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NOISE AND VIBRATION STUDY FOR THE METRO RAIL PROJECT

Final Report

VOLUME II - APPENDICES A, B AND C

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Prepared for:

Southern California Rapid Transit District

Prepared Under the Supervision of:

Steven L. Wolfe

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Project Manager

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APPENDIX A

STATISTICAL DISTRIBUTION OF THE NOISE AT THE MEASUREMENT LOCATIONS

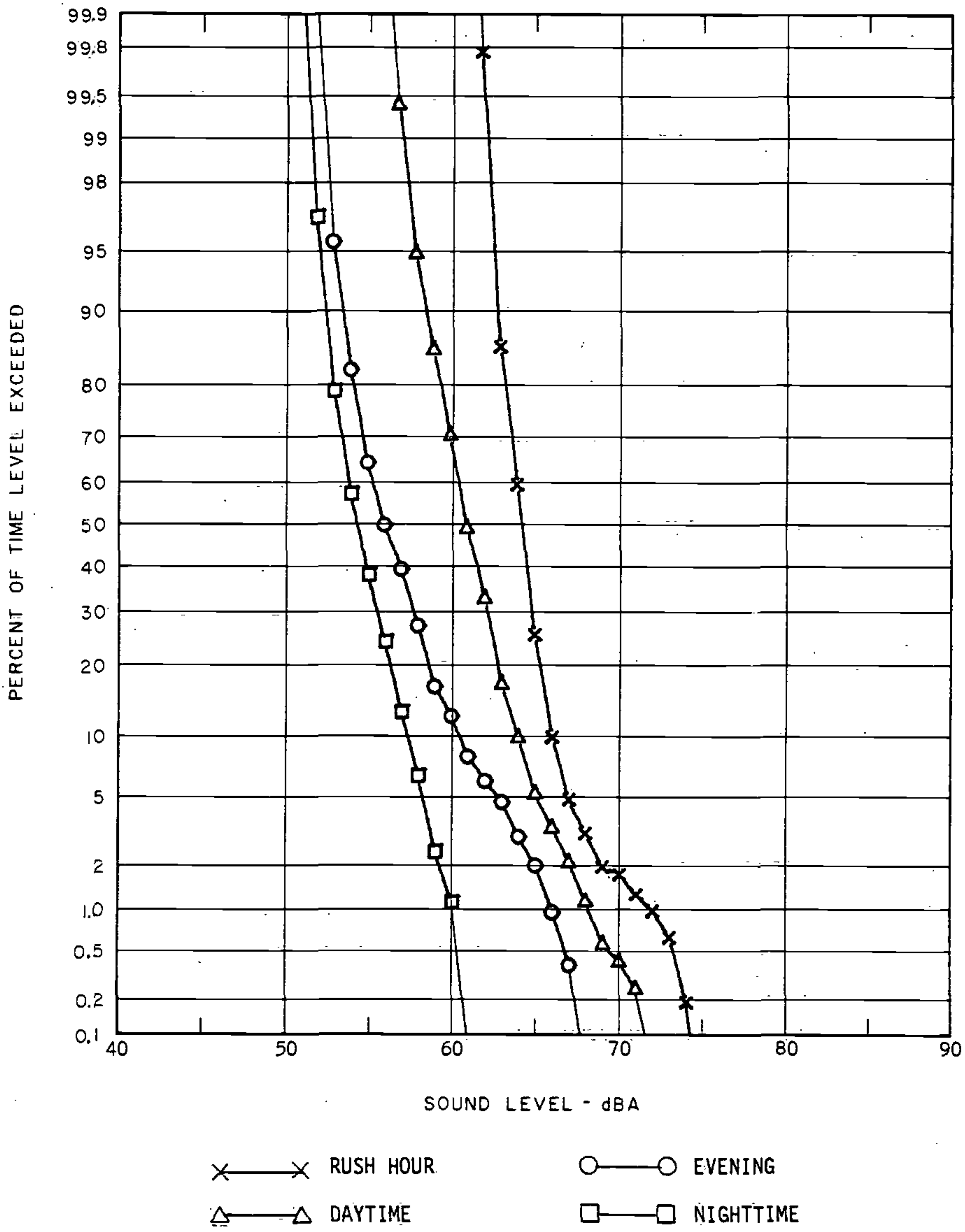
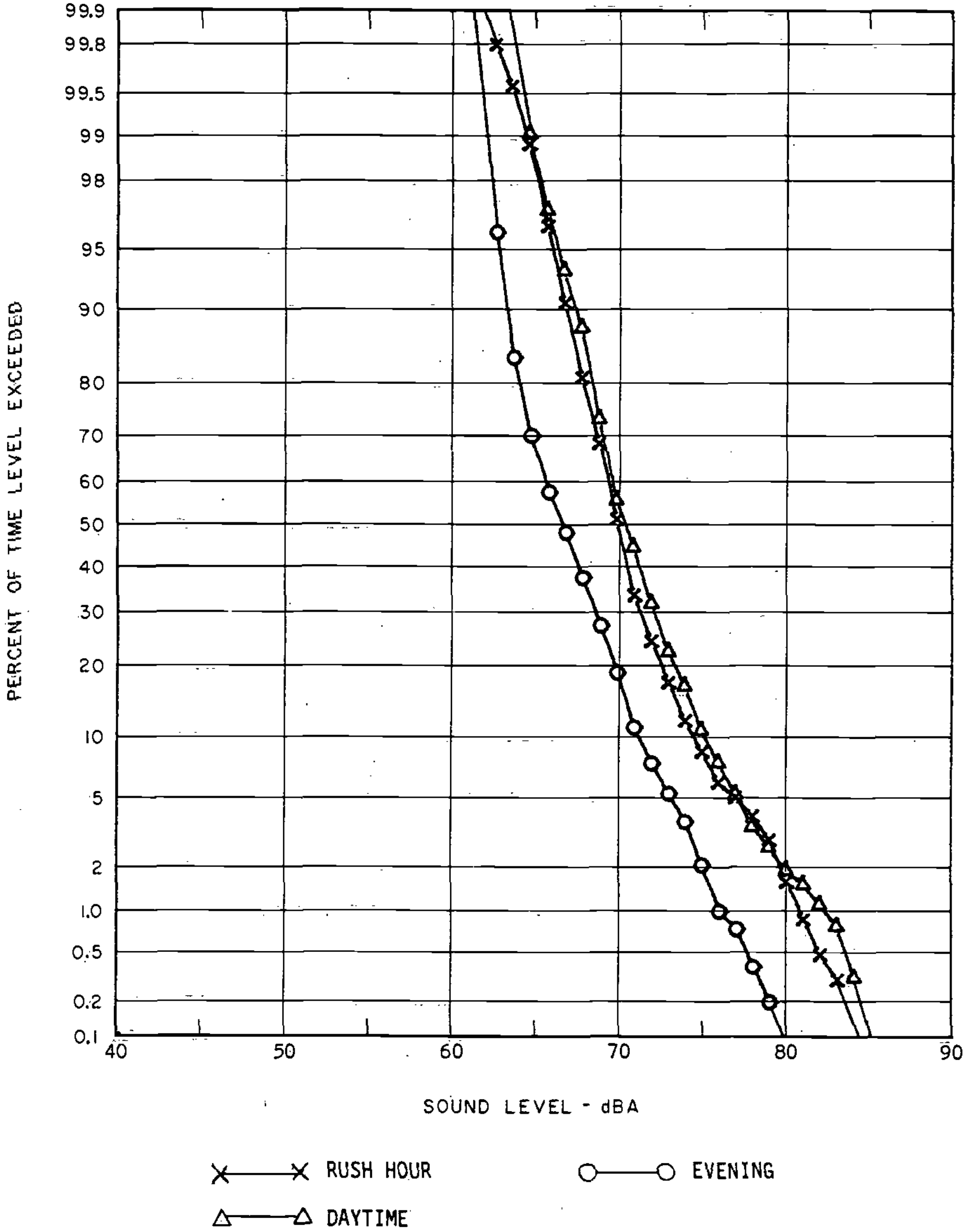


