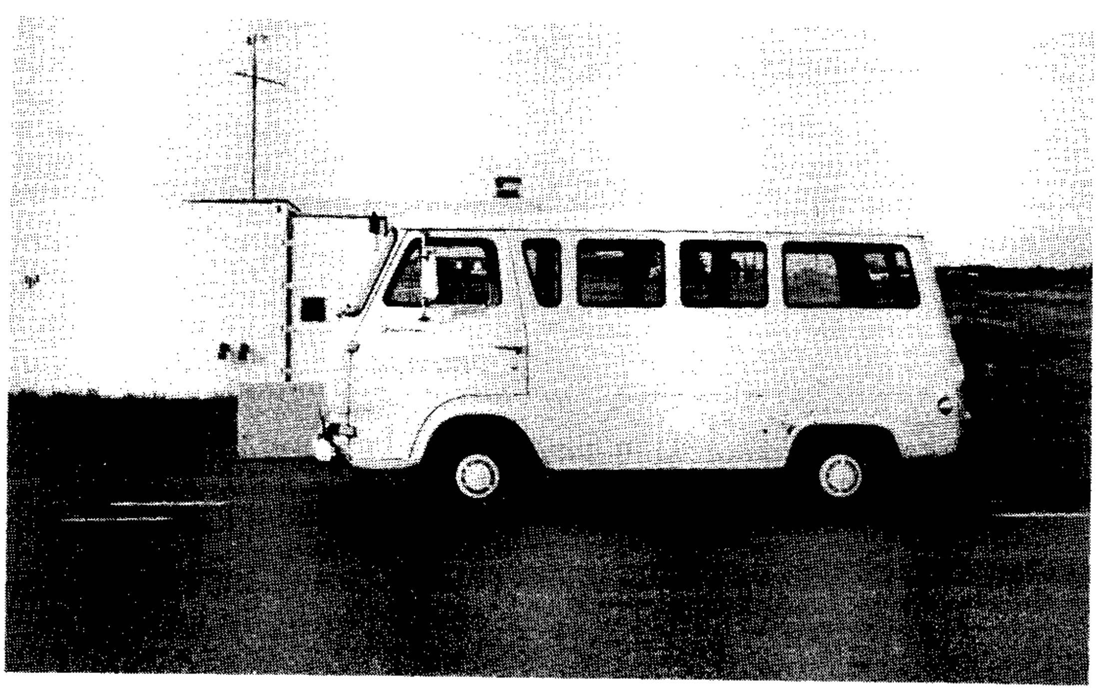
Engine: HP ______ Make ______ Cylinders ______

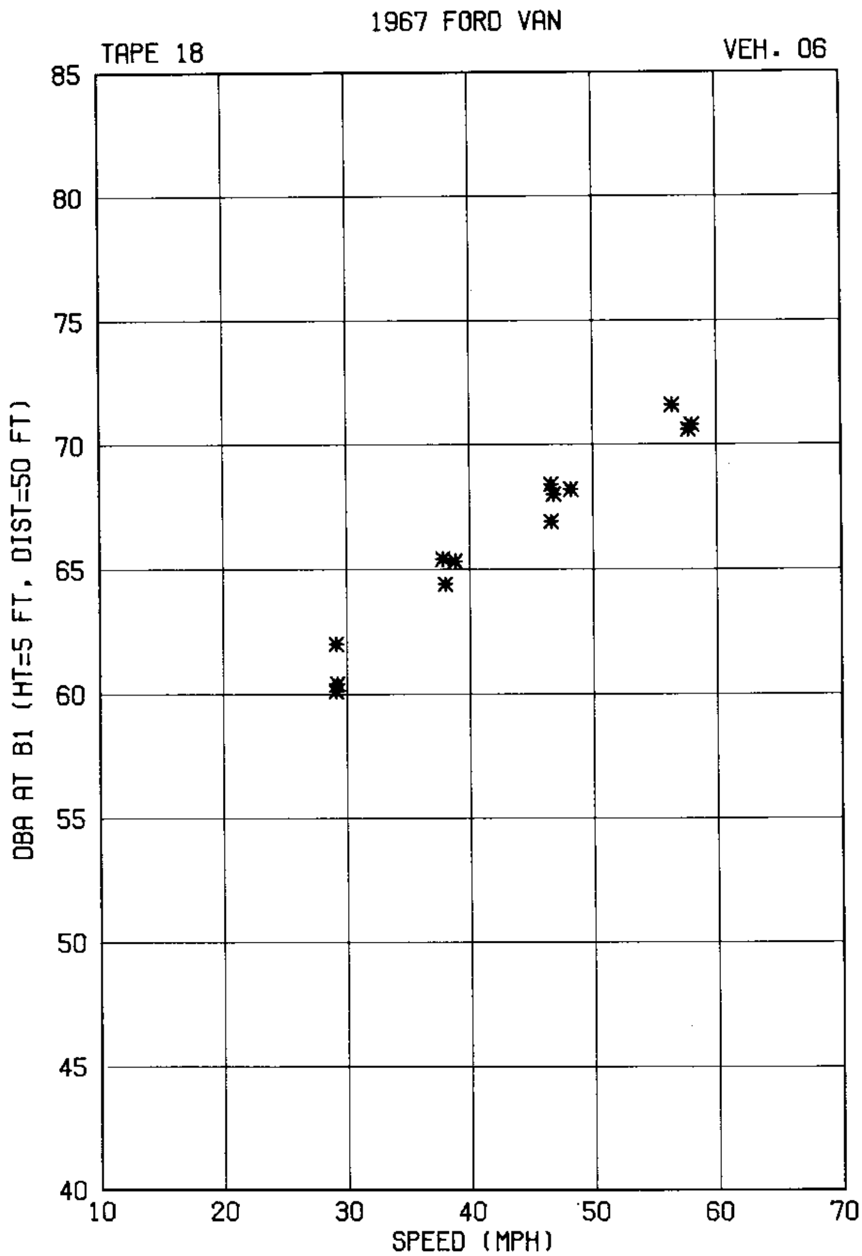
Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

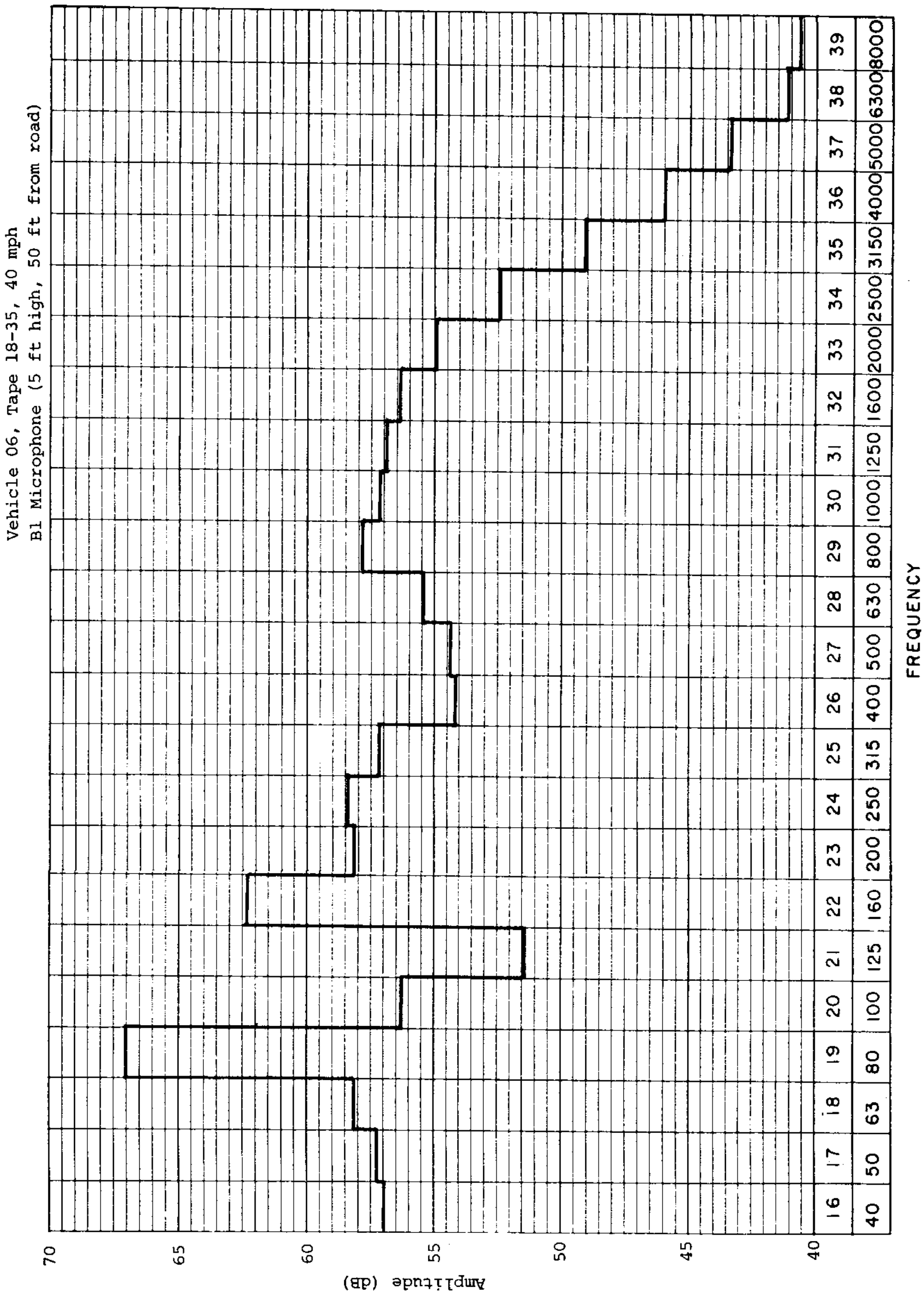
Length of Vehicle ______ Width of Vehicle ______ License # ______

Tires: Size ______ Front ______ Back ______

Speed	9/7 Tape No. 18	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	1					1
30	3					3
40	3					3
50	4					4
60	3					3
					TOTAL	14




1967 FORD VAN
TAPE 18
VEH. 06
85
80
75
70
65
60
55
50
45
40
DBA AT B1 (HT=5 FT, DIST=50 FT)
10
20
30
40
50
60
70
SPEED (MPH)


Vehicle 06, Tape 18-35, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
70
65
60
55
50
45
40
FREQUENCY
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000

Vehicle No. 07

Vehicle Information: 1977 Chevrolet Van 20 #33

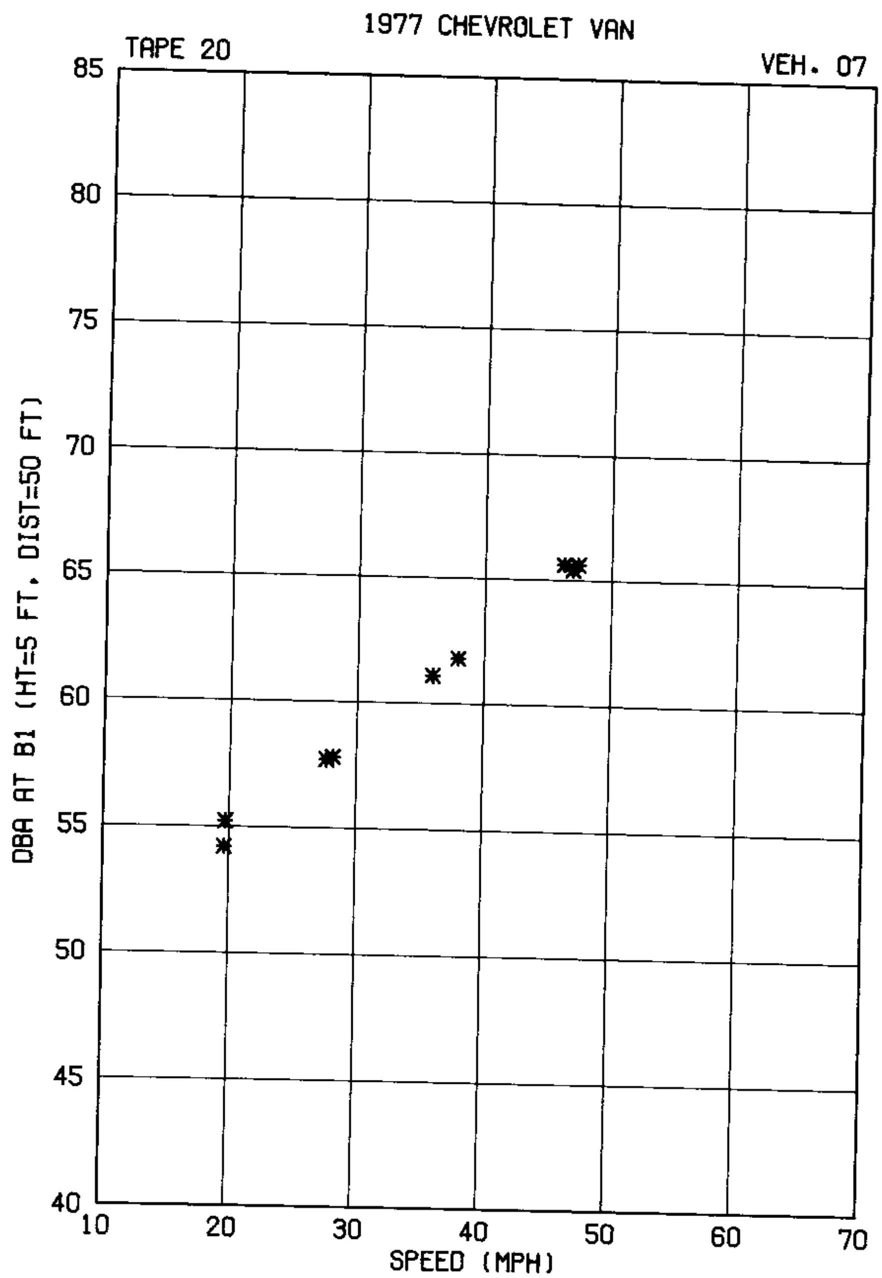
Engine: HP ______ Make ______ Cylinders 8

Ht. to Mid Engine 3' Ht. to Top of Vehicle 6'-8"

Length of Vehicle 16'-6" Width of Vehicle 6'-4" License # B15633

Tires: Size 578-15 Front 2 Ribbed Back 2 Ribbed

Speed	9/13 Tape No. 20	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
30	2					2
40	2					2
50	3					3
					TOTAL	10


1977 CHEVROLET VAN
TAPE 20
VEH. 07
85
80
75
70
65
60
55
50
45
40
DBA AT B1 (HT=5 FT, DIST=50 FT)
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle No. 08

Vehicle Information: 1976 Ford F-350 International Rental #355 with 14' Van, 10,000 Gross Capacity

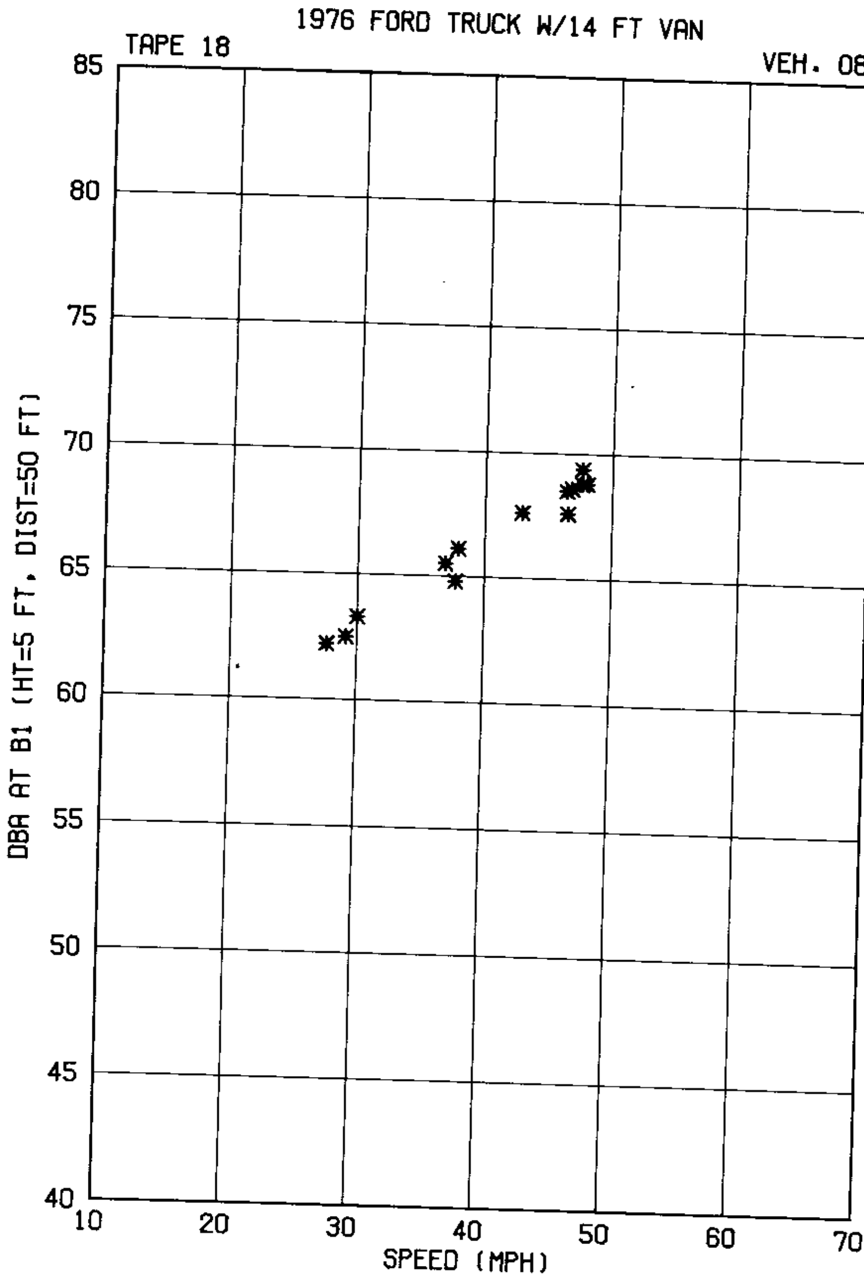
Engine: HP ______ Make 360 Cylinders 8

Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

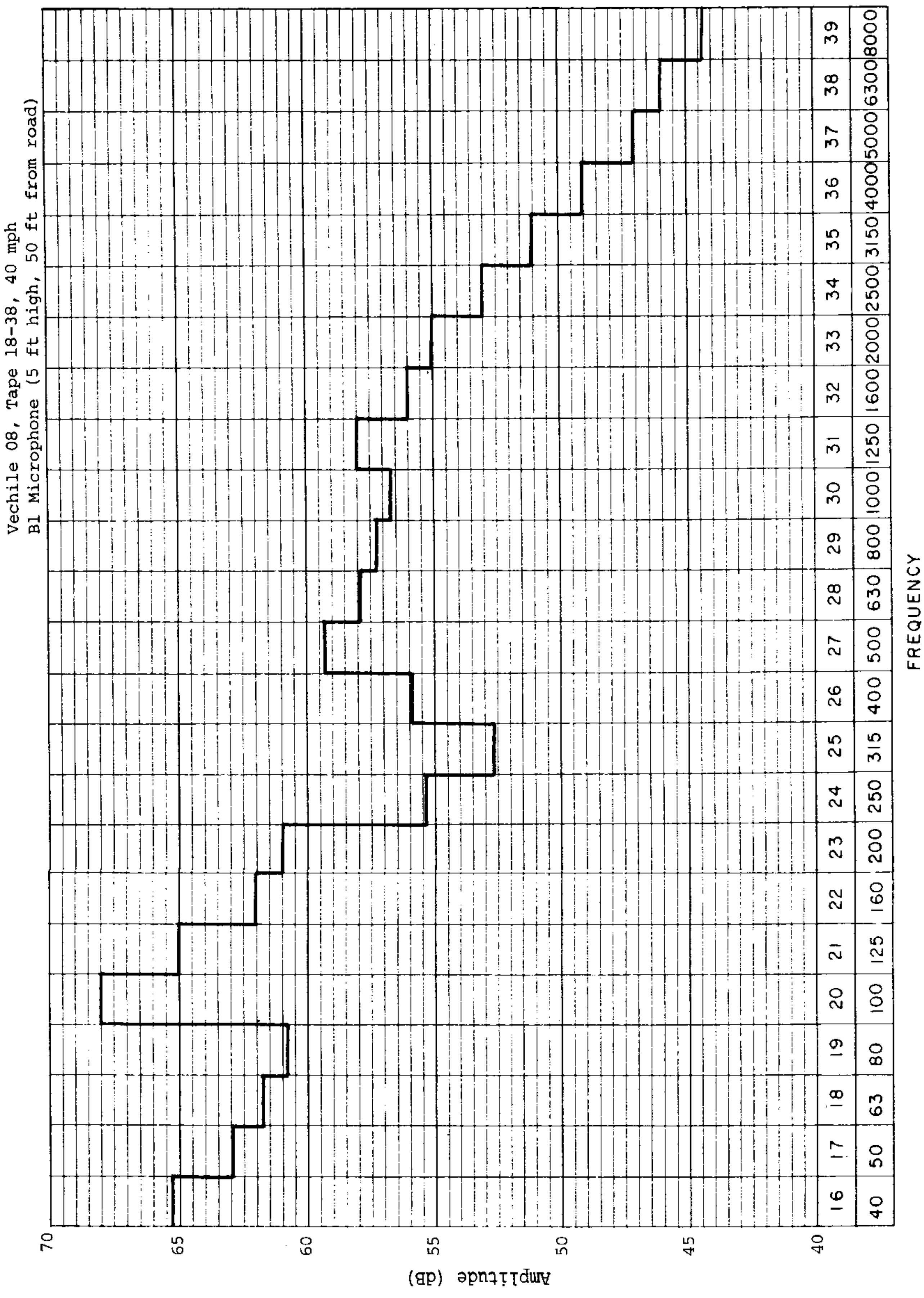
Length of Vehicle ______ Width of Vehicle ______ License # ______