FIGURE A-1 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 1



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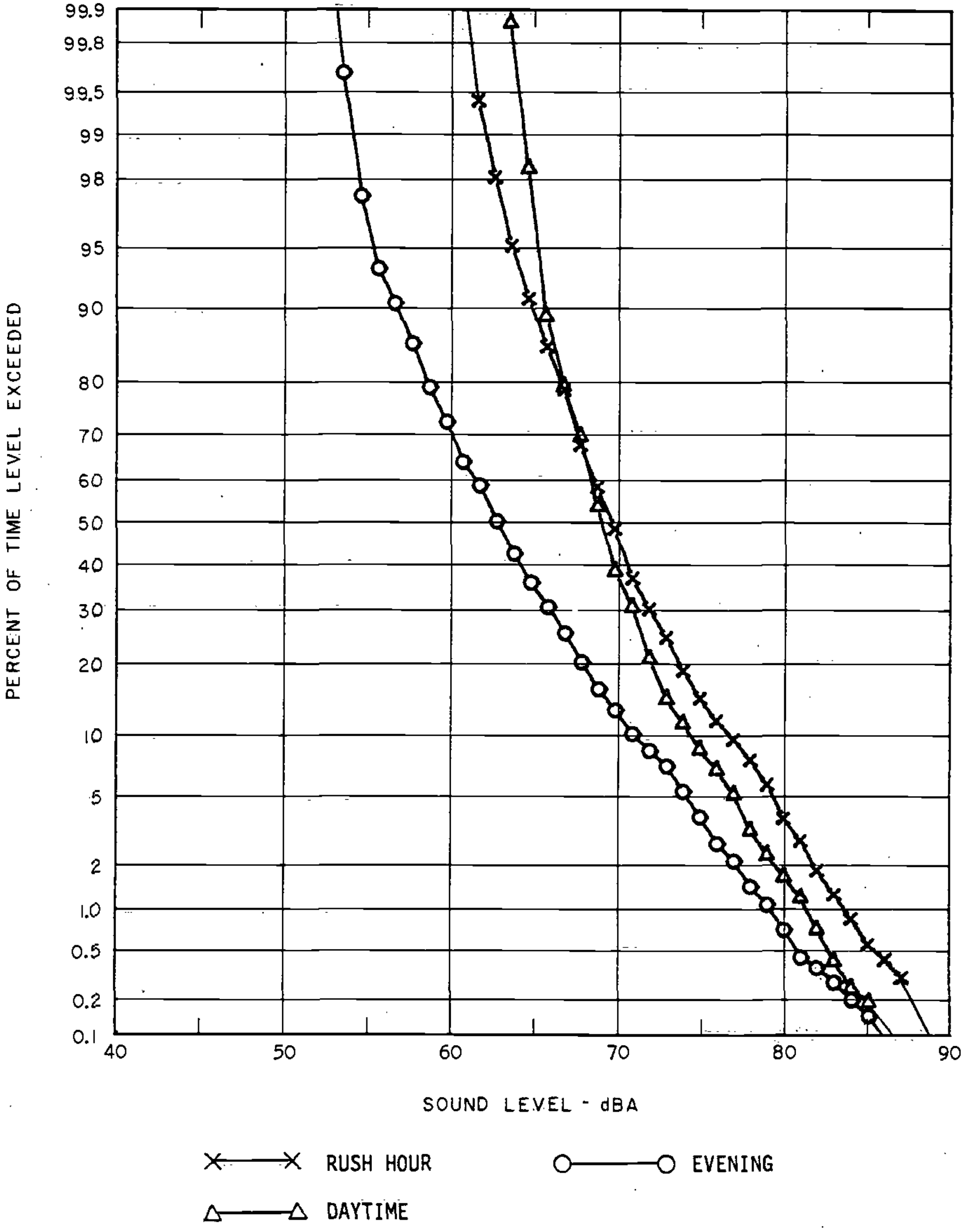

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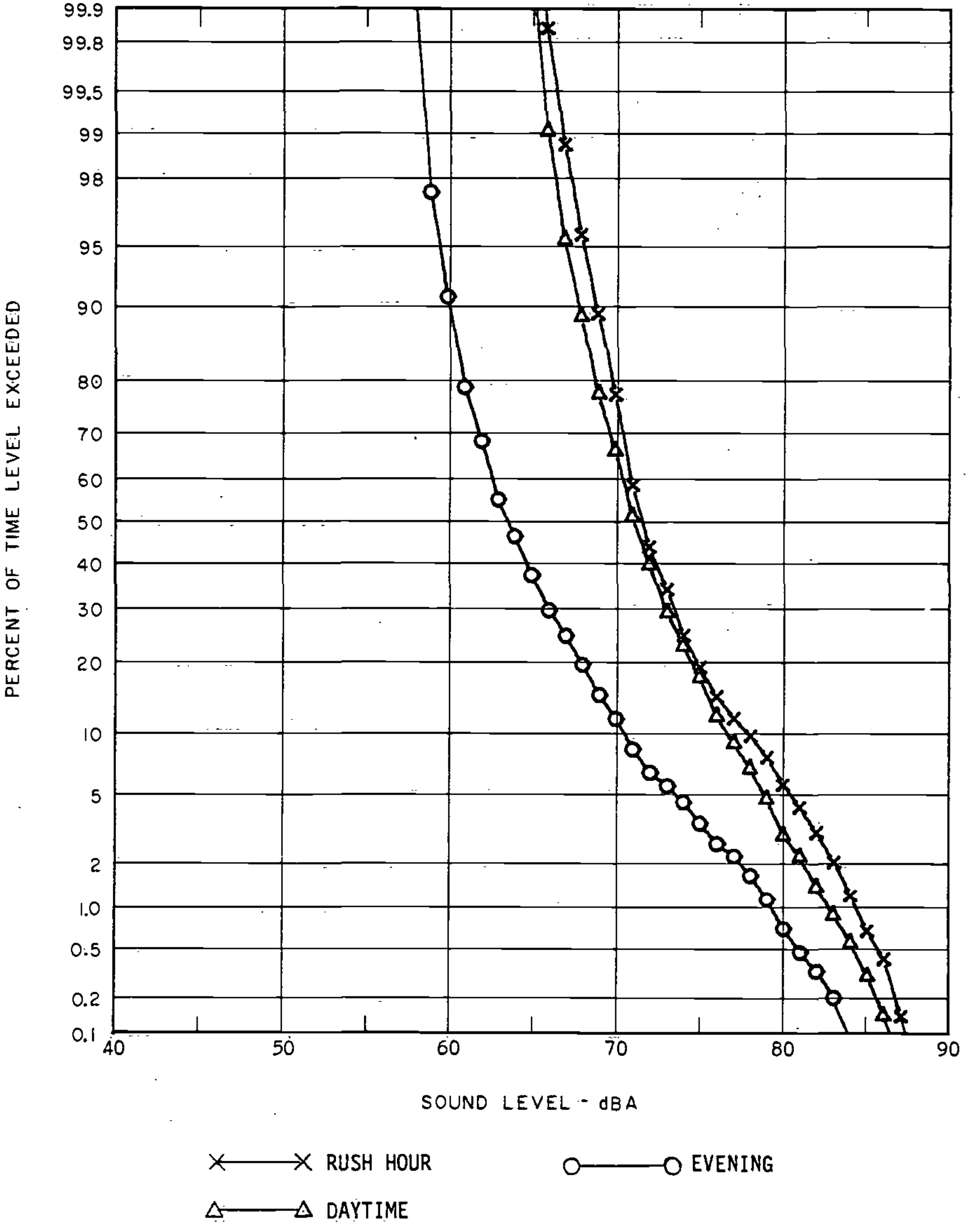