Tires: Size ______ Front 2 Ribbed Back 2 Ribbed

	9/7	/	/	/	/ 1977	
Speed	Tape No. 18	Tape No.	Tape No.	Tape No.	Tape No.	Total
30	3					3
40	3					3
45	1					1
50	6					6
					TOTAL	13



1976 FORD TRUCK W/14 FT VAN
TAPE 18
VEH. 08
85
80
75
70
65
60
55
50
45
40
DBA AT B1 (HT=5 FT, DIST=50 FT)
10
20
30
40
50
60
70
SPEED (MPH)


Vechile 08, Tape 18-38, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
70
65
60
55
50
45
40
FREQUENCY
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000

Vehicle No. 09

Vehicle Information: 1973 Ford C-700 International Rental #713 with 22' Van -- 28,000 Gross Capacity. Exhaust 20" underneath and approx. in middle.

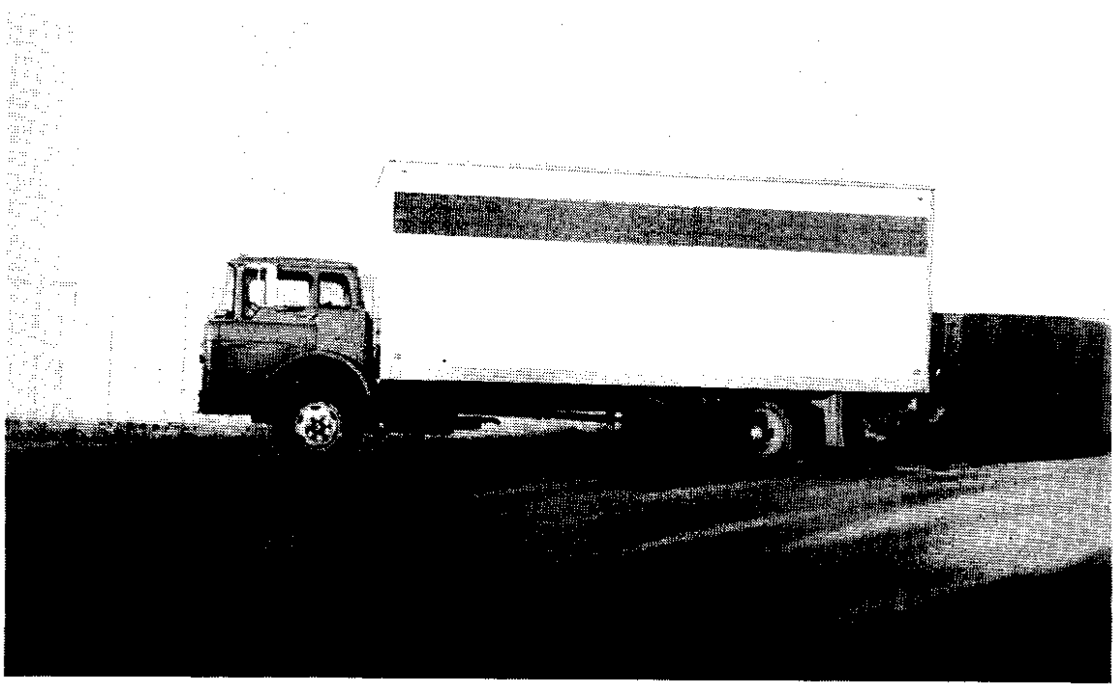
Engine: HP ______ Make 361 Cu. In. Heavy Duty Cylinders 8

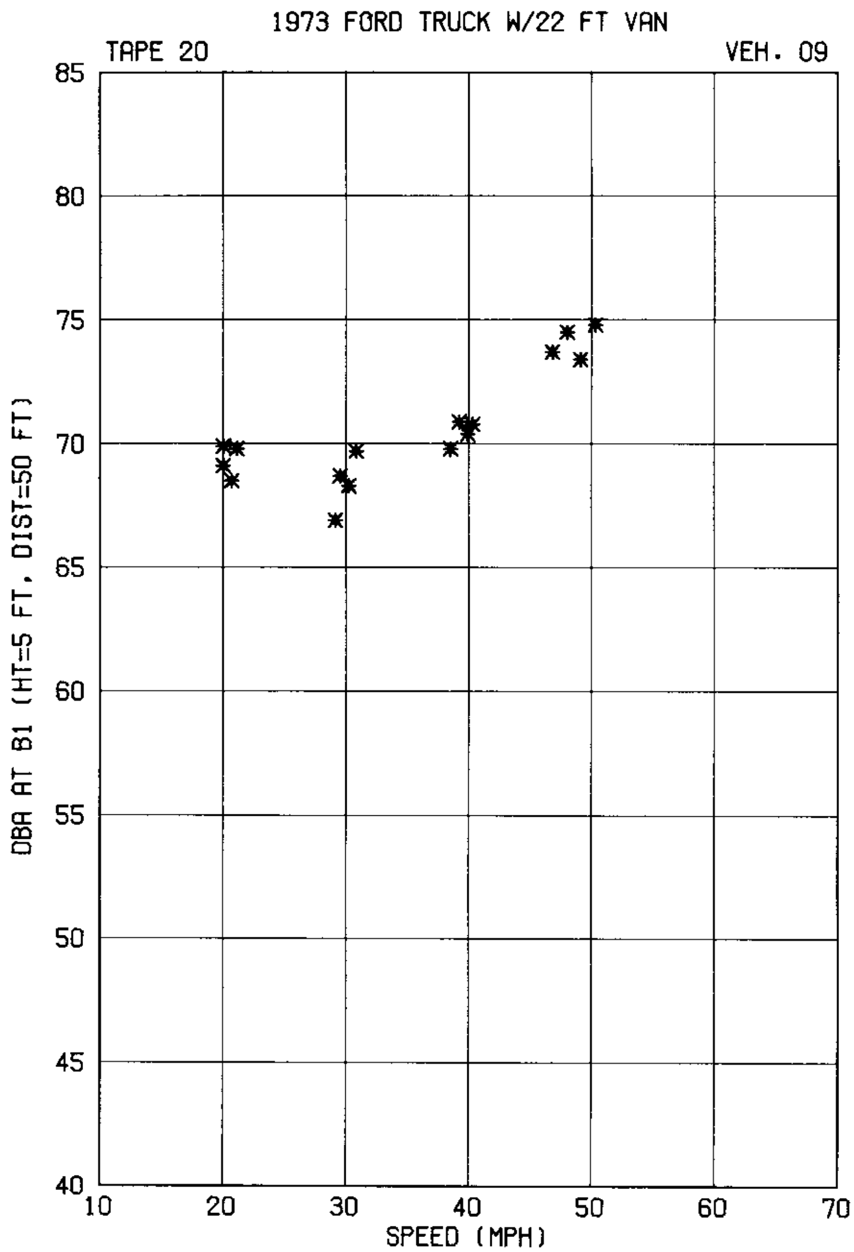
Ht. to Mid Engine 4.5' Ht. to Top of Vehicle (van) 11.5'

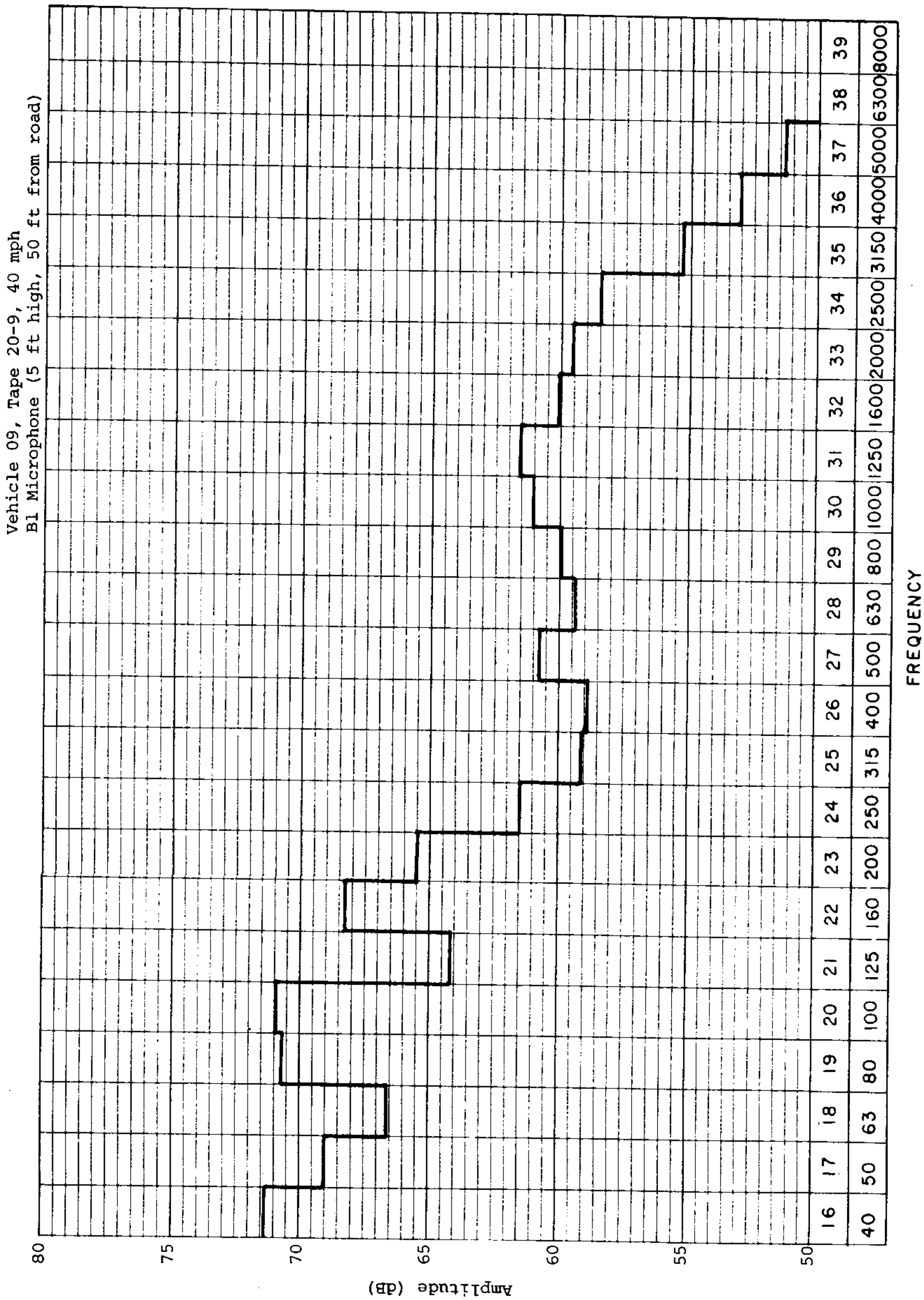
Length of Vehicle ______ Width of Vehicle ______ License # GT 4645

Tires: Size 9.00 x 20 Front 2 Ribbed Back 8 Ribbed

Speed	9/13 Tape No. 20	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	4					4
30	4					4
40	4					4
50	4					4
					TOTAL	16




1973 FORD TRUCK W/22 FT VAN
TAPE 20
VEH. 09
DBA AT B1 (HT=5 FT, DIST=50 FT)
85
80
75
70
65
60
55
50
45
40
10
20
30
40
50
60
70
SPEED (MPH)


Vehicle 09, Tape 20-9, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
80
75
70
65
60
55
50
FREQUENCY
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000

Vehicle No. 10

Vehicle Information: 1976 Saab 99, 2 Door Auto

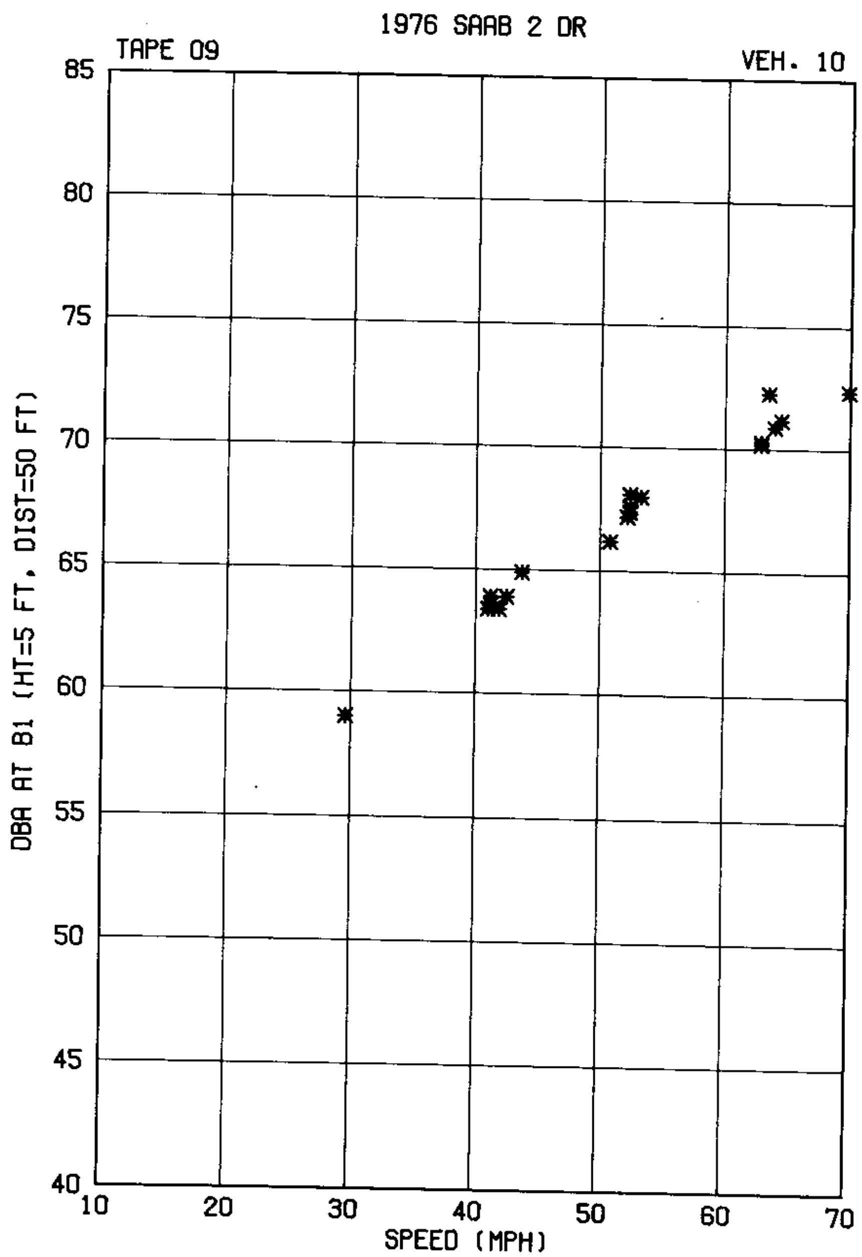
Engine: HP ______ Make ______ Cylinders 4

Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

Length of Vehicle ______ Width of Vehicle ______ License # ______

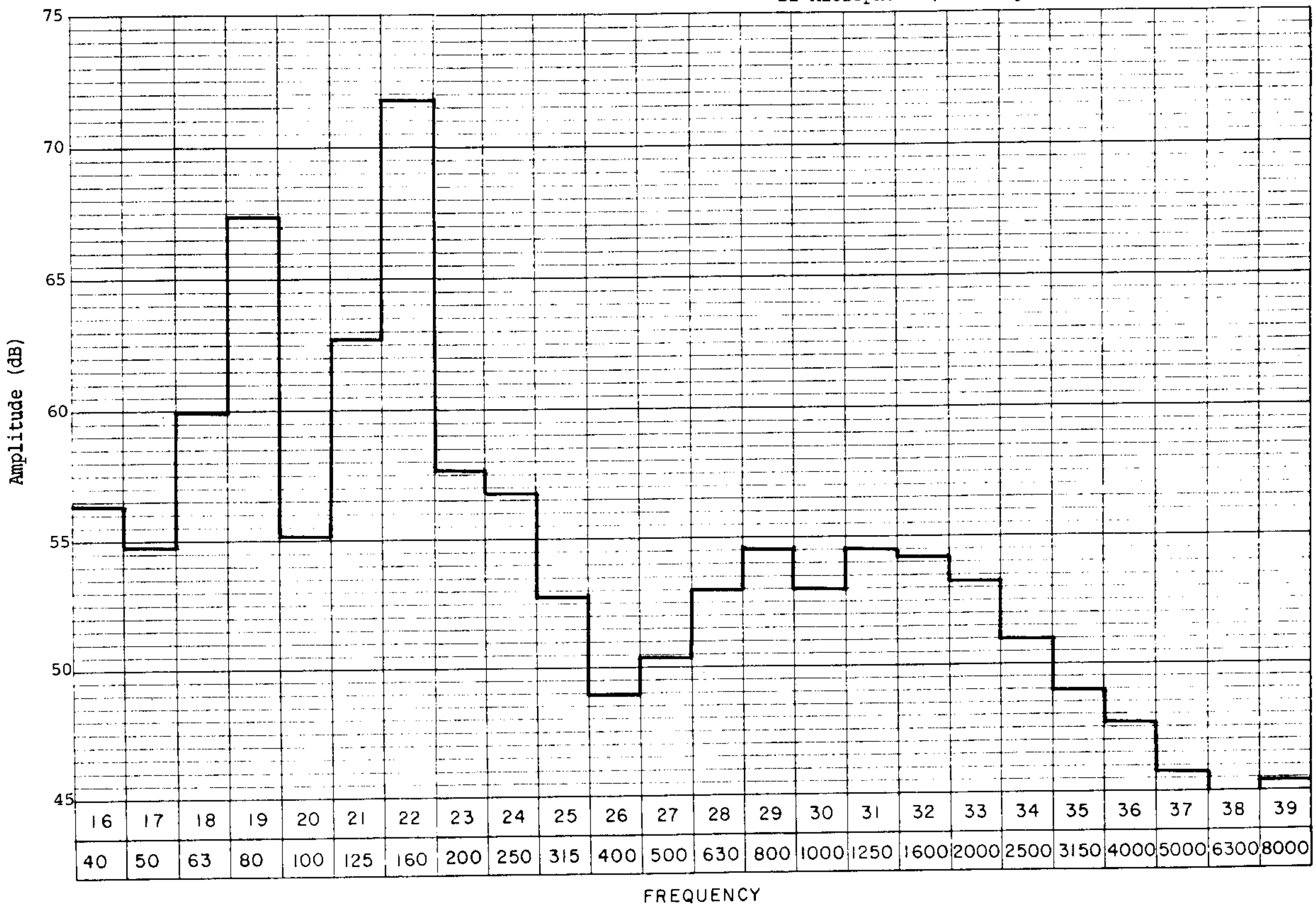
Tires: Size ______ Front ______ Back ______