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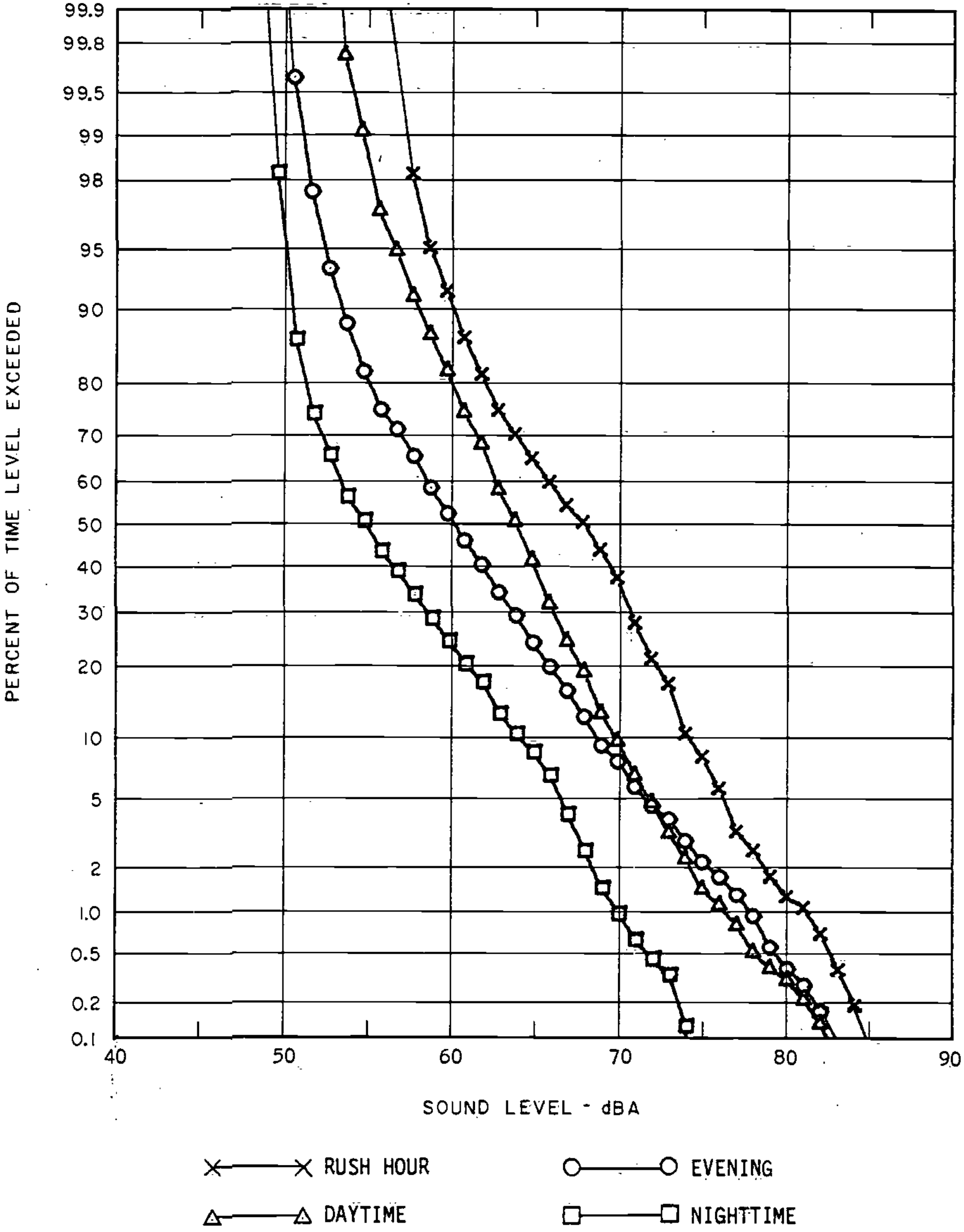

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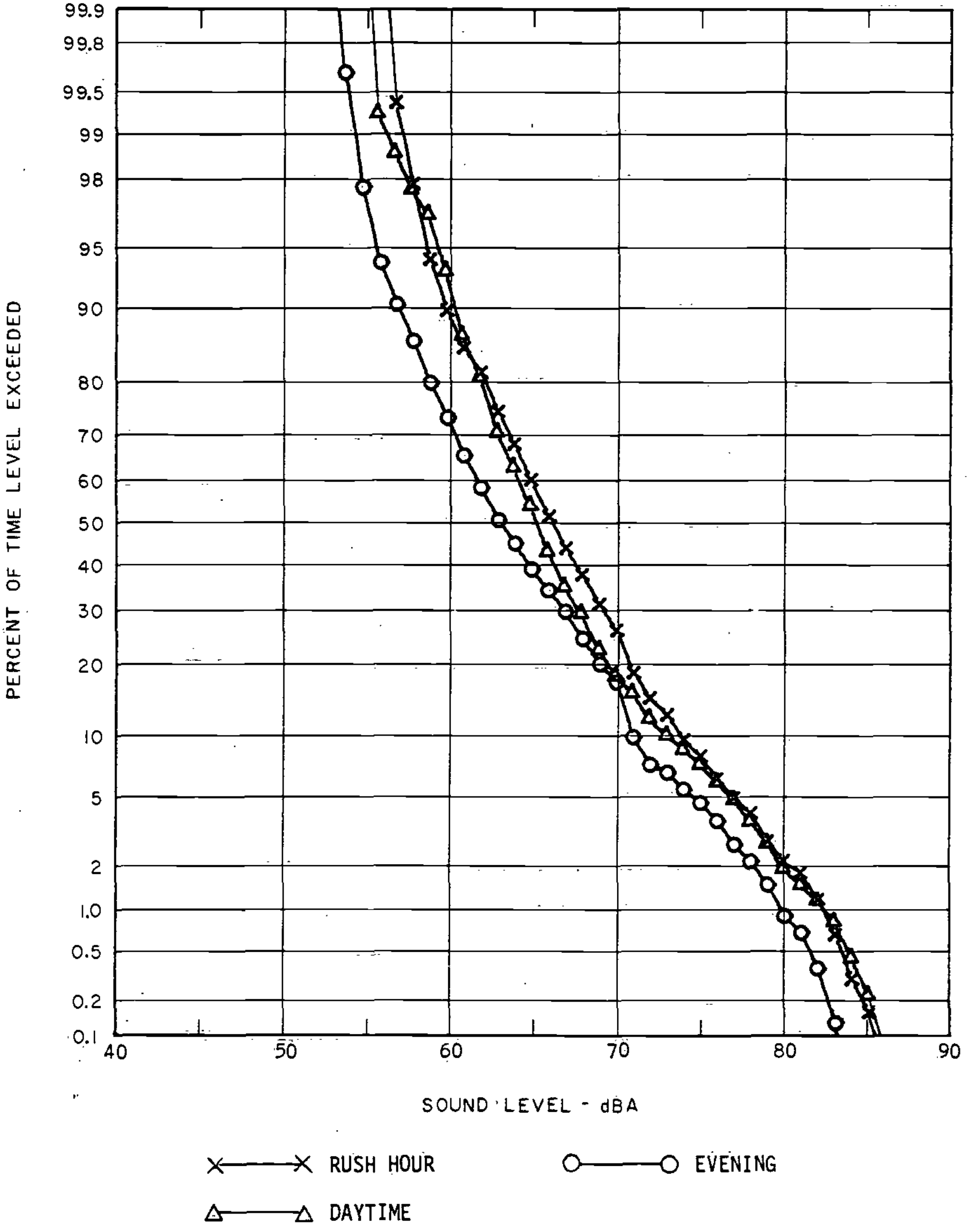