Speed	6/28 Tape No. 1	6/29 & 30 Tape No. 2	7/6 Tape No. 4	7/7 Tape No. 5	7/21 Tape No. 9	Total
20	2		1			3
30	2	2	2	2	4	12
40	3	2	2		7	14
50	4	2	3	2	6	17
55				3		3
60				1	4	5
65					2	2
					TOTAL	56



1976 SAAB 2 DR
TAPE 09
VEH. 10
85
80
75
70
65
60
55
50
45
40
DBA AT B1 (HT=5 FT, DIST=50 FT)
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle 10, Tape 9-36, 40 mph
B1 Microphone (5 ft high, 50 ft from road)



Vehicle No. 11

Vehicle Information: 1970 Buick Gran Sport, 2 Door

Bad Mufflers

4 Speed

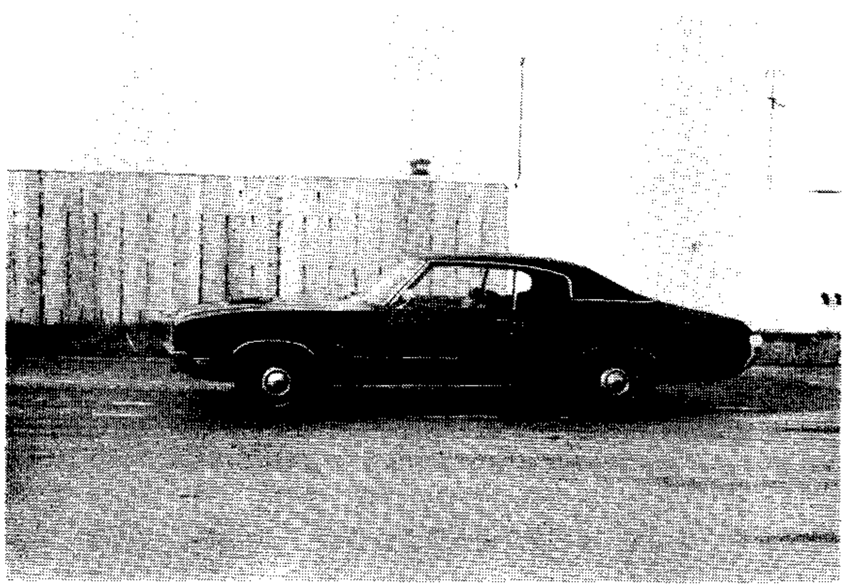
Engine: HP 315 Make 350 Cylinders 8

Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

Length of Vehicle ______ Width of Vehicle ______ License # OSG-178

Tires: Size ______ Front 2 Ribbed Back 2 Ribbed

Speed	6/30 Tape No. 2	7/6 Tape No. 4	7/7 Tape No. 5	7/20 Tape No. 8	/ 1977 Tape No.	Total
20		1				1
30	2	2	2			6
40	7	5	4			16
50	2	5	3			10
55			3			3
60			1			1
				2		2
					TOTAL	39



Vehicle No. 12

Vehicle Information: 1970 Buick Gran Sport, 2 Door (Same as #11)

New Mufflers

4 Speed

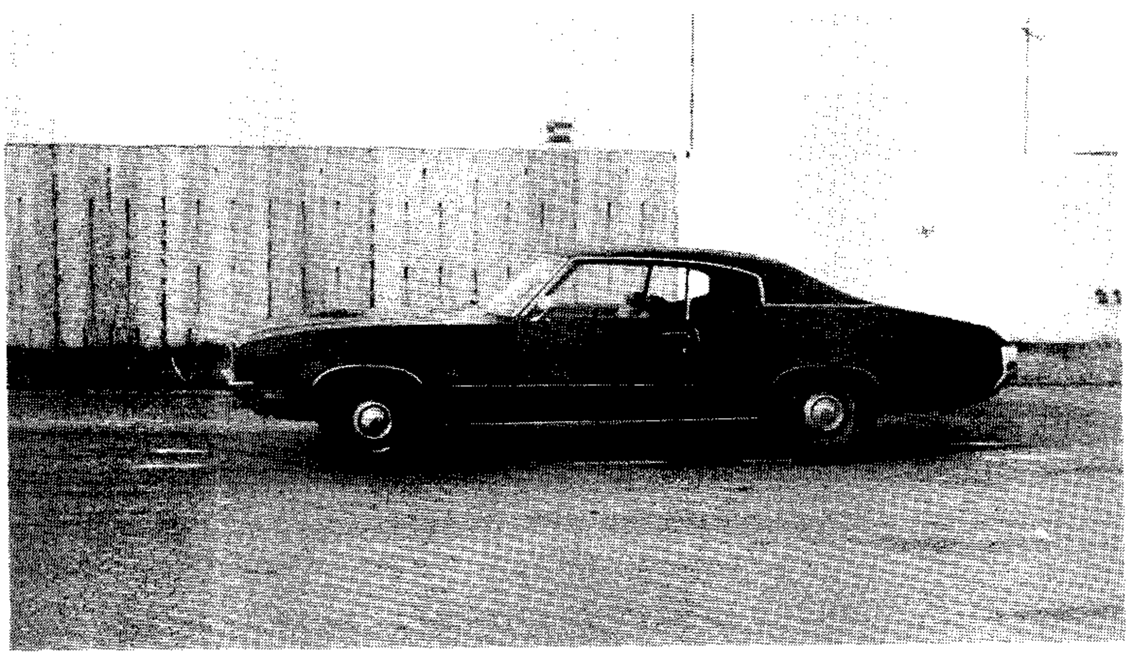
Engine: HP 315 Make 350 Cylinders 8

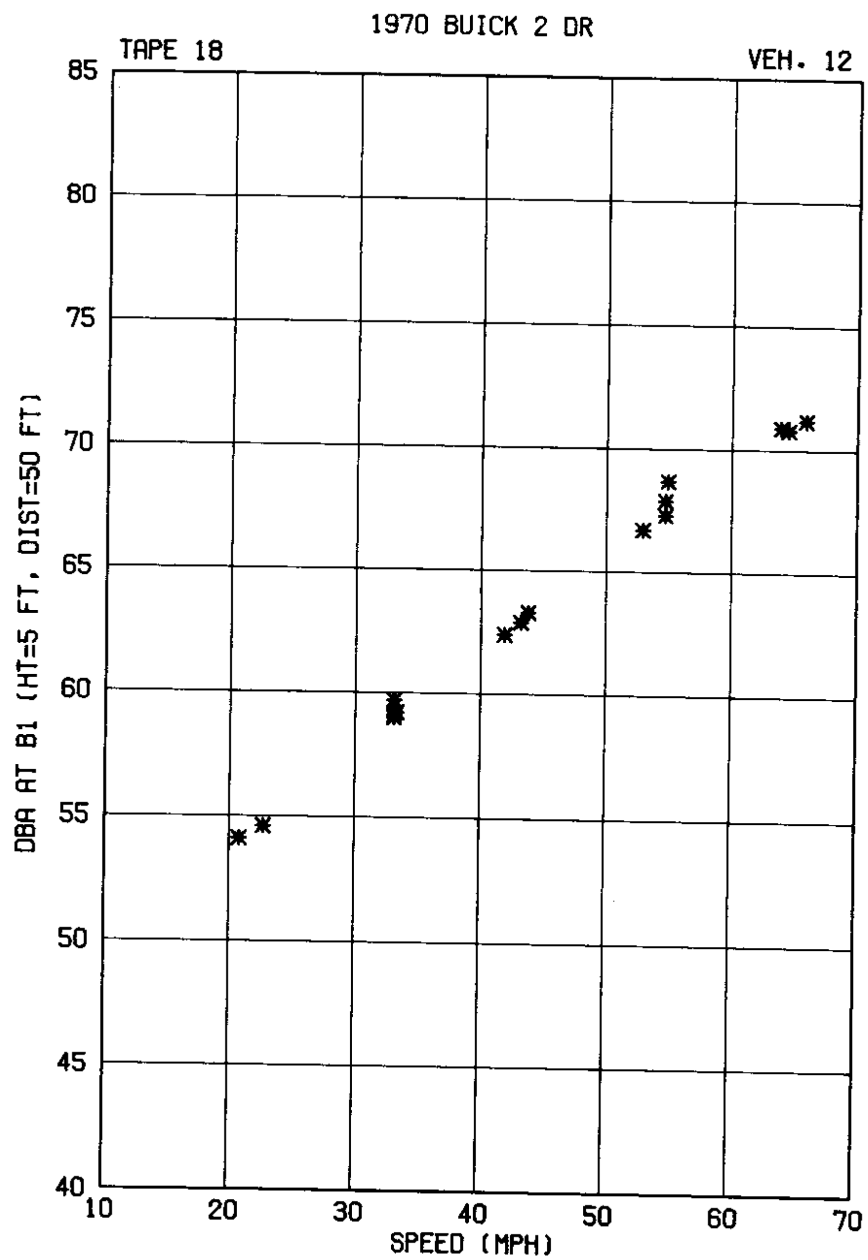
Ht. to Mid Engine ______ Ht. to Top of Vehicle ______

Length of Vehicle ______ Width of Vehicle ______ License # OSG-178

Tires: Size ______ Front 2 Ribbed Back 2 Ribbed

Speed	9/7 Tape No. 18	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	2					2
30	4					4
40	3					3
50	4					4
60	3					3
					TOTAL	16




1970 BUICK 2 DR
TAPE 18
VEH. 12
DBA AT B1 (HT=5 FT, DIST=50 FT)
SPEED (MPH)
85
80
75
70
65
60
55
50
45
40
10
20
30
40
50
60
70

Vehicle No. 13

Vehicle Information: 1970 International Cab-Over, Hogland Rental

Trailer Flatbed

Capacity 40 Ton Wt. Empty 26,000 lb

Engine: HP 325 Make 903 Cummins Cylinders 8

Ht. to Exit Stacks: Left 11'-7" Right 11'-7"

Ht. to Mid Engine 4' Ht. to Top of Van

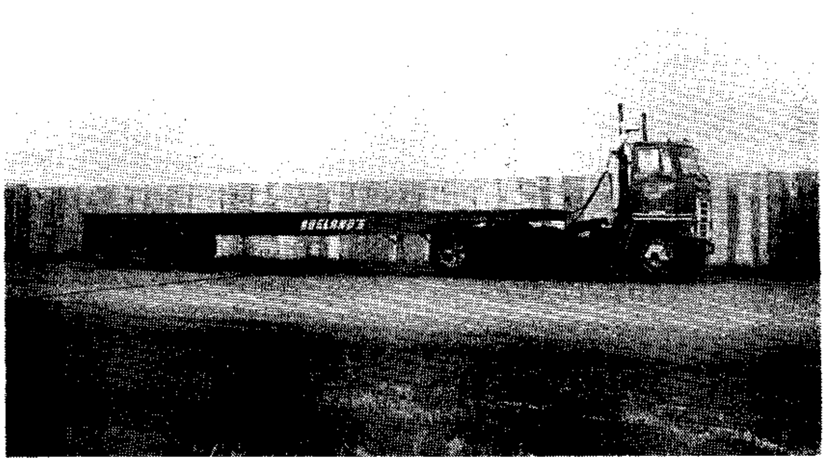
Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed 4 Lug 4

Back Trailer Tires: Ribbed 4 Lug

Tire Size 11 - 24.5 License No. H38728

	6/29	/	/	/	/ 1977	
Speed	Tape No. 2	Tape No.	Tape No.	Tape No.	Tape No.	Total
15	1					1
20	1					1
25	1					1
30	4					4
35	1					1
40	5					5
50	1					1
					TOTAL	14



Vehicle No. 14

Vehicle Information: 1970 International Cab-Over, Hogland Rental

Trailer Van

Capacity 40 Ton Wt. Empty

Engine: HP 325 Make 903 Cummins Cylinders 8

Ht. to Exit Stacks: Left 11'-7" Right 11'-7"

Ht. to Mid Engine 4' Ht. to Top of Van 13.5'

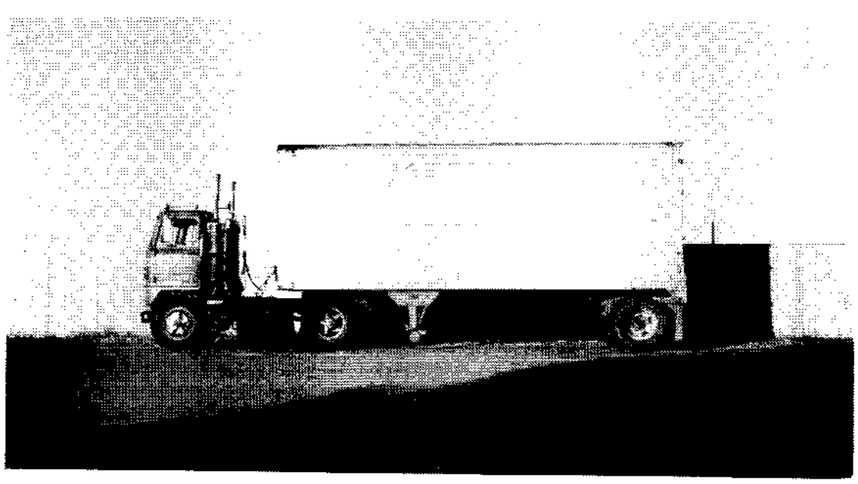
Front Tractor Tires: Ribbed 2 Lug

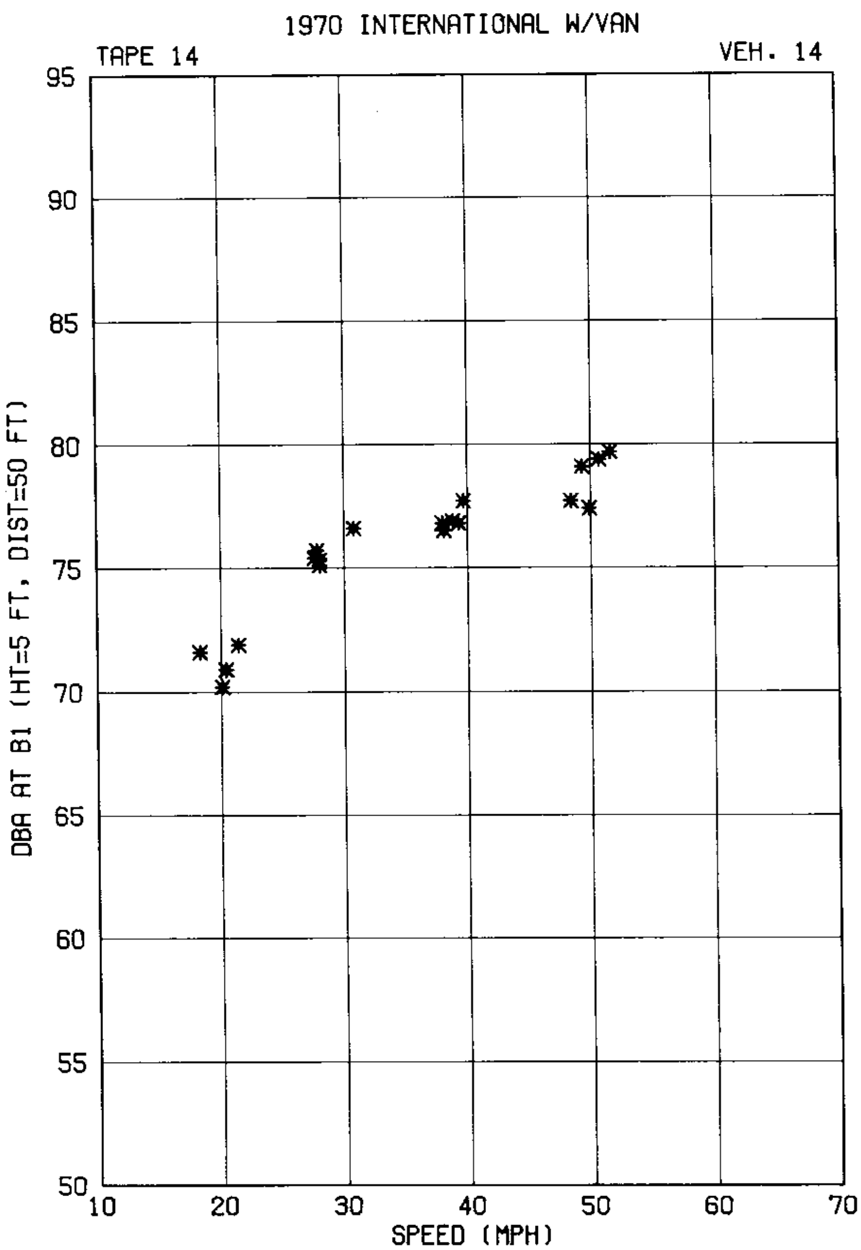
Back Tractor Tires: Ribbed 4 Lug

Back Trailer Tires: Ribbed 4 Lug

Tire Size 11 x 24.5 (10 x 22 Van) License No. H38728

Speed	8/12 Tape No. 14	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	5					5
30	5					5
40	5					5
50	5					5
					TOTAL	20




1970 INTERNATIONAL W/VAN
TAPE 14
VEH. 14
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle No. 15

Vehicle Information: 1964 Peterbilt Conventional, Hogland Rental

Trailer Flatbed

Capacity 40 Ton Wt. Empty 29,580 lbs.