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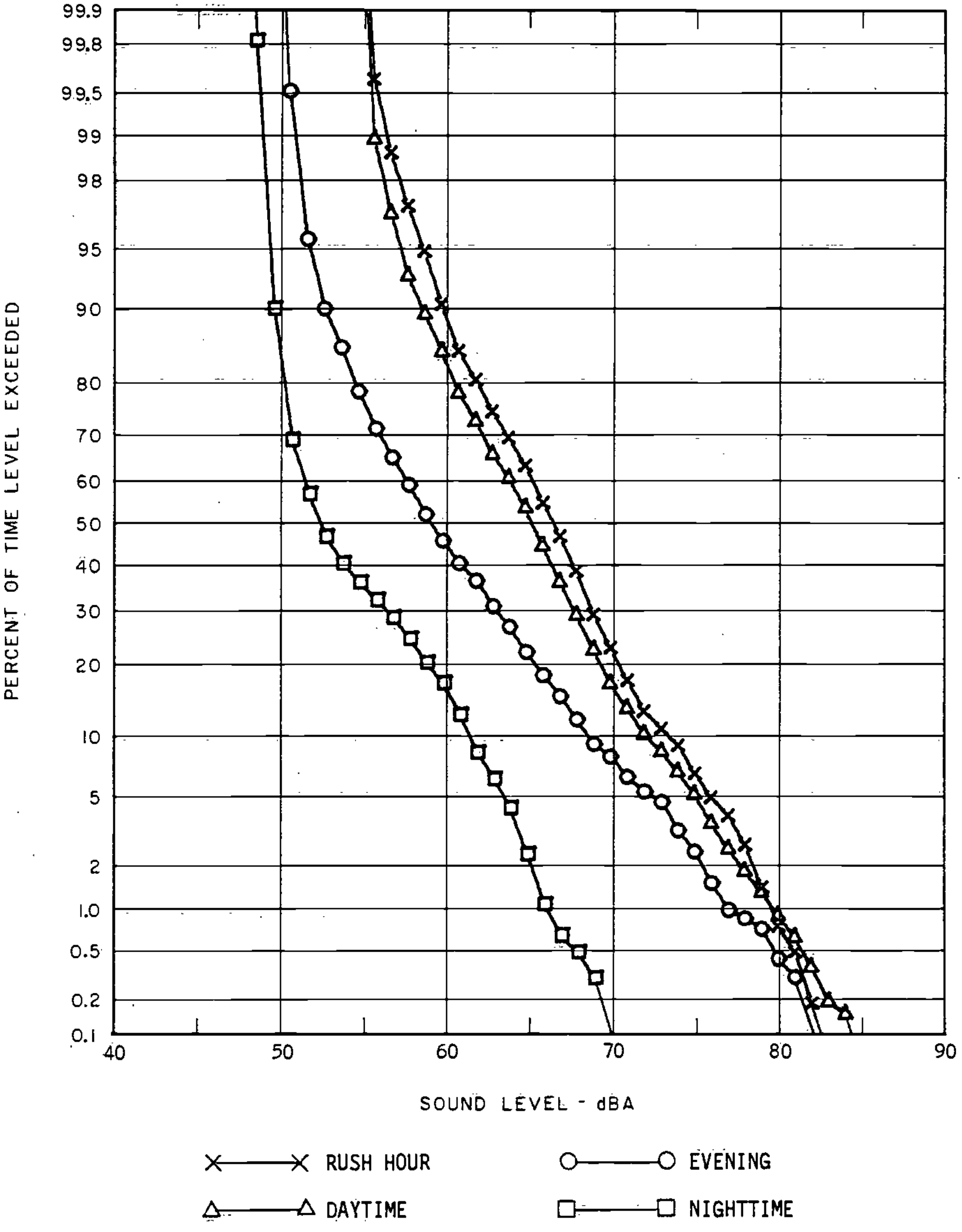