Engine: HP 318 Make 318 GMC Cylinders 8

Ht. to Exit Stacks: Left 11' Right 11'

Ht. to Mid Engine 4.5' Ht. to Top of Van

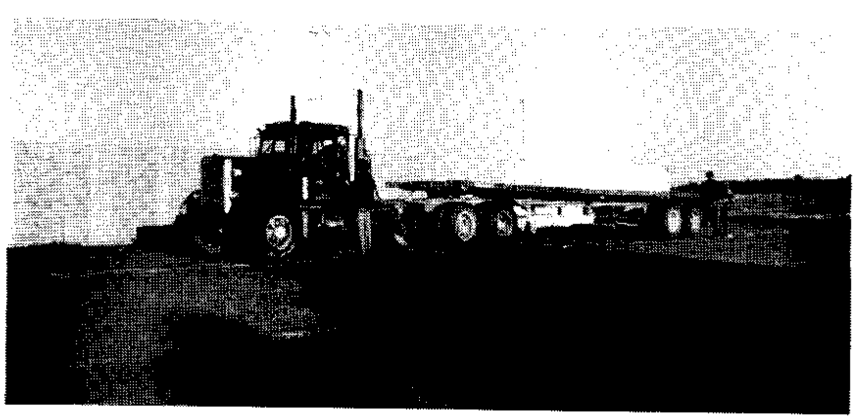
Front Tractor Tires: Ribbed 2 Lug

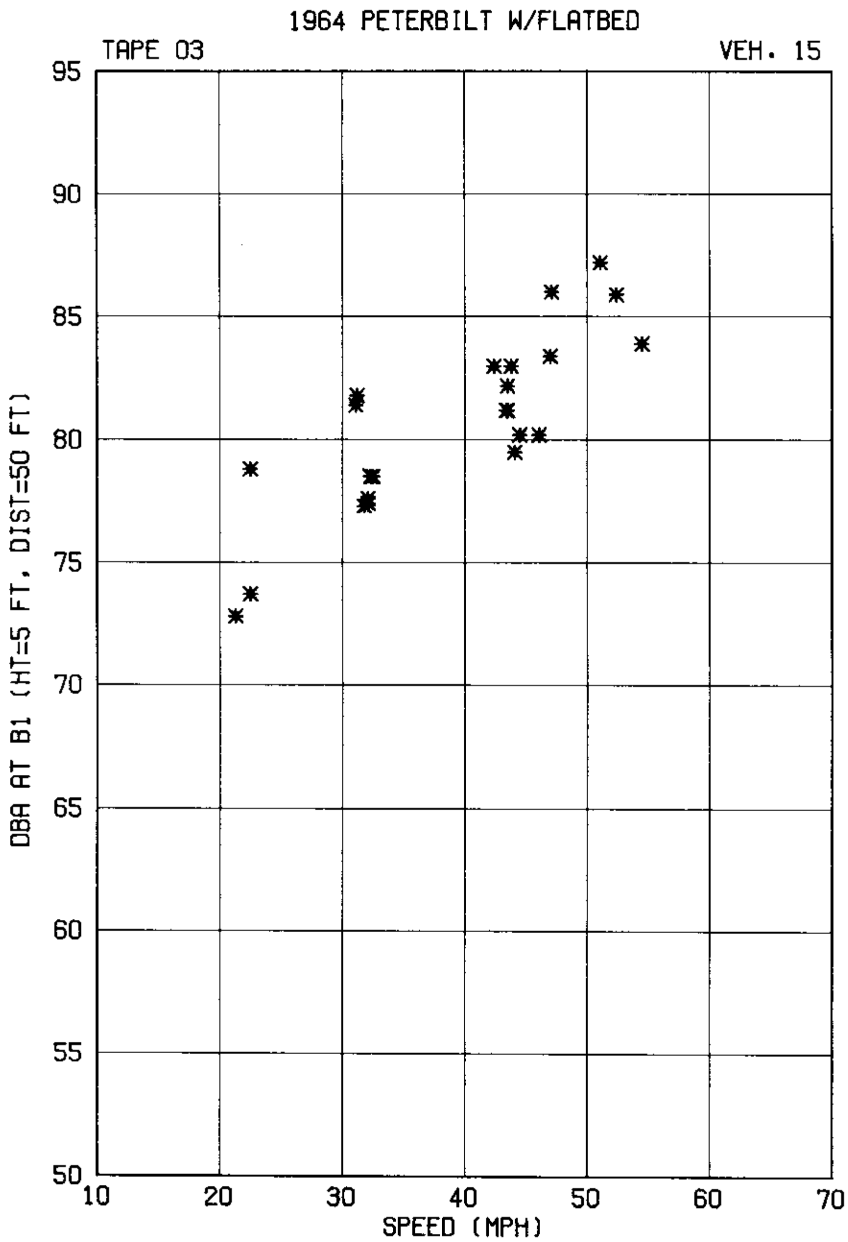
Back Tractor Tires: Ribbed Lug 8

Back Trailer Tires: Ribbed 8 Lug

Tire Size 10.00 x 20 License No. H21555

Speed	6/30 Tape No. 3	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
30	7					7
40	8					8
45	2					2
50	4					4
					TOTAL	24





1964 PETERBILT W/FLATBED
TAPE 03
VEH. 15
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle No. 16

Vehicle Information: 1971 Kenworth Conventional, Hogland Rental

Trailer Flatbed

Capacity 80,000 lbs   Wt. Empty 29,460 lb

Engine: HP 380   Make Cummins   Cylinders 6

Ht. to Exit Stacks: Left ______   Right 10'

Ht. to Mid Engine 5'   Ht. to Top of Van ______

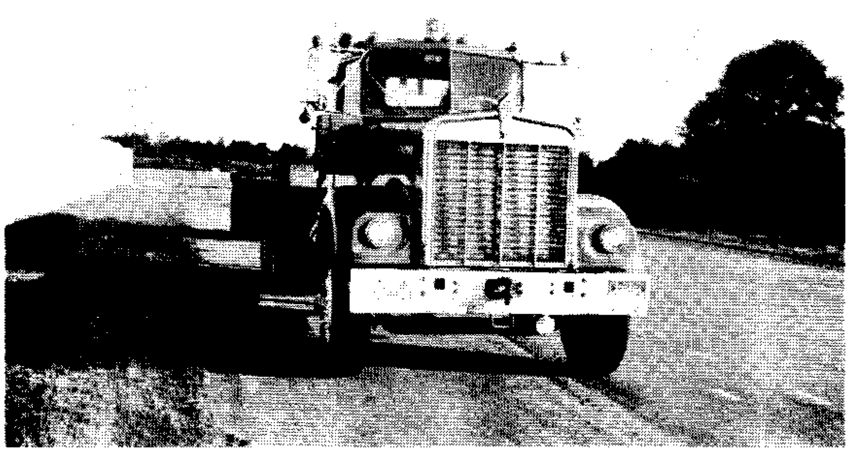
Front Tractor Tires: Ribbed 2   Lug ______

Back Tractor Tires: Ribbed ______   Lug 8

Back Trailer Tires: Ribbed 8   Lug ______

Tire Size 10.00 x 22   License No. H28479

Speed	Tape No. 4 (7/6)	Tape No. 5 (7/6)	Tape No. (/)	Tape No. (/)	Tape No. (/)	Total
20	2					2
30	5					5
35	1					1
40	8	2				10
45	1	1				2
50	8					8
					TOTAL	28



Vehicle No. 17

Vehicle Information: 1971 Kenworth Conventional, Hogland Rental (Same as #16)

Trailer 3 Axle Lowboy

Capacity 40 Ton Wt. Empty 38,700 lb

Engine: HP 380 Make Cummins Cylinders 6

Ht. to Exit Stacks: Left ______ Right 10'

Ht. to Mid Engine 5' Ht. to Top of Van ______

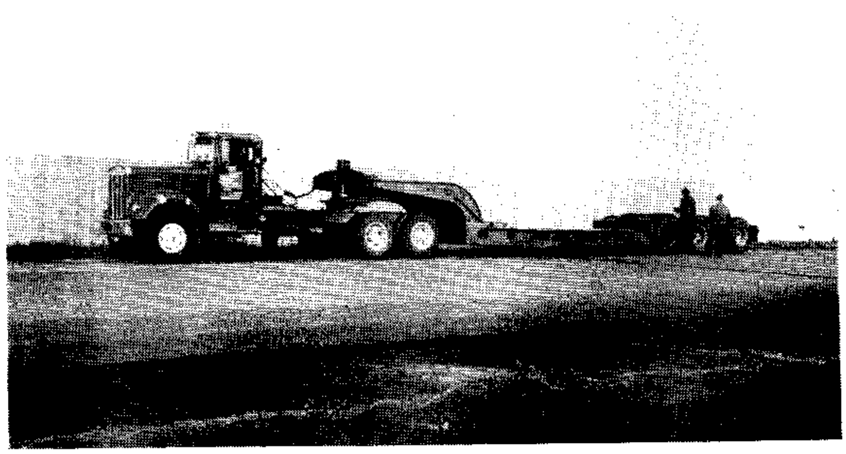
Front Tractor Tires: Ribbed 2 Lug ______

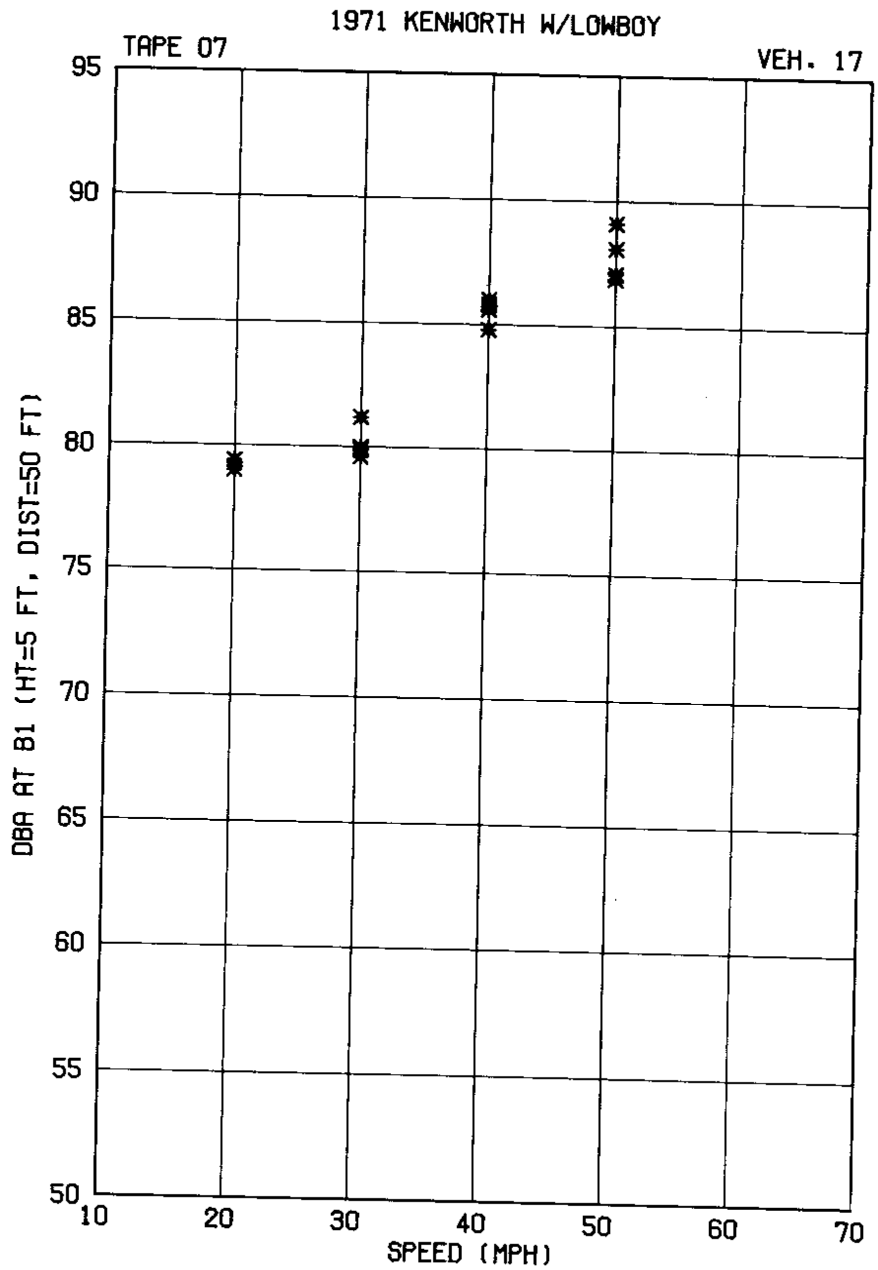
Back Tractor Tires: Ribbed ______ Lug 8

Back Trailer Tires: Ribbed 12 Lug ______

Tire Size 10.00 x 22 License No. H28479

Speed	7/ 8 Tape No. 7	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
30	8					8
40	5					5
50	7					7
					TOTAL	23




1971 KENWORTH W/LOWBOY
TAPE 07
VEH. 17
DBA AT B1 (HT=5 FT, DIST=50 FT)
SPEED (MPH)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70

Vehicle No. 18

Vehicle Information: 1971 Kenworth Conventional, Hogland Rental (Same as #16)

Trailer Van

Capacity 40 Ton Wt. Empty

Engine: HP 380 Make Cummins Cylinders 6

Ht. to Exit Stacks: Left Right 10'

Ht. to Mid Engine 5' Ht. to Top of Van 13.5'

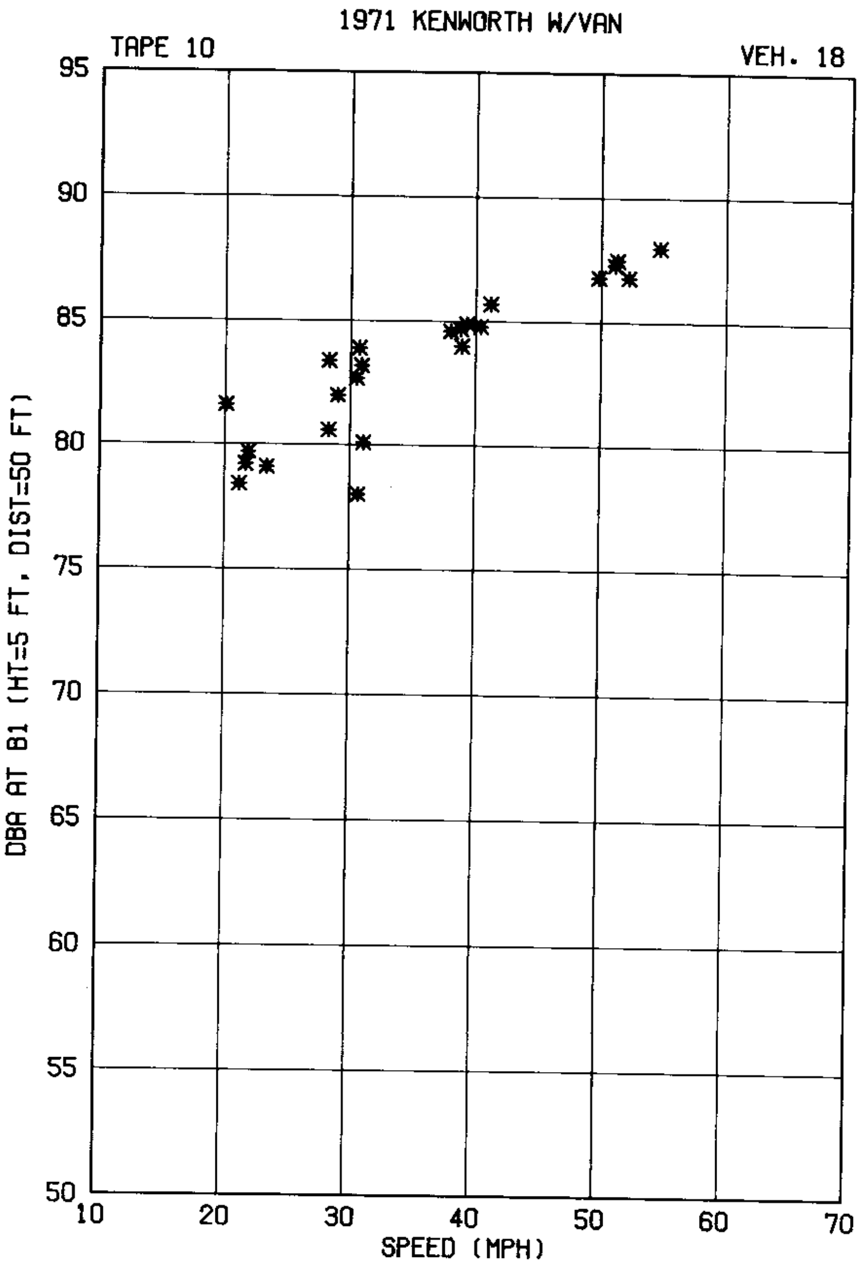
Front Tractor Tires: Ribbed 2 Lug

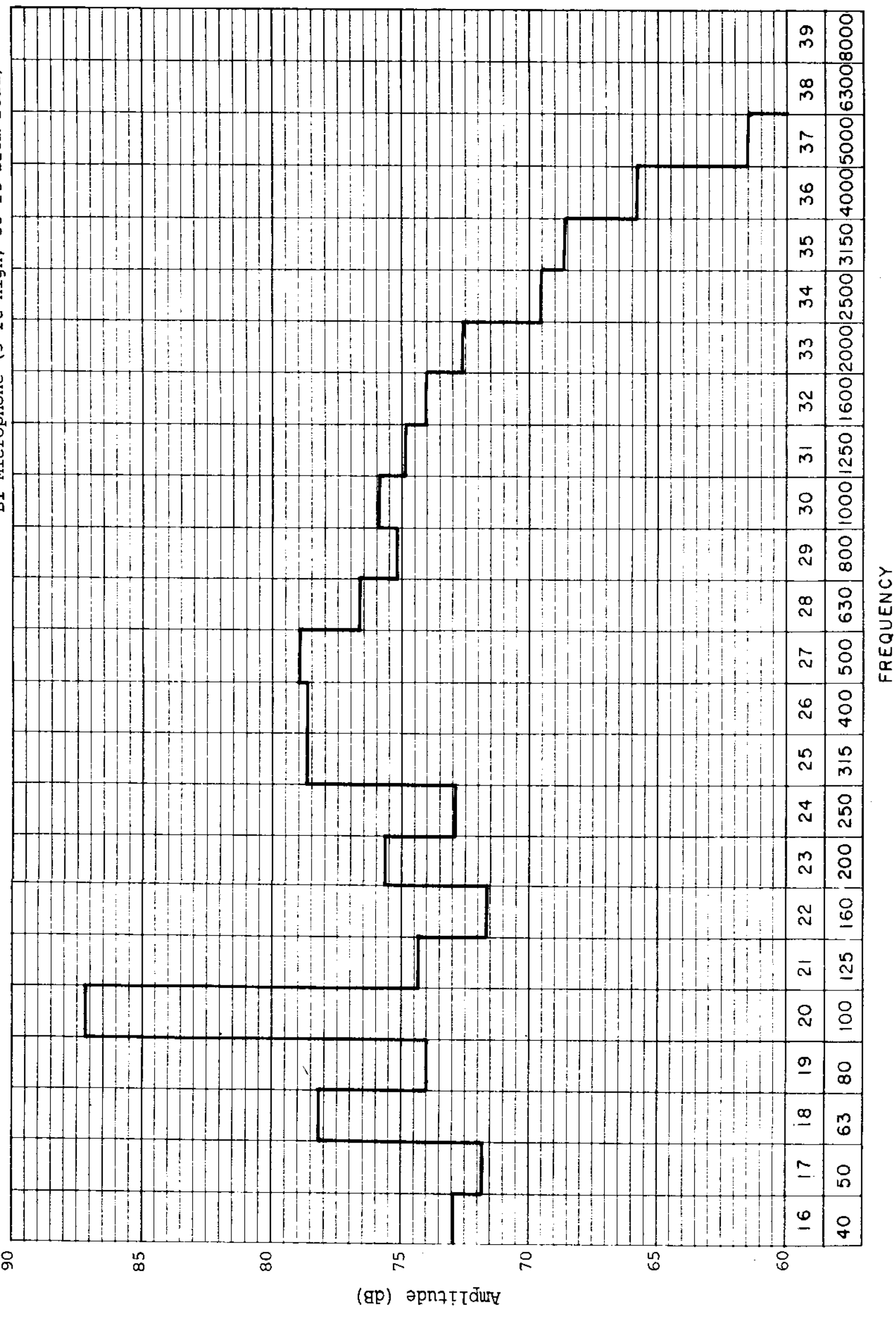
Back Tractor Tires: Ribbed Lug 8

Back Trailer Tires: Ribbed 4 Lug

Tire Size 10.00 x 22 License No. H28479

Speed	7/22 Tape No. 10	8/3 Tape No. 11	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	5	4				9
30	8	3				11
35		1				1
40	6	4				10
50	4	3				7
55	1	1				2
ACC		11				11
					TOTAL	51


1971 KENWORTH W/VAN
TAPE 10
VEH. 18
95
90
85
80
75
70
65
60
55
50
DBA AT B1 (HT=5 FT, DIST=50 FT)
10
20
30
40
50
60
70
SPEED (MPH)



Vehicle 18, Tape 10-18, 40 mph
B1 Microphone (5 ft high, 50 ft from road)

Vehicle No. 19

Vehicle Information: 1964 Peterbilt Conventional, Hogland Rental

Trailer Flatbed

Capacity 72,000 Gross Wt. Empty 31,000 lb

Engine: HP 318 Make Detroit Cylinders 8

Ht. to Exit Stacks: Left 10' Right 10'

Ht. to Mid Engine 4.5' Ht. to Top of Van

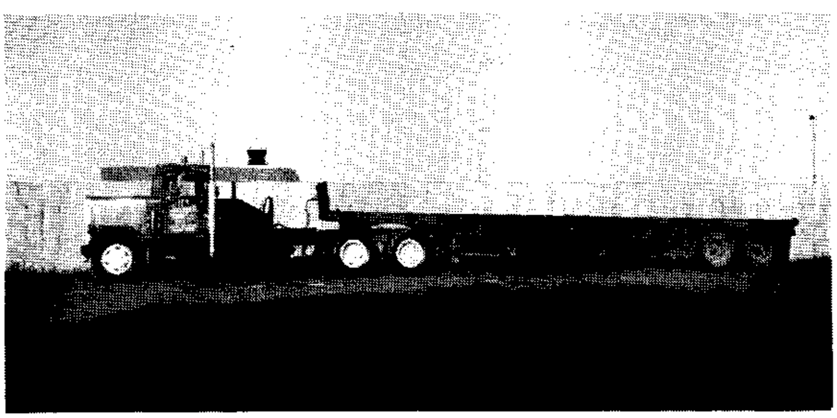
Front Tractor Tires: Ribbed 2 Lug

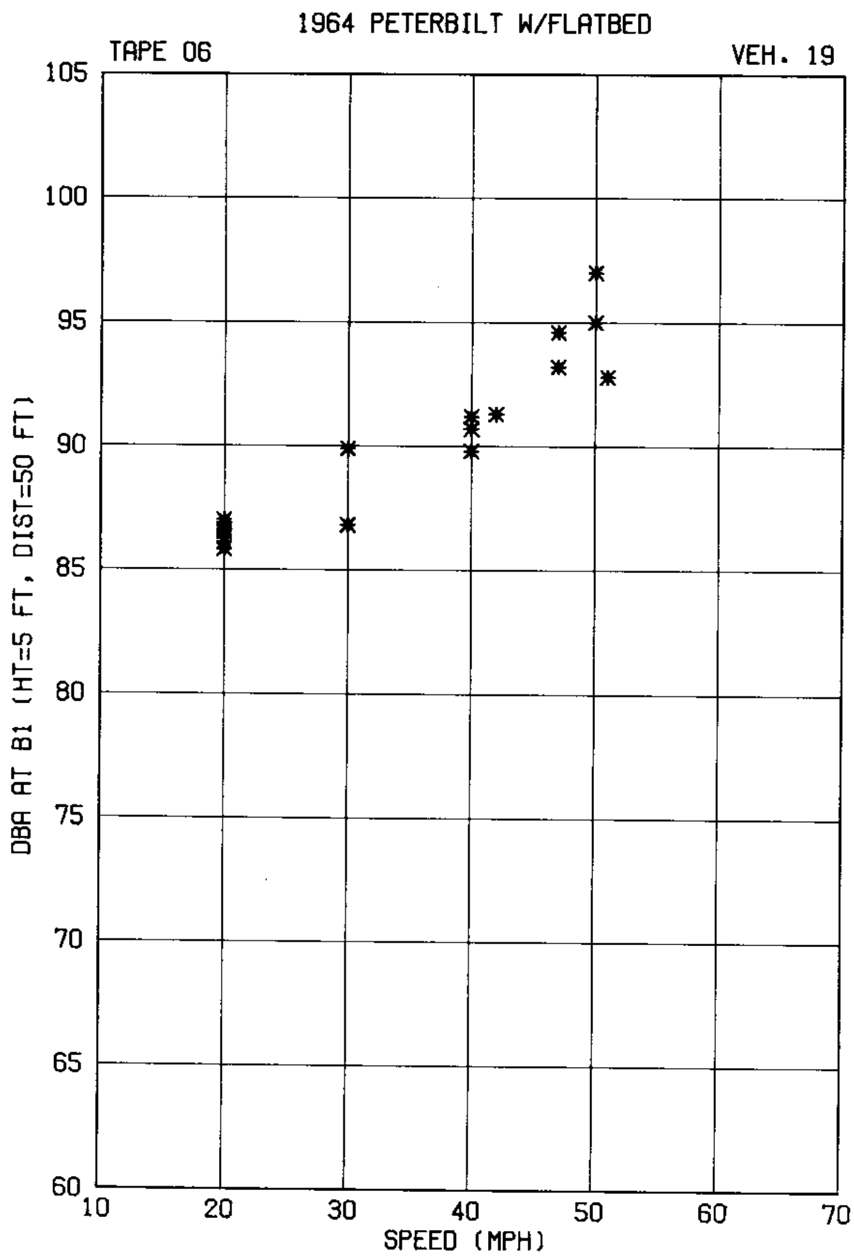
Back Tractor Tires: Ribbed Lug 8

Back Trailer Tires: Ribbed 8 Lug

Tire Size 10.00 x 22 License No. H24559

Speed	7/7 Tape No. 6	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	5					5
30	5					5
40	5					5
45	3					3
50	3					3
					TOTAL	21




1964 PETERBILT W/FLATBED
TAPE 06
VEH. 19
DBA AT B1 (HT=5 FT, DIST=50 FT)
105
100
95
90
85
80
75
70
65
60
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle No. 20

Vehicle Information: 1967 White Freightliner Cab-Over
Hogland Rental

Trailer Flatbed

Capacity 72,000 Gross   Wt. Empty 11,300 lbs.

Engine: HP 220   Make Cummins   Cylinders 6

Ht. to Exit Stacks: Left Single Stack   Right 11'

Ht. to Mid Engine 4.5'   Ht. to Top of Van

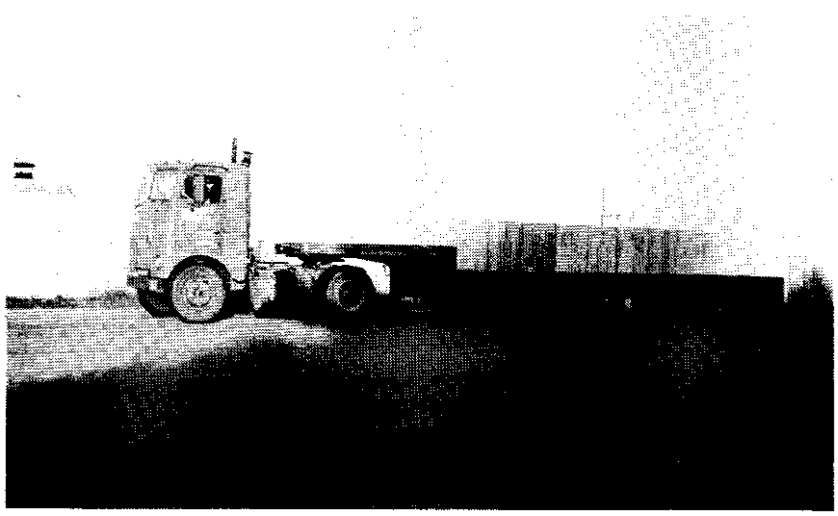
Front Tractor Tires: Ribbed 2   Lug

Back Tractor Tires: Ribbed   Lug 4

Back Trailer Tires: Ribbed 2   Lug

Tire Size 10.00 x 20   License No. H30761

	7/20	/	/	/	/	1977
Speed	Tape No. 8	Tape No.	Tape No.	Tape No.	Tape No.	Total
20	4					4
30	4					4
40	4					4
45	2					2
50	2					2
					TOTAL	16



Vehicle No. 21

Vehicle Information: 1967 White Freightliner Cab-Over

Hogland Rental (Same as #20)

Trailer Van

Capacity 72,000 Gross Wt. Empty

Engine: HP 220 Make Cummins Cylinders 6

Ht. to Exit Stacks: Left Right 11'

Ht. to Mid Engine 4.5' Ht. to Top of Van 13'-6" (13-2" @ front)

Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed Lug 4

Back Trailer Tires: Ribbed 4 Lug

Tire Size 10.00 x 20 License No. H30761

Speed	8/4 Tape No. 12	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	8					8
30	8					8
40	8					8
45	1					1
					TOTAL	25

Vehicle No. 22

Vehicle Information: 1964 Ford Cab-Over, Hogland Rental

Trailer Van

Capacity ______ Wt. Empty 11,920 lb

Engine: HP 184 Make ______ Cylinders 8

Ht. to Exit Stacks: Left ______ Right 10'-8"

Ht. to Mid Engine 4' Ht. to Top of Van 13-'6" (13'-2" @ front)

Front Tractor Tires: Ribbed 2 Lug ______

Back Tractor Tires: Ribbed ______ Lug 4

Back Trailer Tires: Ribbed 4 Lug ______

Tire Size ______ License No. H16975

Speed	8/5 Tape No. 13	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	7					7
30	6					6
40	7					7
45	2					2
50	3					3
					TOTAL	25

Vehicle No. 23

Vehicle Information: 1973 Peterbilt Conventional, PACCAR Test Vehicle

Trailer Tanker 3/4 full of water (approx 74,000 lb)

Capacity 80,000 lb Wt. Empty

Engine: HP 380 Make NT 380 Cummins Cylinders 6

Ht. to Exit Stacks: Left 11.5' Right 11.5'

Ht. to Mid Engine 4.5' Ht. to Top of Van 10'

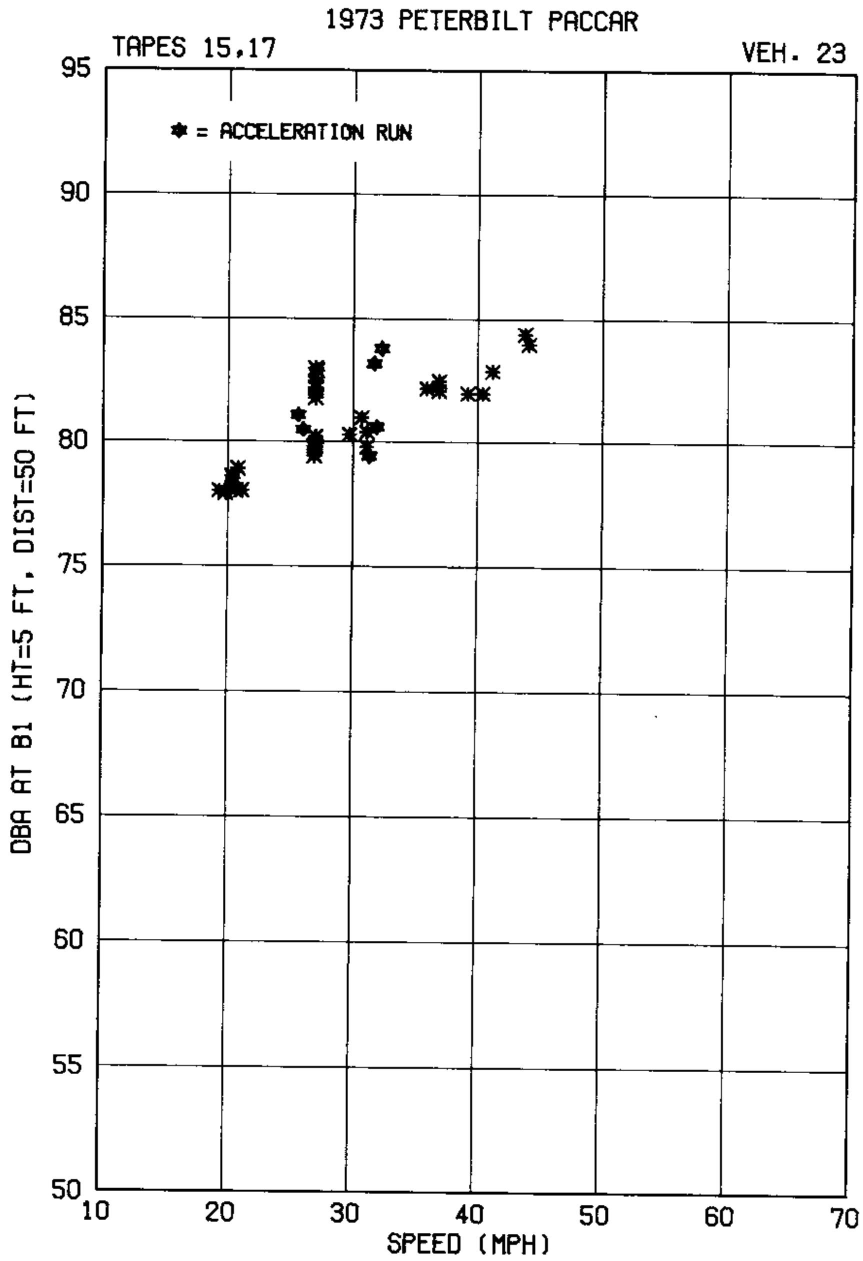
Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed Lug 8

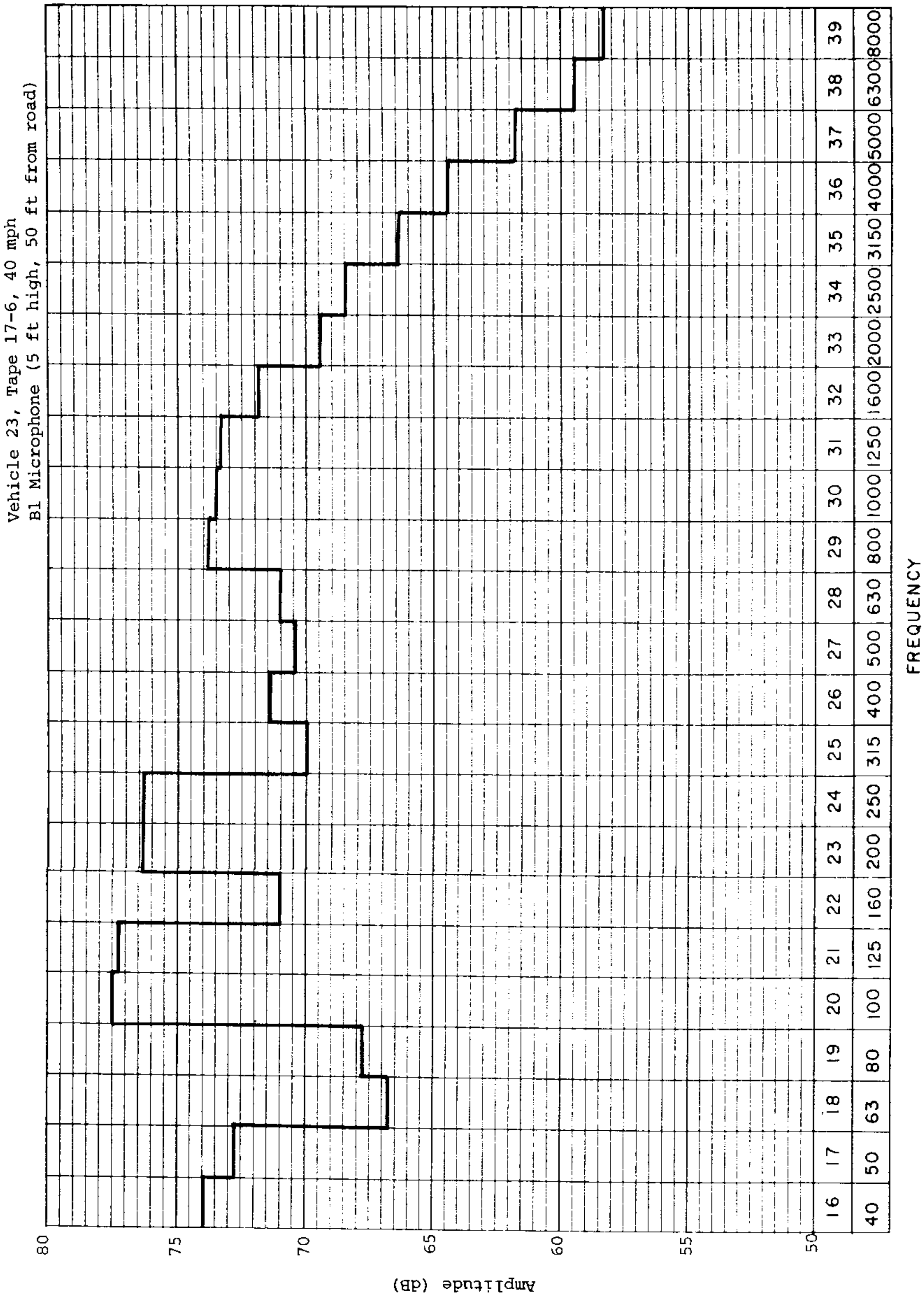
Back Trailer Tires: Ribbed 8 Lug

Tire Size 10.00 x 22 License No. 8303M Trailer 8303L

Speed	8/17 Tape No.	9/2 Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3	4				7
25	9					9
30		4				4
35		3				3
40		3				3
45		2				2
ACC	4	2				6
					TOTAL	34



1973 PETERBILT PACCAR
TAPES 15,17
VEH. 23
✱ = ACCELERATION RUN
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)



Vehicle 23, Tape 17-6, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
80
75
70
65
60
55
50
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

Vehicle No. 24

Vehicle Information: 1976 Kenworth Conventional PACCAR Test Vehicle

Trailer Tanker, 36' - 3/4 full of water (approx. 72,700 lb)

Capacity 80,000 lb Wt. Empty

Engine: HP 400 Make NTC Cummins Cylinders 6

Ht. to Exit Stacks: Left Right 11'-6"

Ht. to Mid Engine 4'-6" Ht. to Top of Van 10'