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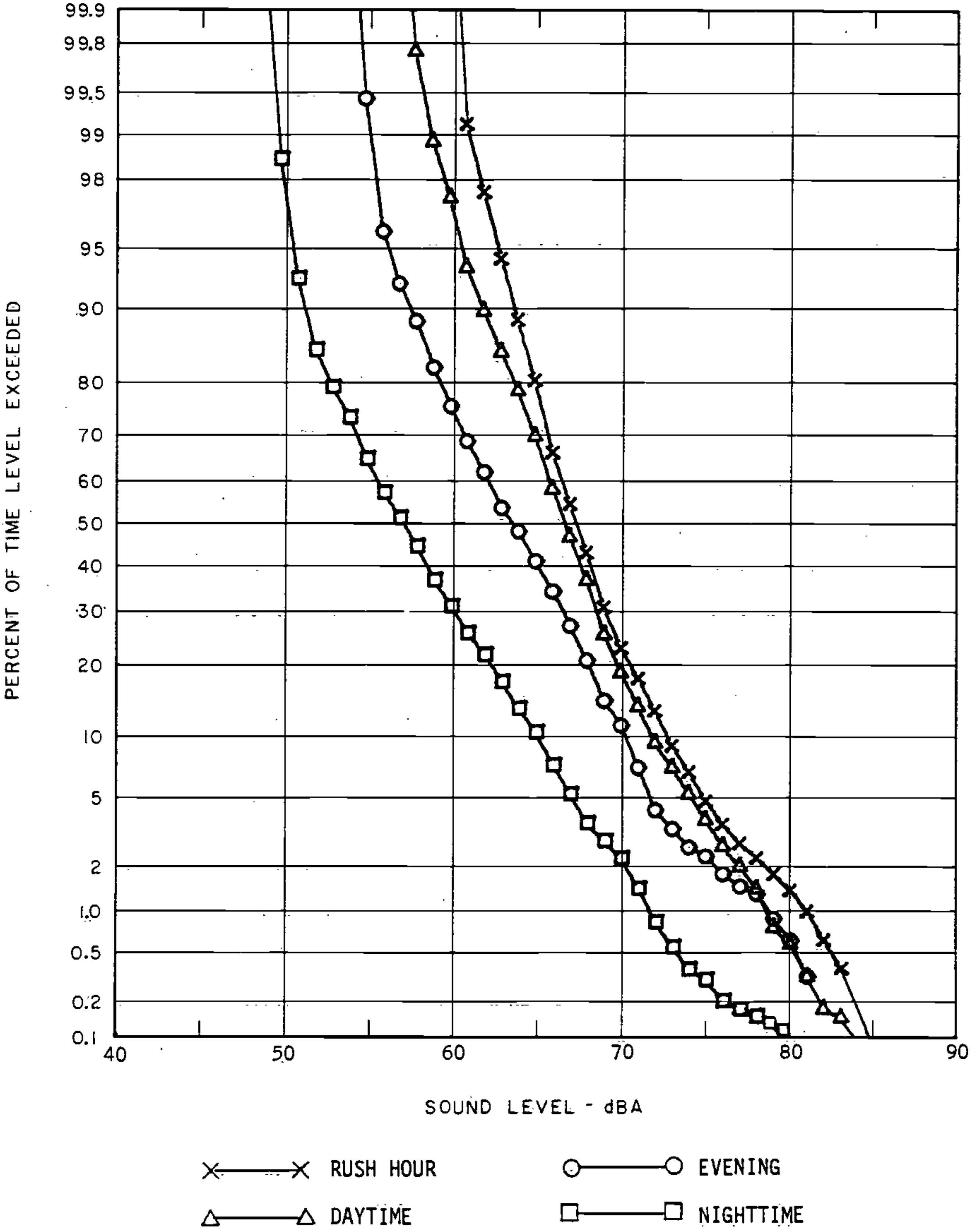

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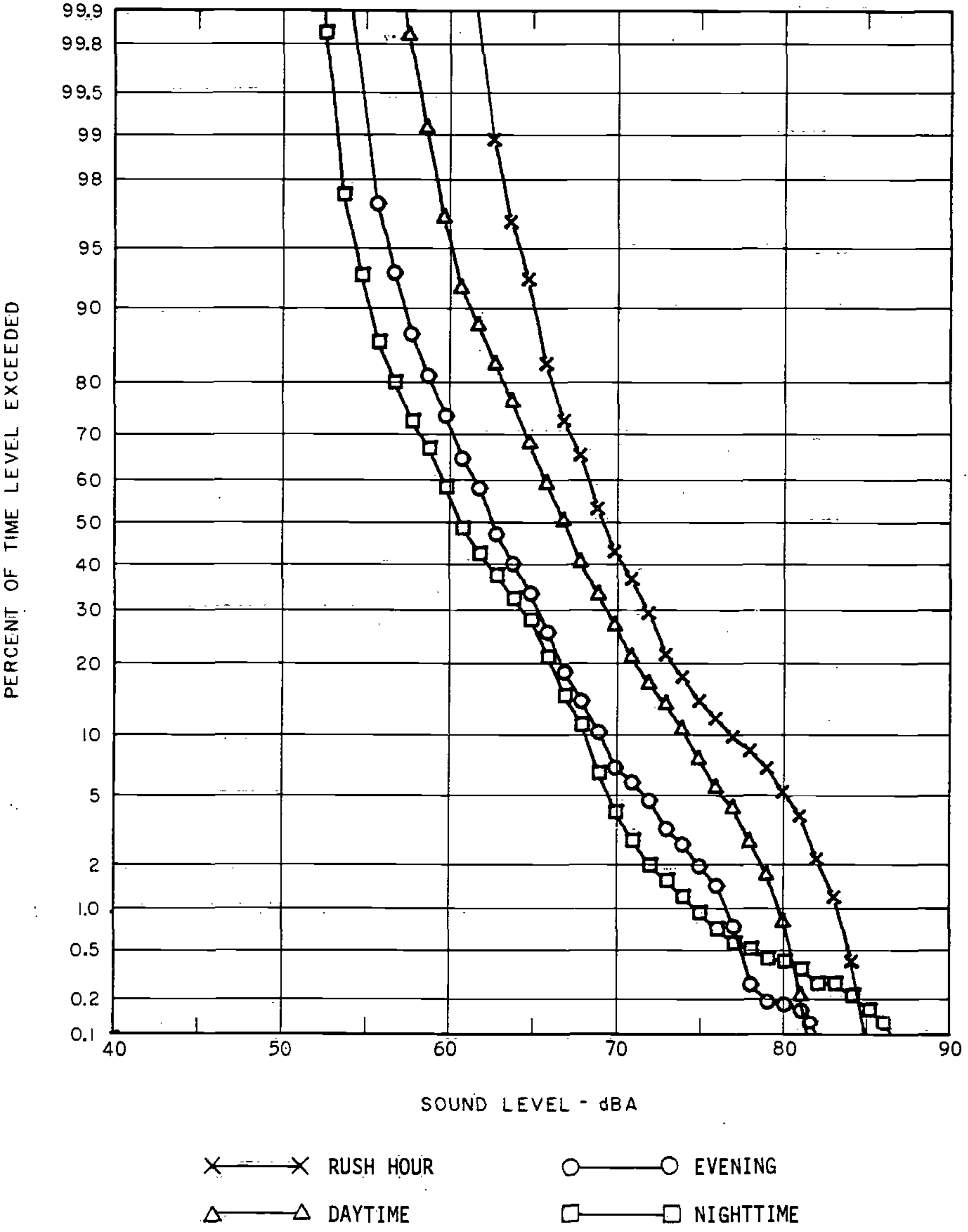