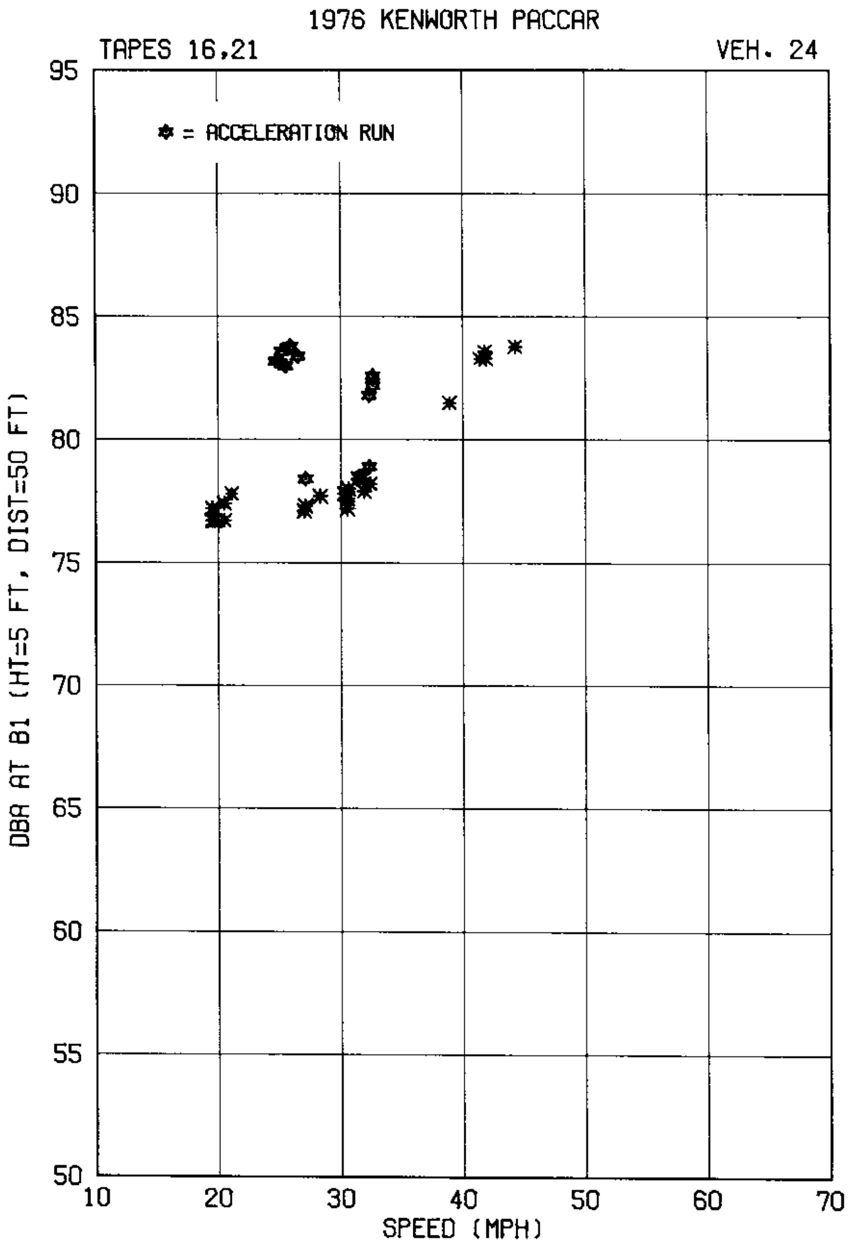
Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed Lug 8

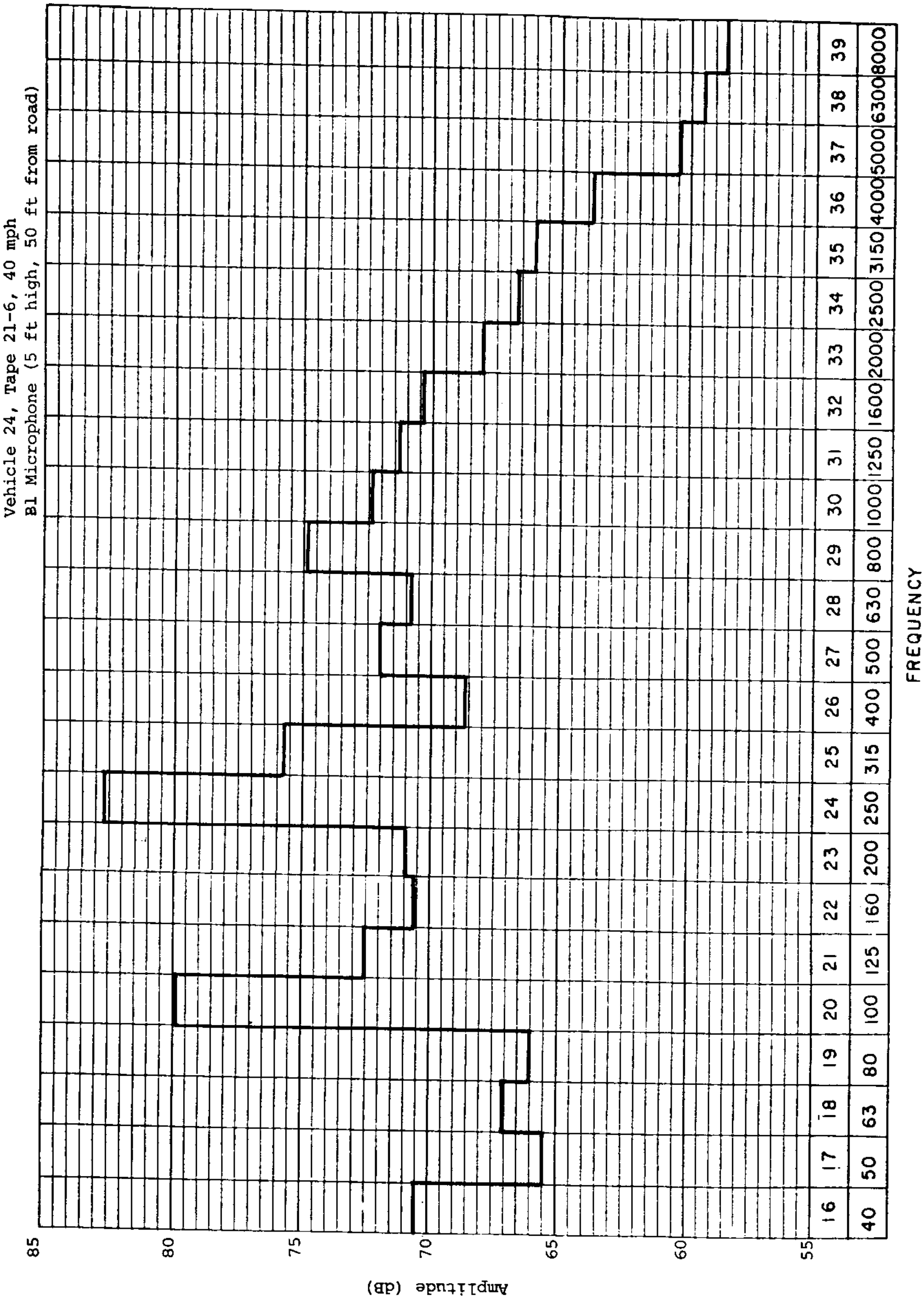
Back Trailer Tires: Ribbed 8 Lug

Tire Size 10.00 x 22 License No. 8303N 8303L (Trailer)

Speed	8/19 Tape No. 16	9/14 Tape No. 21	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3	3				6
25	2					2
30	6	3				9
40		4				4
45		1				1
ACC	11					11
					TOTAL	33



1976 KENWORTH PACCAR
TAPES 16,21
VEH. 24
✱ = ACCELERATION RUN
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)


Vehicle 24, Tape 21-6, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
85
80
75
70
65
60
55
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

Vehicle No. 25

Vehicle Information: 1973 Kenworth Conventional, PACCAR Test Vehicle

Trailer Flatbed loaded with cement blocks (approx 68,000 lb)

Capacity 80,000 lb Wt. Empty

Engine: HP Make NTC 350 Cummins Cylinders 6

Ht. to Exit Stacks: Left 11'-4" Right 11'-4"

Ht. to Mid Engine 4'-4" Ht. to Top of Van 4'-8"

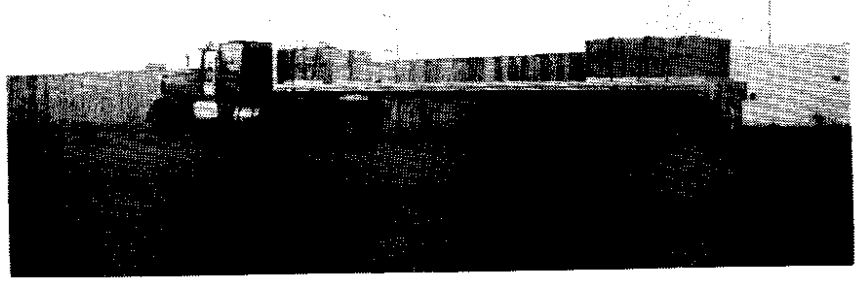
Front Tractor Tires: Ribbed 2 Lug

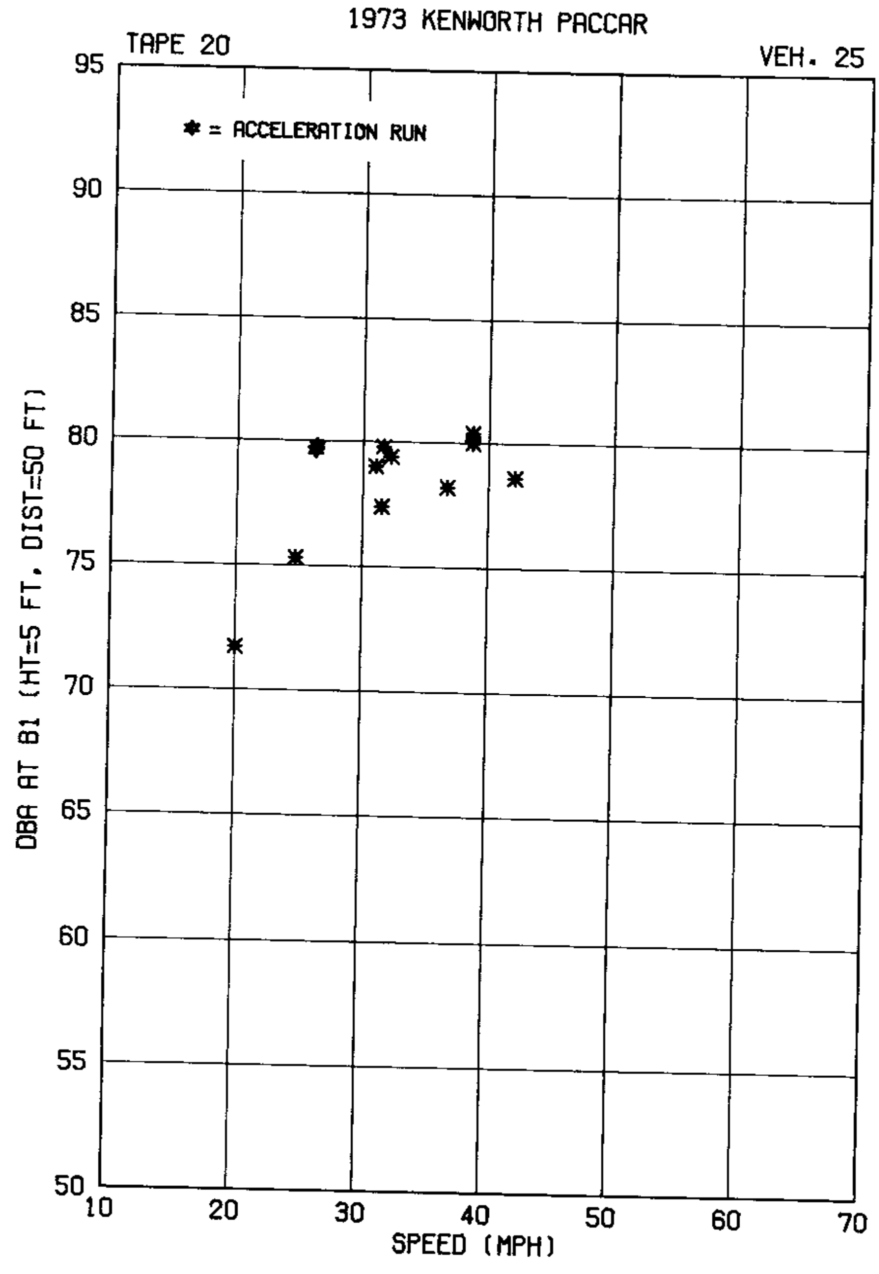
Back Tractor Tires: Ribbed Lug 8

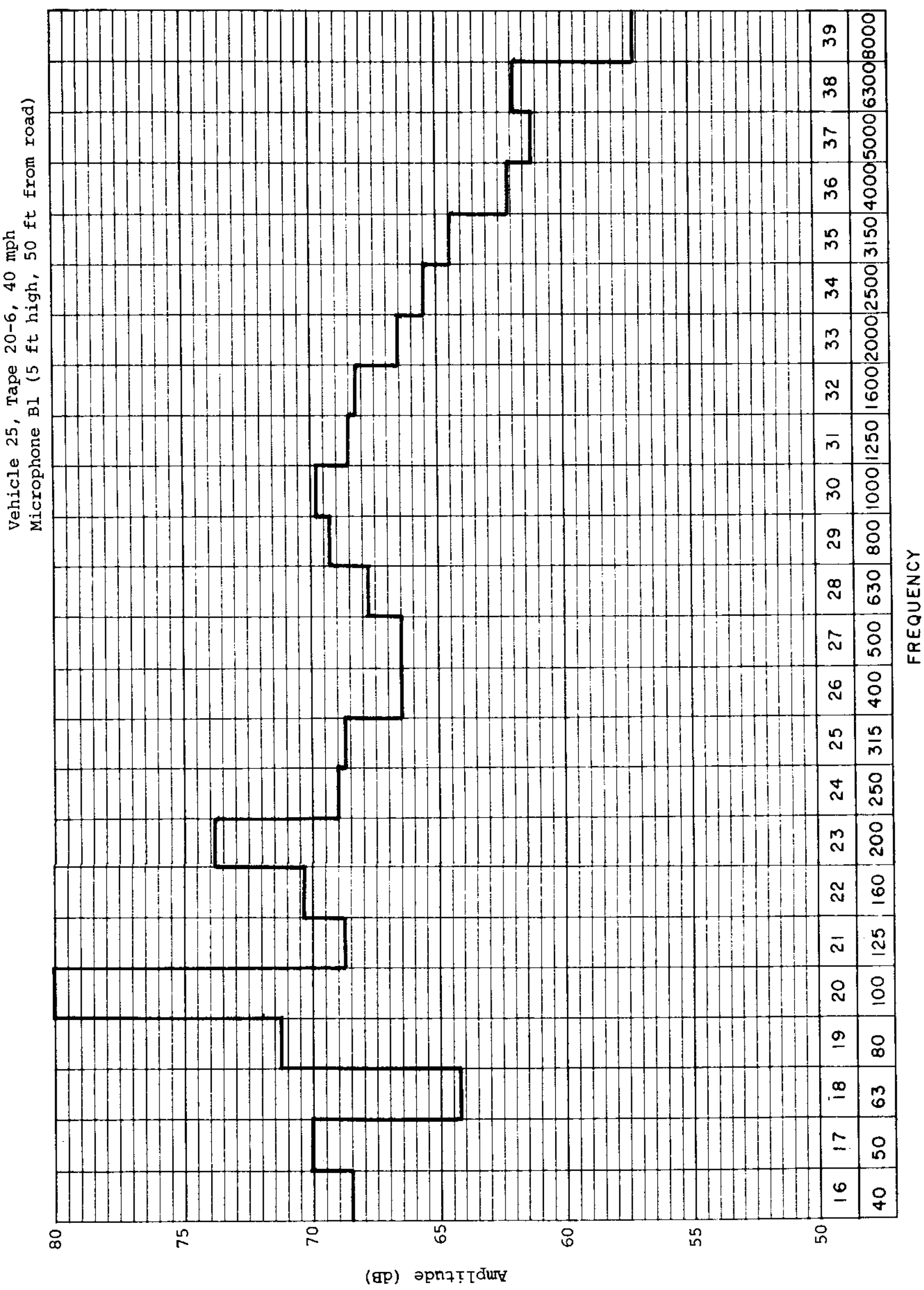
Back Trailer Tires: Ribbed 8 Lug

Tire Size 10.00 x 22 License No.

	9/13	/	/	/	/	1977
Speed	Tape No. 20	Tape No.	Tape No.	Tape No.	Tape No.	Total
20	1					1
25	1					1
30	4					4
35	3					3
40	1					1
ACC	2					2
					TOTAL	12




1973 KENWORTH PACCAR
TAPE 20
VEH. 25
✱ = ACCELERATION RUN
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)


Vehicle 25, Tape 20-6, 40 mph
Microphone B1 (5 ft high, 50 ft from road)
Amplitude (dB)
80
75
70
65
60
55
50
FREQUENCY
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000

Vehicle No. 26

Vehicle Information: (Old) 700 Series GM Bus - Metro #701

(photo is of a similar 700 series Metro bus)

Trailer

Capacity Wt. Empty 21,500 lb

Engine: HP Make 8V71 Detroit Diesel Cylinders 8

Ht. to Exit Stacks: Left Right

Ht. to Mid Engine Ht. to Top of Van 120" (40' long)

Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed Lug

Back Trailer Tires: Ribbed Lug

Tire Size License No.

Speed	9/14 Tape No. 21	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
30	3					3
40	2					2
45	2					2
					TOTAL	10

Vehicle No. 27

Vehicle Information: 1976 1100 Series AM General Bus - Metro #1105

(photo is of a similar 1100 series Metro bus)

Trailer

Capacity Wt. Empty 25,000 lb

Engine: HP Make 8V71 Detroit Diesel Cylinders 8

Ht. to Exit Stacks: Left 123" Right

Ht. to Mid Engine Ht. to Top of Van 123" (40' x 8-1/2')

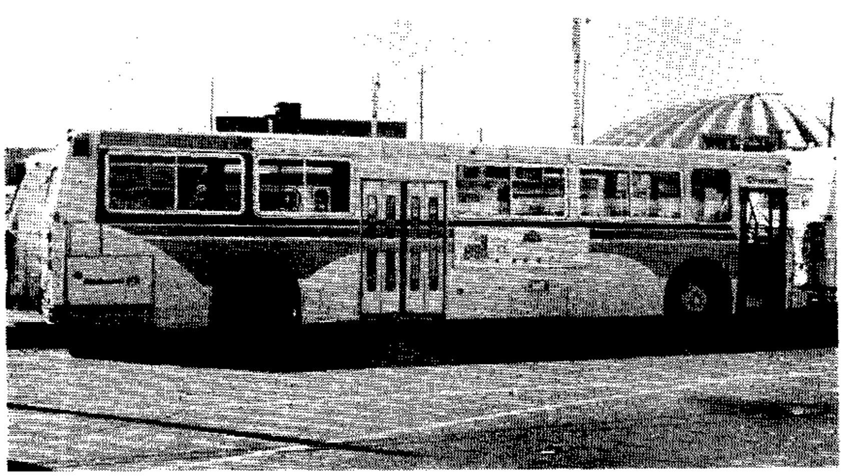
Front Tractor Tires: Ribbed 2 Lug

Back Tractor Tires: Ribbed Lug

Back Trailer Tires: Ribbed Lug

Tire Size License No.

Speed	9/14 Tape No. 21	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
25	1					1
30	2					2
40	2					2
45	1					1
50	2					2
					TOTAL	11



Vehicle No. 28

Vehicle Information: 1963 Metro Bus #551

40' long x 8-1/2' wide

Trailer

Capacity Wt. Empty

Engine: HP Make Cylinders

Ht. to Exit Stacks: Left Right

Ht. to Mid Engine Ht. to Top of Van

Front Tractor Tires: Ribbed Lug

Back Tractor Tires: Ribbed Lug

Back Trailer Tires: Ribbed Lug

Tire Size License No.

	11/1	/	/	/	/	1977
Speed	Tape No. 23	Tape No.	Tape No.	Tape No.	Tape No.	Total
30	1					1
30 (opp. direction)	1					1
35	1					1
40	2					2
ACC	6					6
					TOTAL	11

Vehicle No. 29

Vehicle Information: (New) Metro Bus #1154

Trailer

Capacity Wt. Empty

Engine: HP Make Cylinders

Ht. to Exit Stacks: Left Right

Ht. to Mid Engine Ht. to Top of Van

Front Tractor Tires: Ribbed Lug

Back Tractor Tires: Ribbed Lug

Back Trailer Tires: Ribbed Lug

Tire Size License No.