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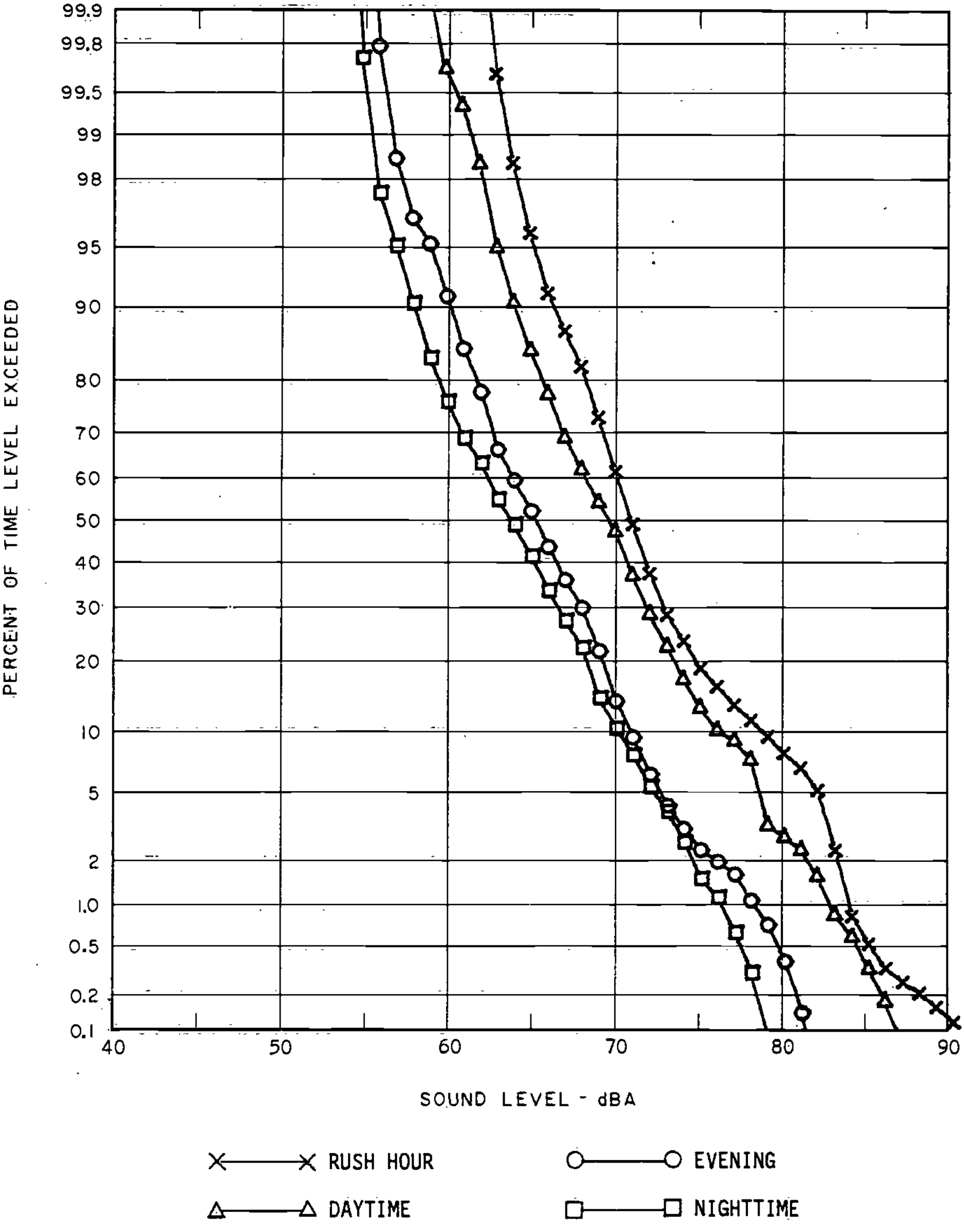

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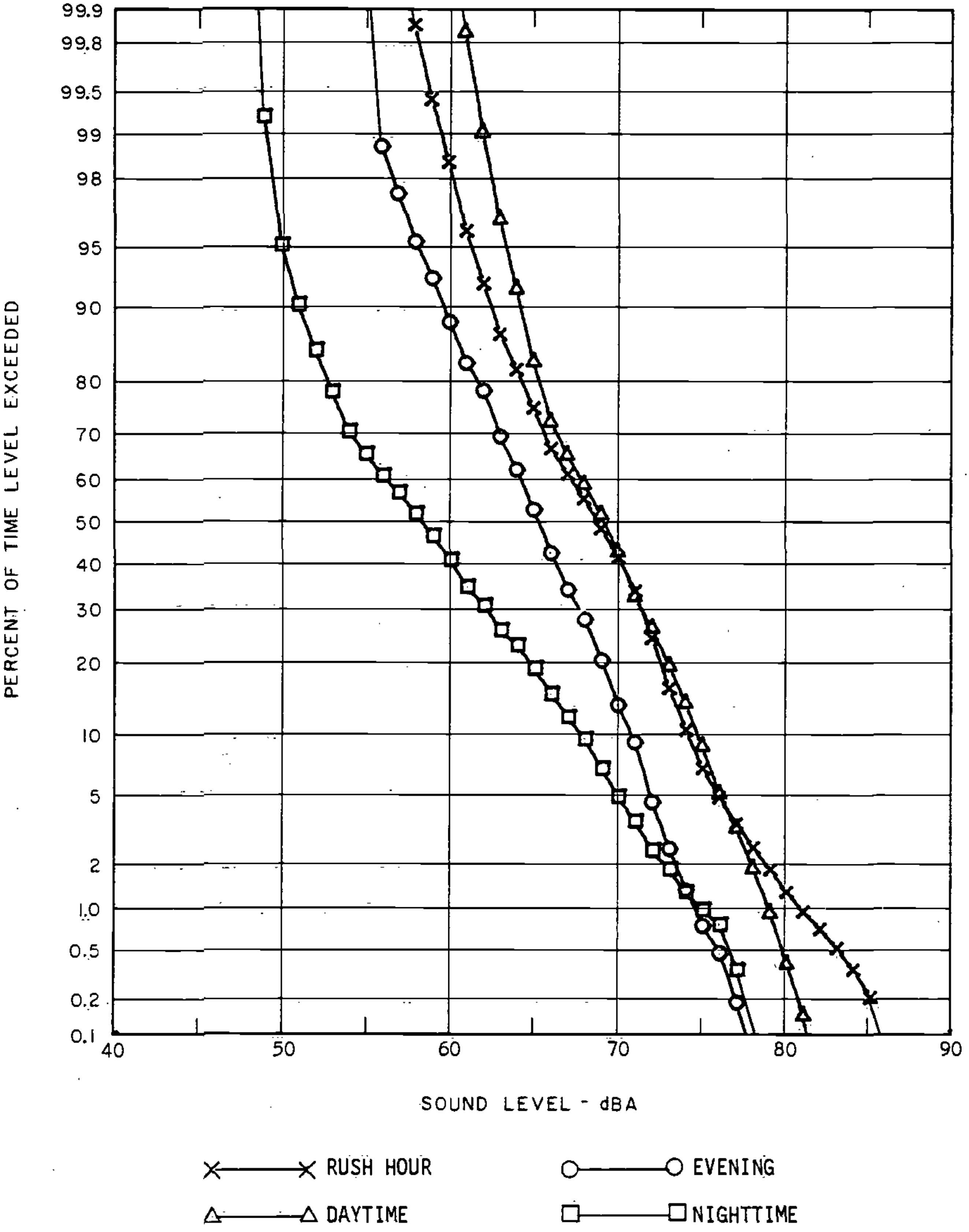