Speed	11/1 Tape No. 23	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
30	1					1

Comments: This bus got stuck in mud and only did one run.

Vehicle No. 30

Vehicle Information: 1976 Kenworth W900 PACCAR Test Vehicle

Trailer 40' van, empty

Capacity ___ Wt. Empty 26,500 lbs.

Engine: HP 360 Make 3406 Caterpiller 893 cu Supercharger Cylinders 6

Ht. to Exit Stacks: Left ___ Right ___

Ht. to Mid Engine 4.5' Ht. to Top of Van 12'-3"

Front Tractor Tires: Ribbed 2 Lug ___

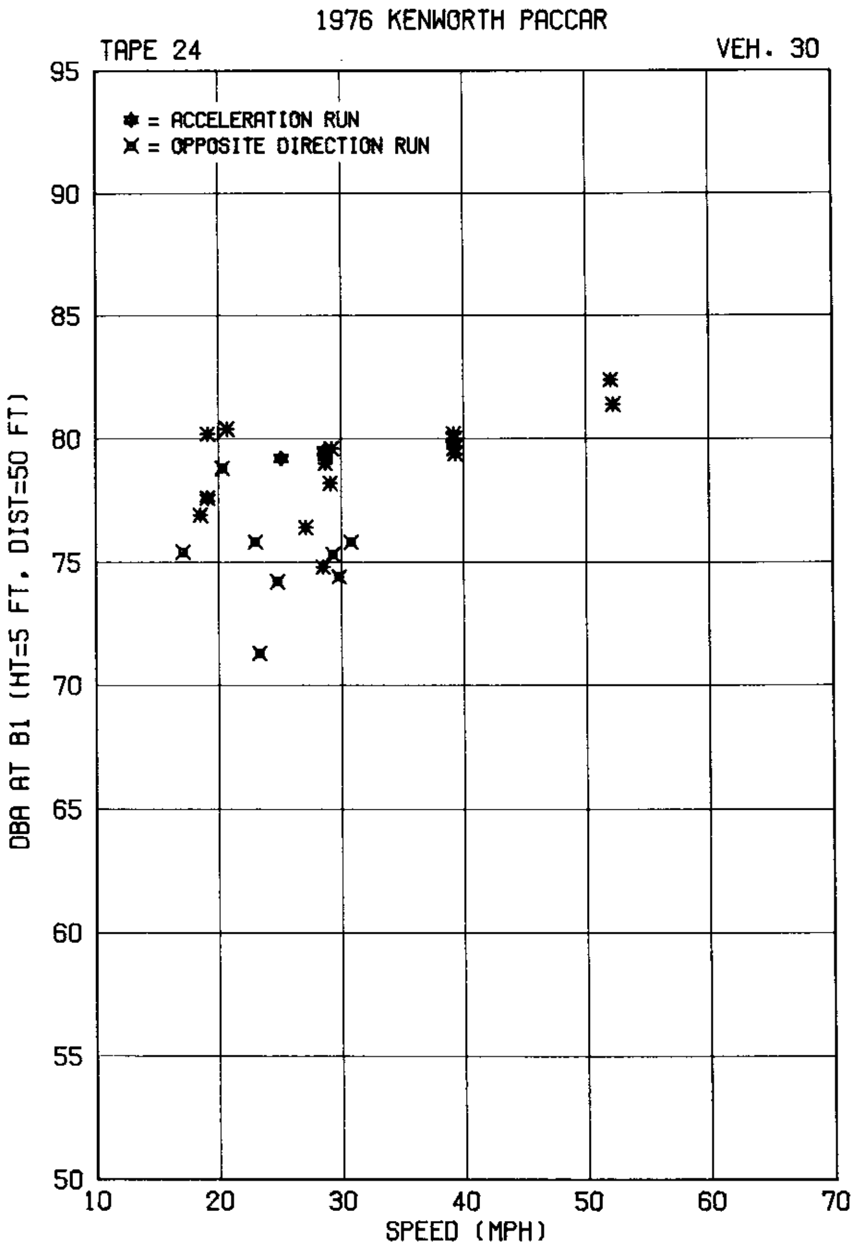
Back Tractor Tires: Ribbed 8 Lug ___

Back Trailer Tires: Ribbed 4 Lug ___

Tire Size ___ License No. 8303R

Speed	11/8 Tape No. 24	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	3					3
20 (opp dir)	2					2
25 (opp dir)	3					3
30	6					6
30 (opp dir)	3					3
40	4					4
50	3					3
ACC	2					2
ACC (opp dir)	2					2
					TOTAL	28

Comments: 9" dual Donaldson mufflers MPN 090161 (11.5' top). Air intakes on both sides (Donaldson also). 17'-6" to traction tires first set, 21'-10" to second set, 49'-2" on trailer van, 53'-2" back van. Exhaust 7' back first set RTO 12513 transmission--Fuller. Rear axle ratio 4.11 to 1 14770 chassis lead.


1976 KENWORTH PACCAR
TAPE 24
VEH. 30
✱ = ACCELERATION RUN
✱ = OPPOSITE DIRECTION RUN
DBA AT B1 (HT=5 FT, DIST=50 FT)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70
SPEED (MPH)

Vehicle No. 31

Vehicle Information: (Old) 700 Series Bus, Metro #704

(photo is of a similar 700 series Metro bus)

Trailer

Capacity Wt. Empty

Engine: HP Make Cylinders

Ht. to Exit Stacks: Left Right

Ht. to Mid Engine Ht. to Top of Van

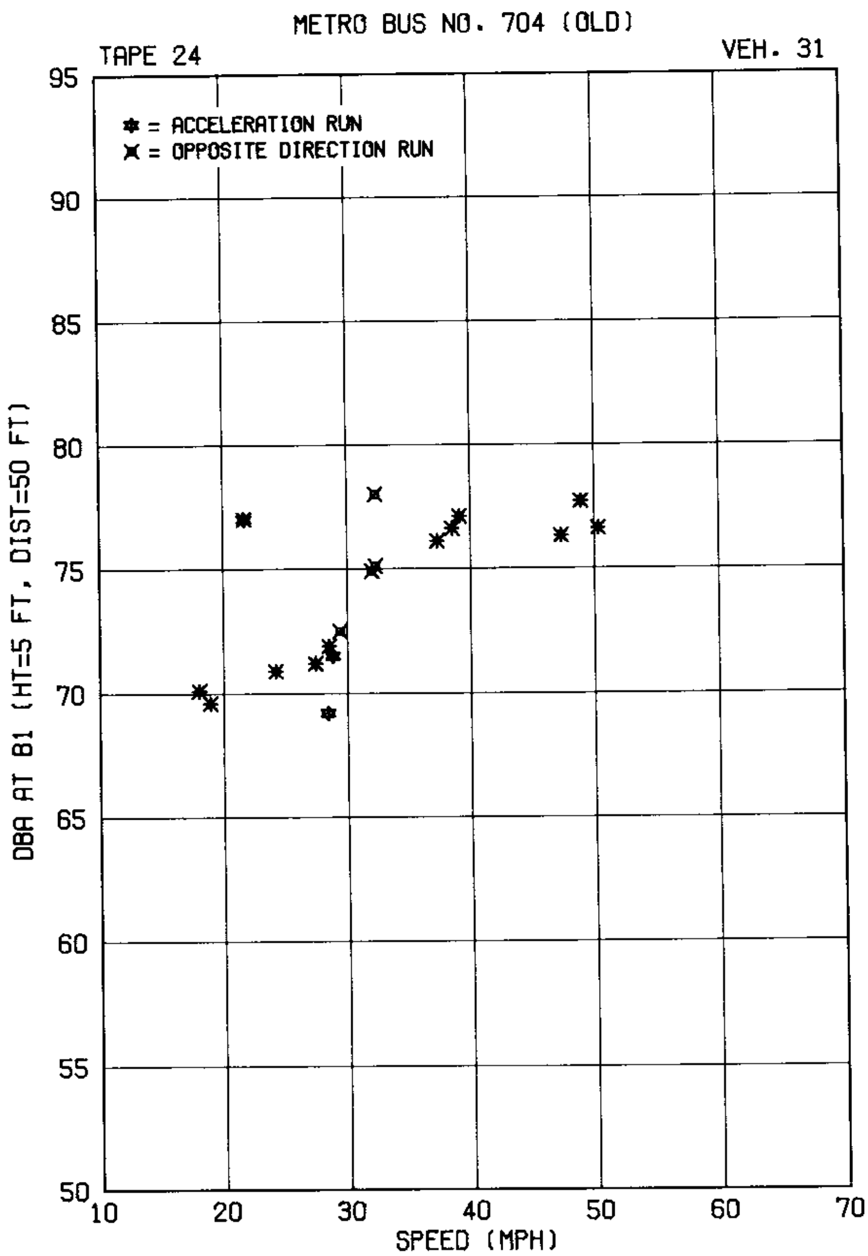
Front Tractor Tires: Ribbed Lug

Back Tractor Tires: Ribbed Lug

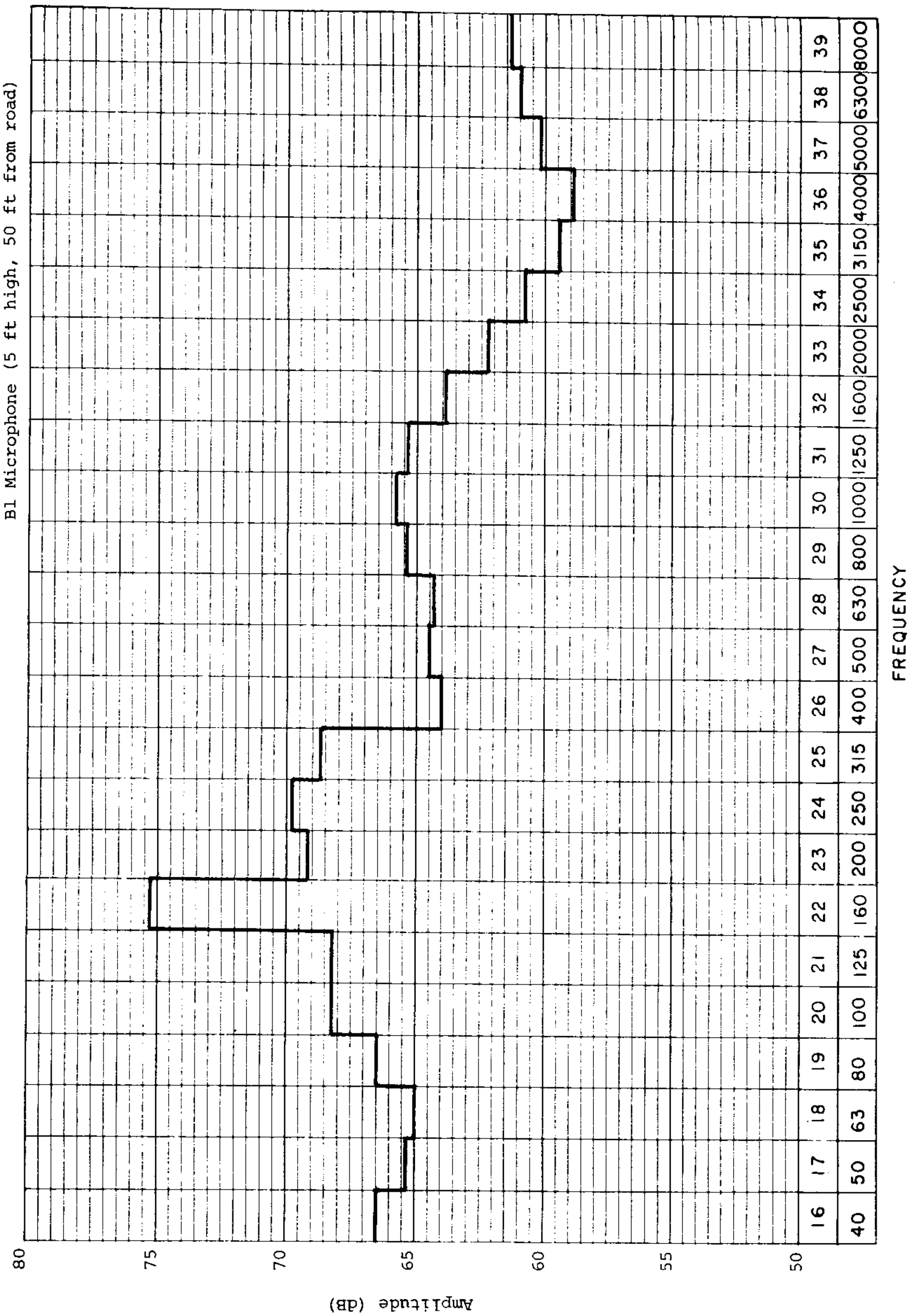
Back Trailer Tires: Ribbed Lug

Tire Size License No.

	11/8	/	/	/	/	1977
Speed	Tape No. 24	Tape No.	Tape No.	Tape No.	Tape No.	Total
20	2					2
25	1					1
30	2					2
30 (opp dir)	1					1
35 (opp dir)	3					3
40	3					3
50	3					3
ACC	2					2
ACC (opp dir)	1					1
					TOTAL	18


METRO BUS NO. 704 (OLD)
TAPE 24
VEH. 31
✱ = ACCELERATION RUN
✖ = OPPOSITE DIRECTION RUN
DBA AT B1 (HT=5 FT, DIST=50 FT)
SPEED (MPH)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70

Vehicle 31, Tape 24-19, 40 mph
B1 Microphone (5 ft high, 50 ft from road)



Vehicle No. 32

Vehicle Information: (New) 1100 Series Bus, Metro #1111

(photo is of a similar 1100 series Metro bus)

Trailer

Capacity Wt. Empty

Engine: HP Make Cylinders

Ht. to Exit Stacks: Left Right

Ht. to Mid Engine Ht. to Top of Van

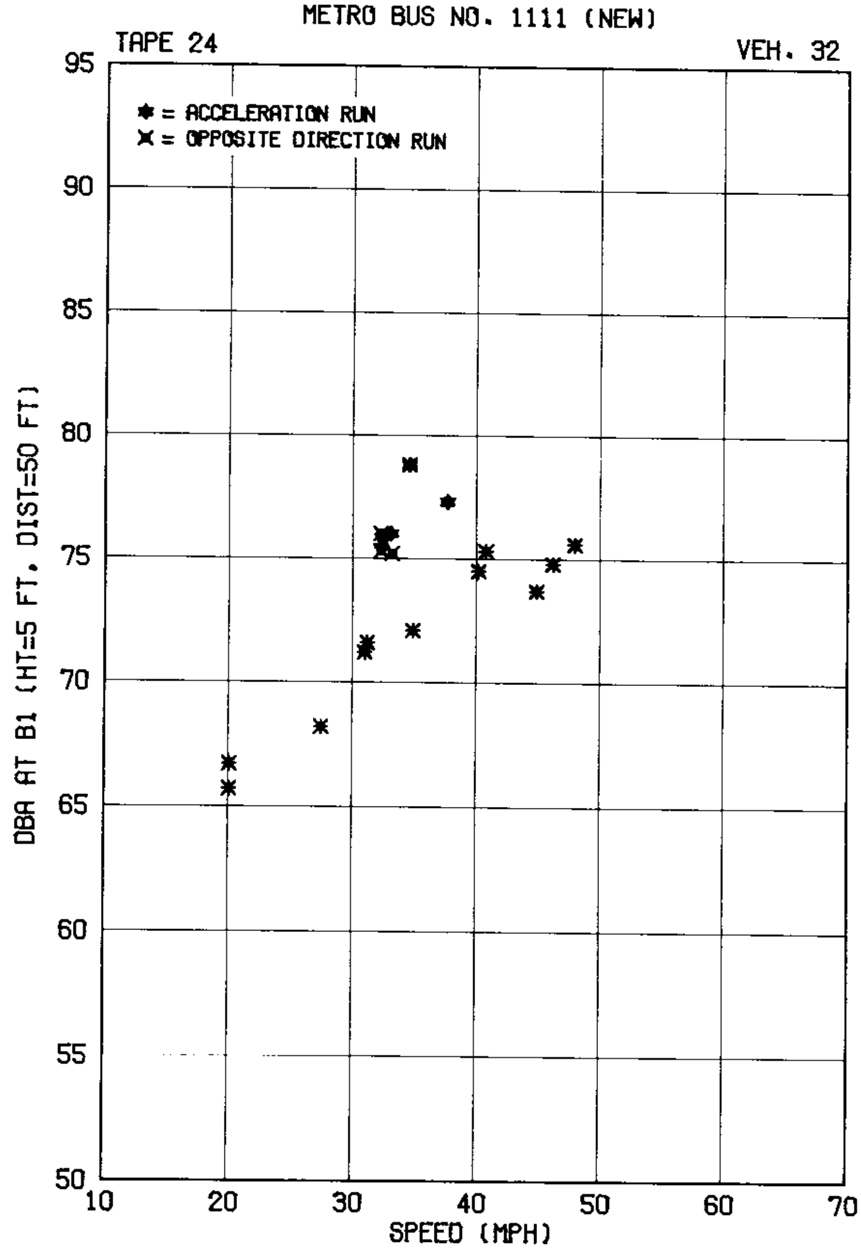
Front Tractor Tires: Ribbed Lug

Back Tractor Tires: Ribbed Lug

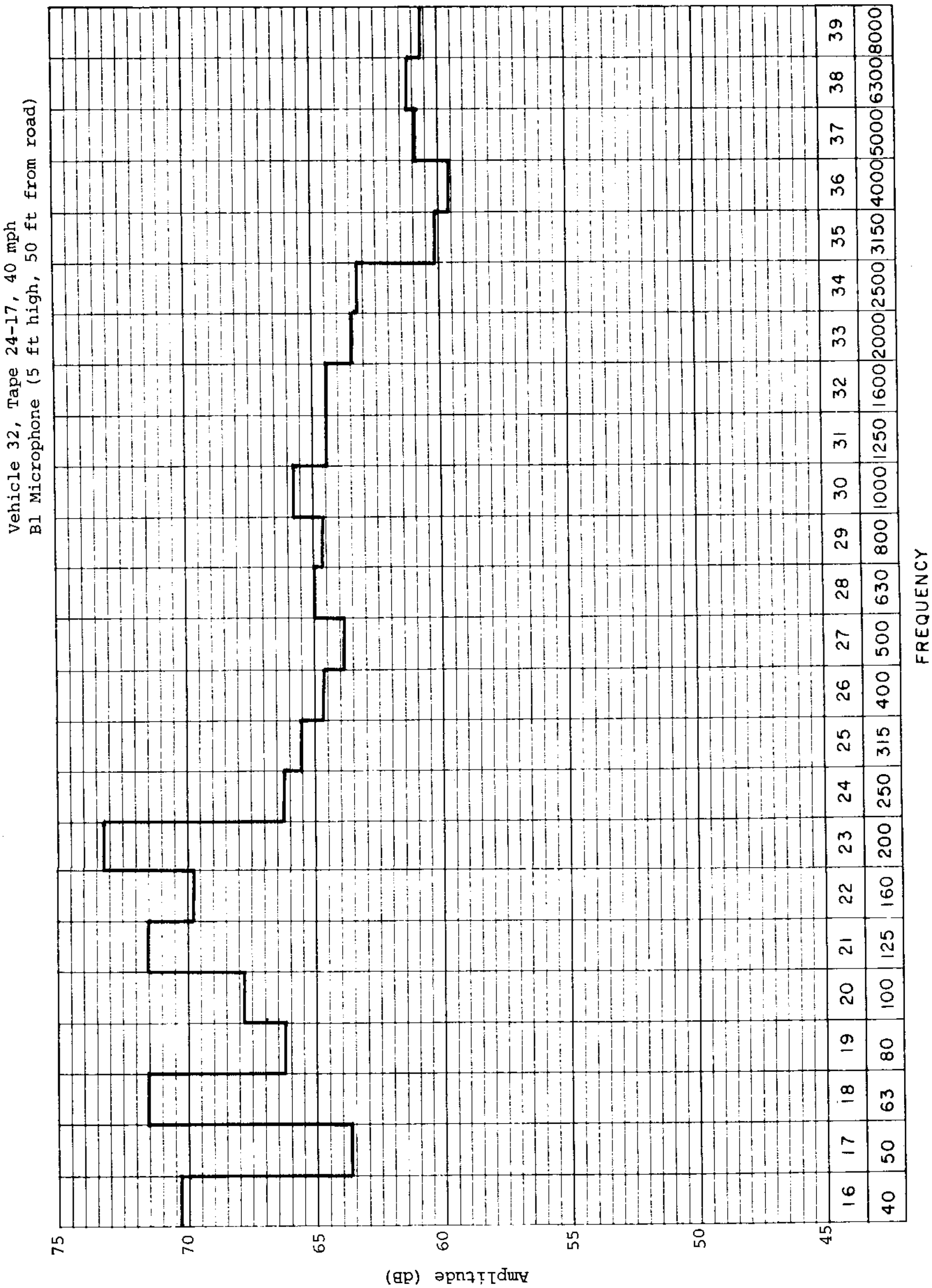
Back Trailer Tires: Ribbed Lug

Tire Size License No.