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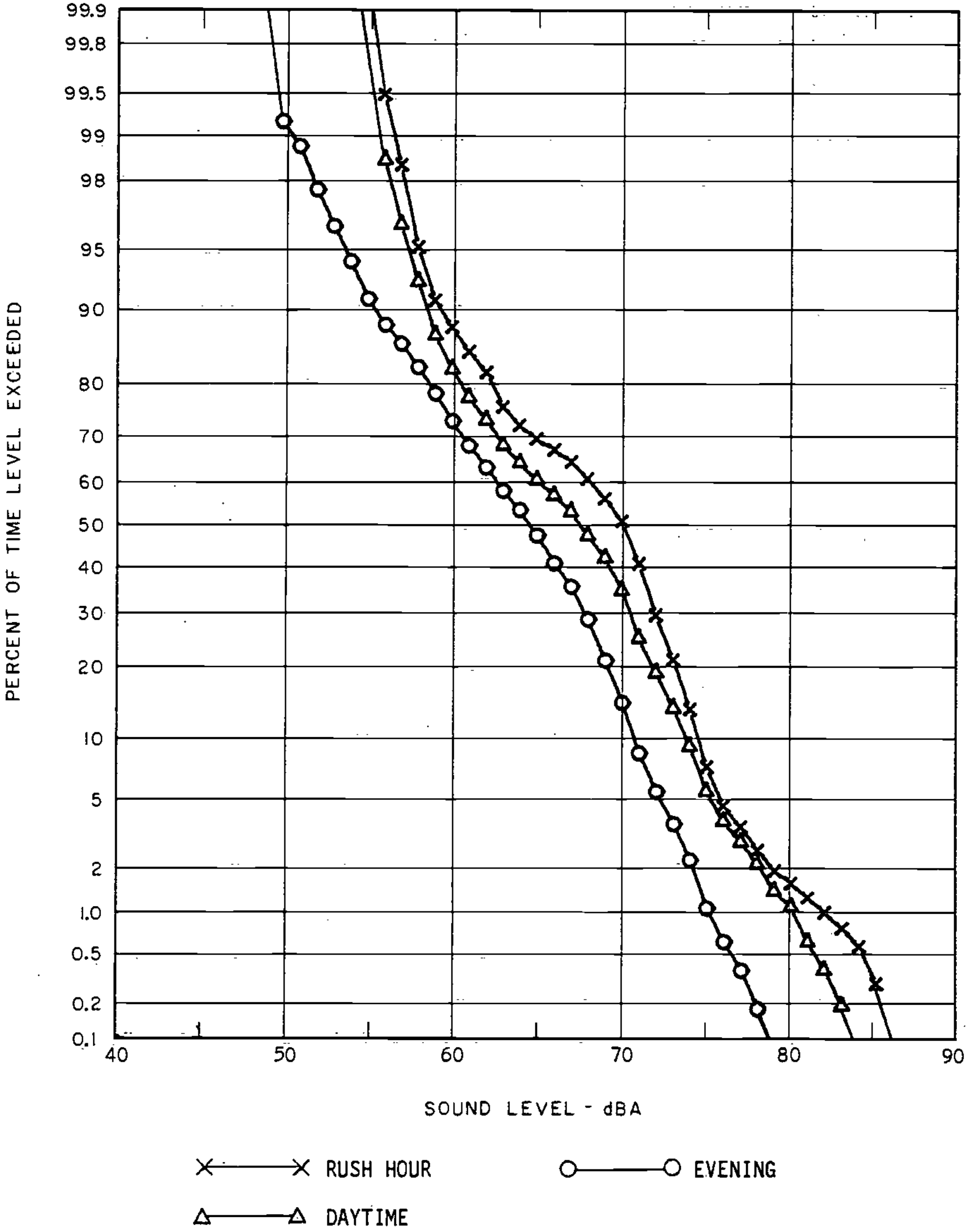

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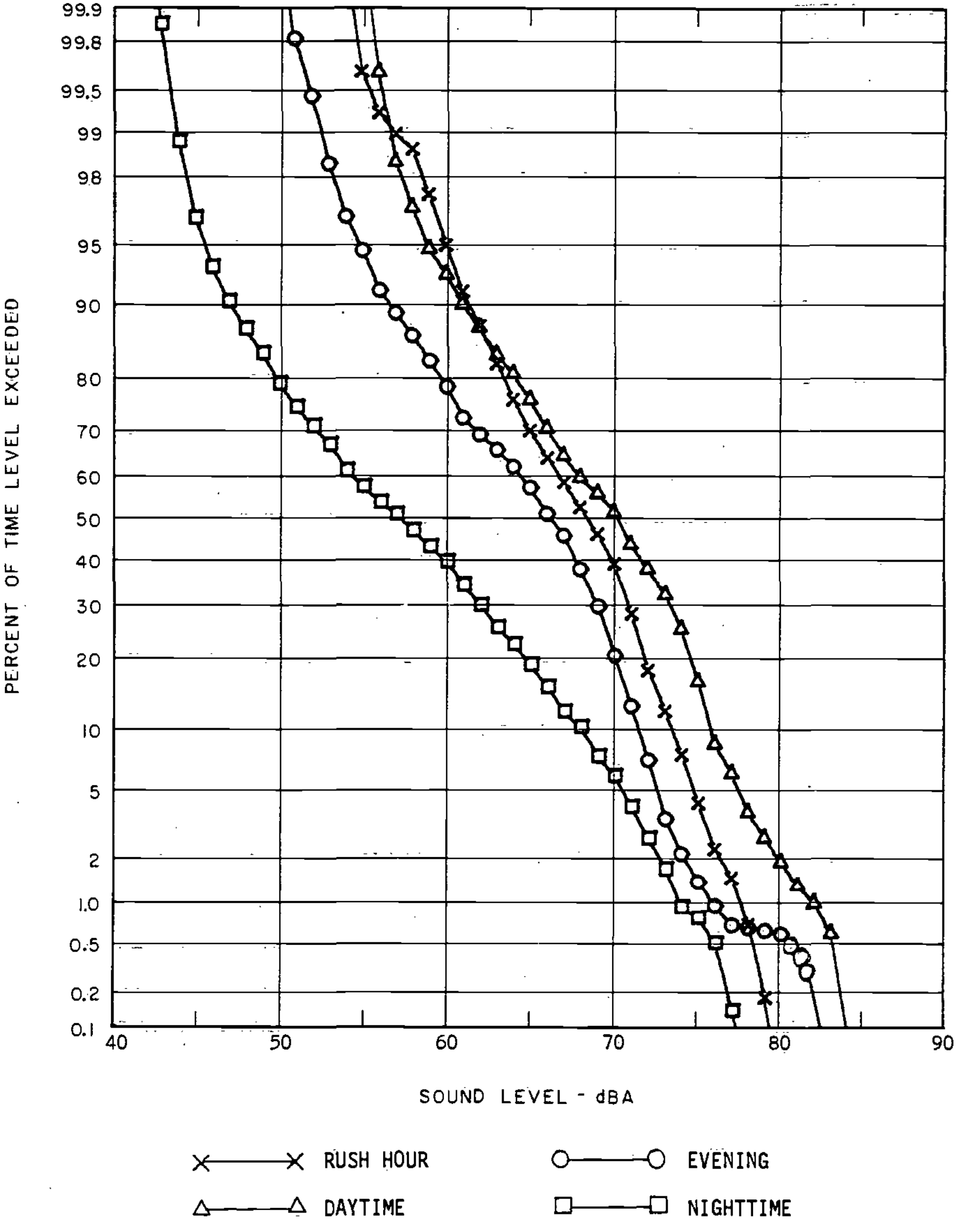