Speed	11/8 Tape No. 24	/ Tape No.	/ Tape No.	/ Tape No.	/ Tape No.	1977 Total
20	2					2
30	3					3
30 (opp dir)	2					2
35	1					1
35 (opp dir)	2					2
40	2					2
45	3					3
ACC	2					2
ACC (opp dir)	1					1
					TOTAL	18



METRO BUS NO. 1111 (NEW)
TAPE 24
VEH. 32
✱ = ACCELERATION RUN
✱ = OPPOSITE DIRECTION RUN
DBA AT B1 (HT=5 FT. DIST=50 FT)
SPEED (MPH)
95
90
85
80
75
70
65
60
55
50
10
20
30
40
50
60
70


Vehicle 32, Tape 24-17, 40 mph
B1 Microphone (5 ft high, 50 ft from road)
Amplitude (dB)
75
70
65
60
55
50
45
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39
40 50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000
FREQUENCY

APPENDIX B

REFLECTION EFFECTS

To determine whether reflections from the surface of the ground were affecting the experimental data, an attempt was made to find a correction factor that would account for the variations in radiating height observed at low frequencies. A correction factor was calculated for each frequency bin and then added to or subtracted from our measured amplitude data to give values without reflections present.

Two reflections were considered: the first bounces of the sound ray before and after it passed over the wall. The geometry used in these calculations is shown in Figures B1 and B2. In calculating the reflected path, the sound source was assumed to be a mirror image located below the ground. The effect of reflections on each side of the wall was considered individually as well as the effect of both. The procedure was as follows. Let

S = the experimentally measured sound level at the microphone (in energy)

and

S_A = the sound level that would be received at the microphone due to the radiating source only (in energy).

Then $S = S_A$ + the correction term.

The correction term was a function of: K, the reflection coefficient of the ground; S_B, the level at the microphone due to sound from the mirror image of the radiating source (in energy); and, since the reflection will be correlated with the main signal, a phase term. For the roadside reflection, the phase term was determined by the difference between the distance traveled on the first "over-the-wall" path and that traveled on the reflected "over-the-wall" path. In Figure A1, the direct "over-the-wall" path is A + C, and the reflected "over-the-wall" path is B + C, where B is the distance from the mirror image below the ground to the top of the wall (the same distance the first bounce would travel). The difference between the two is B - A. This term was converted to wavelengths and then to degrees to yield the phase angle between the direct and reflected paths:

$$\text{Phase angle} = \frac{360^\circ\ (B - A)\ f}{c},$$

where f is the frequency and c is the speed of sound. The cosine of this angle was then used for calculating how the direct and reflected signals would combine.

The next step was to calculate the relationship between S_A (the energy from the direct source) and S_B (the energy from the reflected image) using Fresnel diffraction.

$$H = \frac{S_A}{S_B}.$$

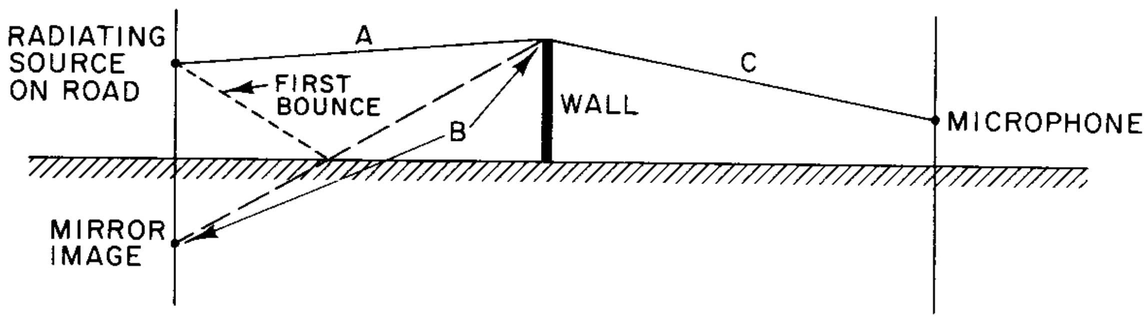


Figure B1. Roadside reflection.

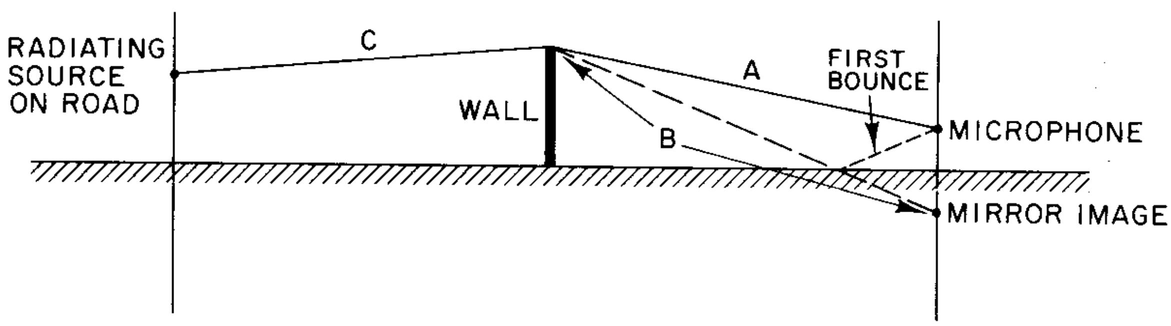


Figure B2. Microphone-side reflection.

We then calculated the attenuative effect of an 8-ft wall on the sound received at a particular microphone based on a 5.8-ft radiating source on the road. (See Reference 1 for calculation of Fresnel diffraction levels.) We also calculated the attenuative effect that the wall would produce at that microphone on the reflection from a mirror image radiator of the same frequency. By subtracting these two decibel levels and converting from a decibel difference to an energy ratio between the direct source and first bounce reflection, we found a value for H at this specific frequency.

Going back to the original equation, we were able to specify the corrective term:

$$S = S_A + \text{corrective term}$$
$$= S_A + KS_B \cos\left[\frac{360^\circ\ (B - A)\ f}{c}\right] ,$$

where

$$S_B = HS_A$$
$$S = S_A + KHS_A \cos\left[\frac{360^\circ\ (B - A)\ f}{c}\right]$$
$$= S_A \left\{1 + KH \cos\left[\frac{360^\circ\ (B - A)\ f}{c}\right]\right\}.$$

Converting back to decibels, we obtained

$$20 \log S = 20 \log S_A + 20 \log \left\{1 + KH \cos\left[\frac{360^\circ\ (B - A)\ f}{c}\right]\right\} ,$$

or

$$\underbrace{20 \log S_A}_{\text{level with no reflection (dB)}} = \underbrace{20 \log S}_{\text{level measured experimentally (dB)}} - \underbrace{20 \log \left\{1 + KH \cos\left[\frac{360^\circ\ (B - A)\ f}{c}\right]\right\}}_{\text{correction term (dB)}} .$$

These calculations were repeated for each microphone and all one-third octave frequencies of interest. The result was a table giving the corrective values for roadside reflection for a source height of 5.8 ft, which corresponded to the speaker height used in a series of tests on the wall. A reflection coefficient of K = 1 was assumed to yield the maximum effect. The corrective values were added to or subtracted from, as appropriate, our measured data. These corrected data were then used to calculate the effective radiating height of the source, and the results compared with the effective radiating heights calculated previously using our measured data alone. These comparisons, along with those for the microphone-side reflections and for both sides combined, are shown in Figure B3.

As can be seen, the corrected data were not much different from the data without the correction factor--even when 100% reflection at the ground surface was assumed.

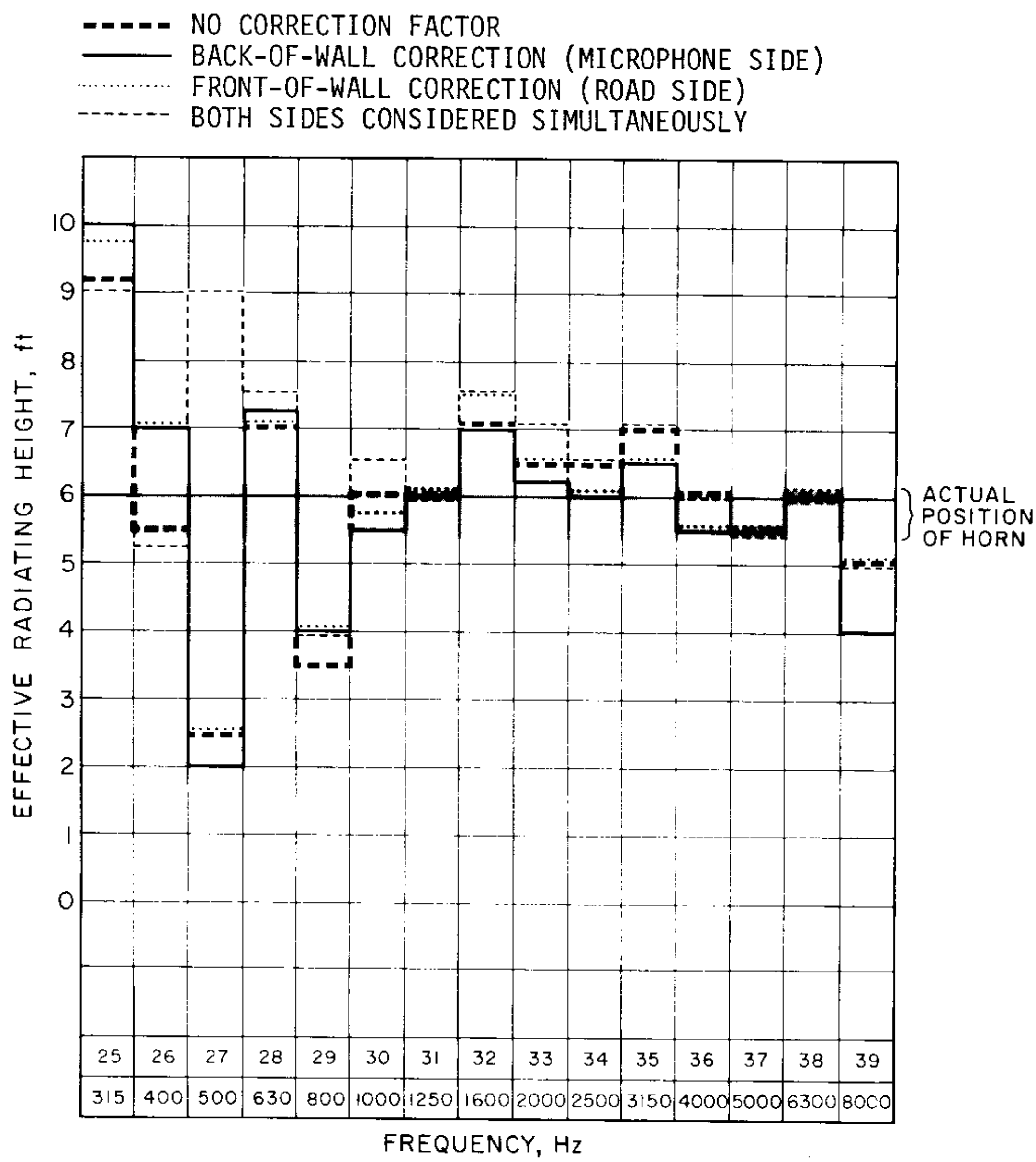
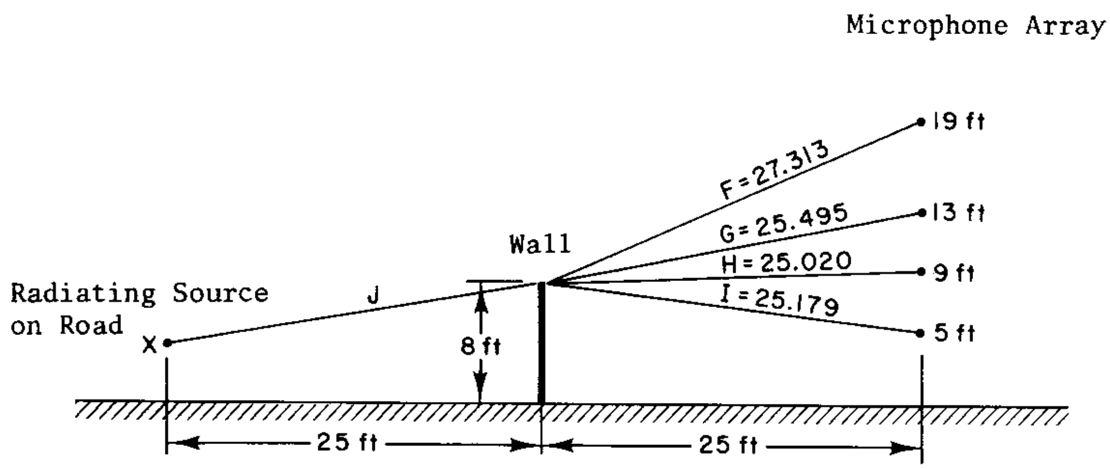


Figure B3. Sample speaker test with reflections from the ground taken into account.

APPENDIX C

FRESNEL DIFFRACTION VERSUS MAEKAWA'S THEORY

Figure C1 shows a cross-section of the geometry involved in the field observations. To demonstrate the differences between the effective radiating heights predicted from Fresnel's equations and those predicted using Maekawa's curve, we will start by calculating the attenuation predicted by Fresnel diffraction for a 4-ft high source, a frequency of 300 Hz, and a sound speed of 1125 ft/sec. Using the same parameters, we will then calculate the radiating height that gives the same attenuation using Maekawa's theory.



$$J = \sqrt{(8-4)^2 + 25^2} = 25.318 \qquad H = \sqrt{(9-8)^2 + 25^2} = 25.020$$

$$F = \sqrt{(19-8)^2 + 25^2} = 27.313 \qquad I = \sqrt{(5-8)^2 + 25^2} = 25.179$$

$$G = \sqrt{(13-8)^2 + 25^2} = 25.495$$

Figure C1. Geometry of experiment.

For the 5-ft microphone,

$$\sqrt{(5-4)^2 + 50^2} = 50.010 ,$$

$$\delta = 25.318 + 25.179 - 50.010$$

$$= 0.487 ,$$

and

$$N = \frac{2\delta}{\lambda} = \frac{2f\delta}{c} = \frac{2(300)(0.487)}{1125} = 0.260 .$$

For the 9-ft microphone,

$$\sqrt{(9-4)^2 + 50^2} = 50.249 ,$$
$$\delta = 25.318 + 25.020 - 50.249$$
$$= 0.089 ,$$

and

$$N = \frac{2(300)(0.089)}{1125} = 0.047 .$$

For the 13-ft microphone,

$$\sqrt{(13-4)^2 + 50^2} = 50.804 ,$$
$$\delta = -(25.318 + 25.495 - 50.804)$$
$$= -0.009 ,$$

and

$$N = \frac{2(300)(-0.009)}{1125} = -0.0048 .$$

For the 19-ft microphone,

$$\sqrt{(19-4)^2 + 50^2} = 52.202 ,$$
$$\delta = -(25.318 + 27.313 - 52.202)$$
$$= -0.429 ,$$

and

$$N = \frac{2(300)(-0.429)}{1125} = -0.229 .$$

Using Fresnel's equations, the attenuations calculated from these N values are

5-ft microphone - 11.786 dB
9-ft microphone - 8.769 dB
13-ft microphone - 5.169 dB
19-ft microphone - 0.372 dB

The N values are the same for the Maekawa calculations. The attenuations calculated from these N values using Maekawa's equations are

5 ft → 0.260 → 9.279 dB

9 ft → 0.047 → 6.934 dB

13 ft → -0.0048 → 4.468 dB

19 ft → -0.229 → 0.731 dB .

When these values are subtracted from the corresponding Fresnel values at each microphone, the mean and standard deviation of the differences are:

1.171 mean

1.263 standard deviation

2.434 |sum| .

For a 1-ft radiating height, Maekawa's theory predicts

5 ft → 0.523 → 10.985 dB

9 ft → 0.184 → 8.632 dB

13 ft → 0.020 → 6.331 dB

19 ft → -0.071 → 2.668 dB

-0.630 mean

1.378 standard deviation

2.008 |sum| .

The best fit was found at 2.15 ft, which yields

-0.0391 mean

1.3410 standard deviation

1.380 |sum| .

Therefore, at 300 Hz, when Fresnel diffraction predicts a 4-ft radiating height for our D-tower setup, Maekawa's theory would predict a 2.15-ft radiating height.

APPENDIX D

SPREADING LOSS EFFECTS

Simple Fresnel diffraction was used to calculate the reduction in the sound received at the various microphones because of diffraction. The microphones were not, however, all an equal distance from the top edge of the wall so that, in addition to diffraction, the differences in the sound levels at the various microphones also included a spreading loss due to the differing distances. That is, if there had been no wall between the source and the microphones, the top microphone, for example, would have received less sound than the other microphones simply because it would have been a greater distance from the source. With the wall in place, there was, of course, no direct path between the source and the bottom microphones. Since the sound reaching these microphones, of necessity, had to go to the top of the wall and back down again, the amount of spreading in the portion of the sound path between the source and the top of the wall was substantially the same for all the microphones. Thus, this part of the spreading loss was of no consequence to our measurements which were concerned only with the difference in the levels received at the microphones. The spreading loss between the top of the wall and the individual microphones would, however, in principle, be different for each microphone.

Since the spreading loss was reflected in the values measured in the experimental part of the program, it was duplicated in the calculated part. The sound was considered as one system from the source to the vicinity of the top of the wall; at that point, Huygens' principle was applied and the sound considered to come from a new, reradiating source. This assumed reradiator would not now, of course, be a point source. For purposes of the calculations, a simplifying assumption was made. The assumed radiator was considered to be a cylindrical source which would result in a spreading loss of 10 log distance for the remainder of the sound's journey to each of the microphones. Calculations were then performed using the assumption of an effective axial center of reradiation at the top of the wall. In comparing the final effective radiating height and frequency calculations done with and without the spreading loss calculations, the results were only <u>very weakly</u> dependent on whether the spreading loss was taken into account or not. However, for theoretical accuracy, the spreading loss corrections were taken into account in all calculations.