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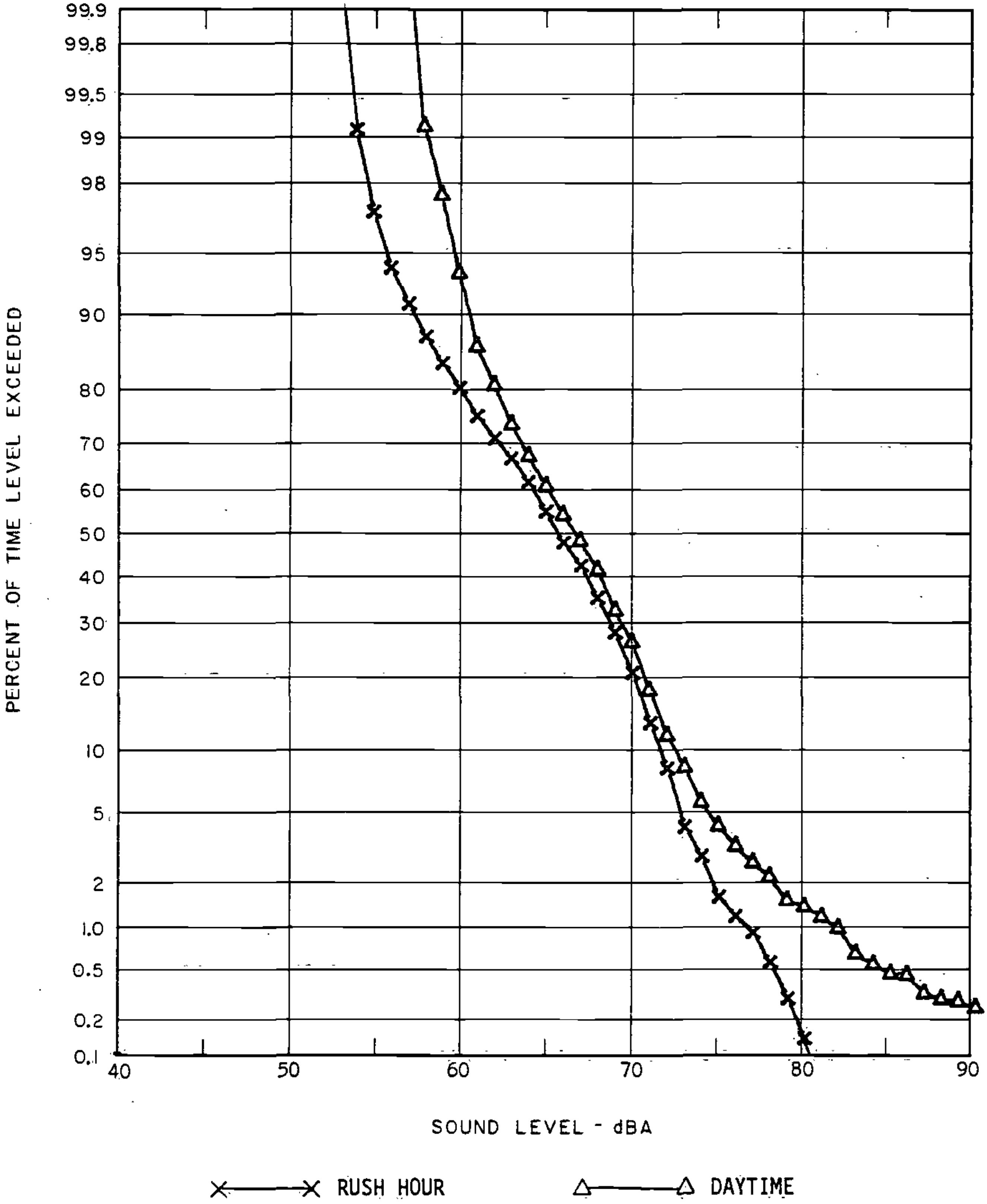

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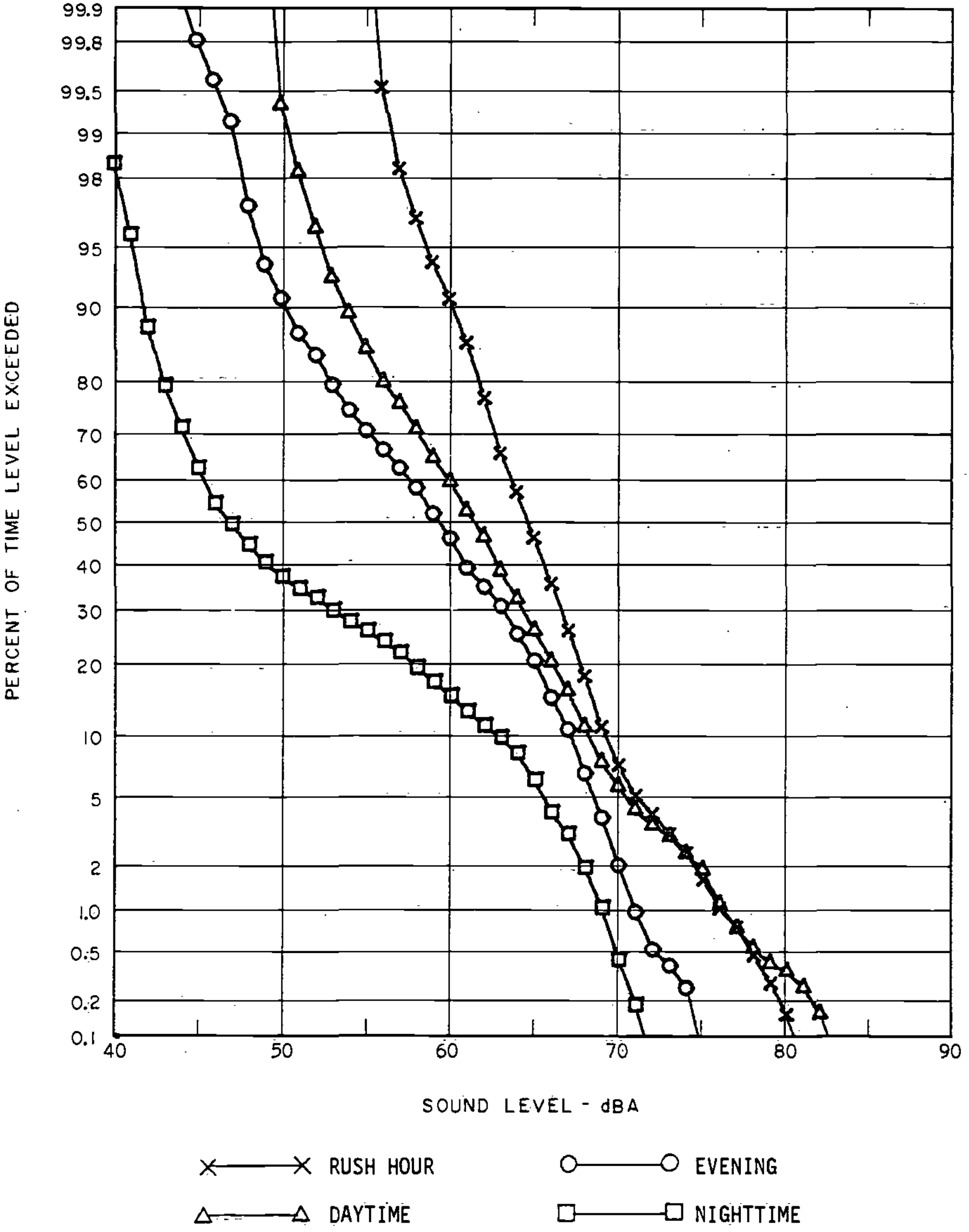

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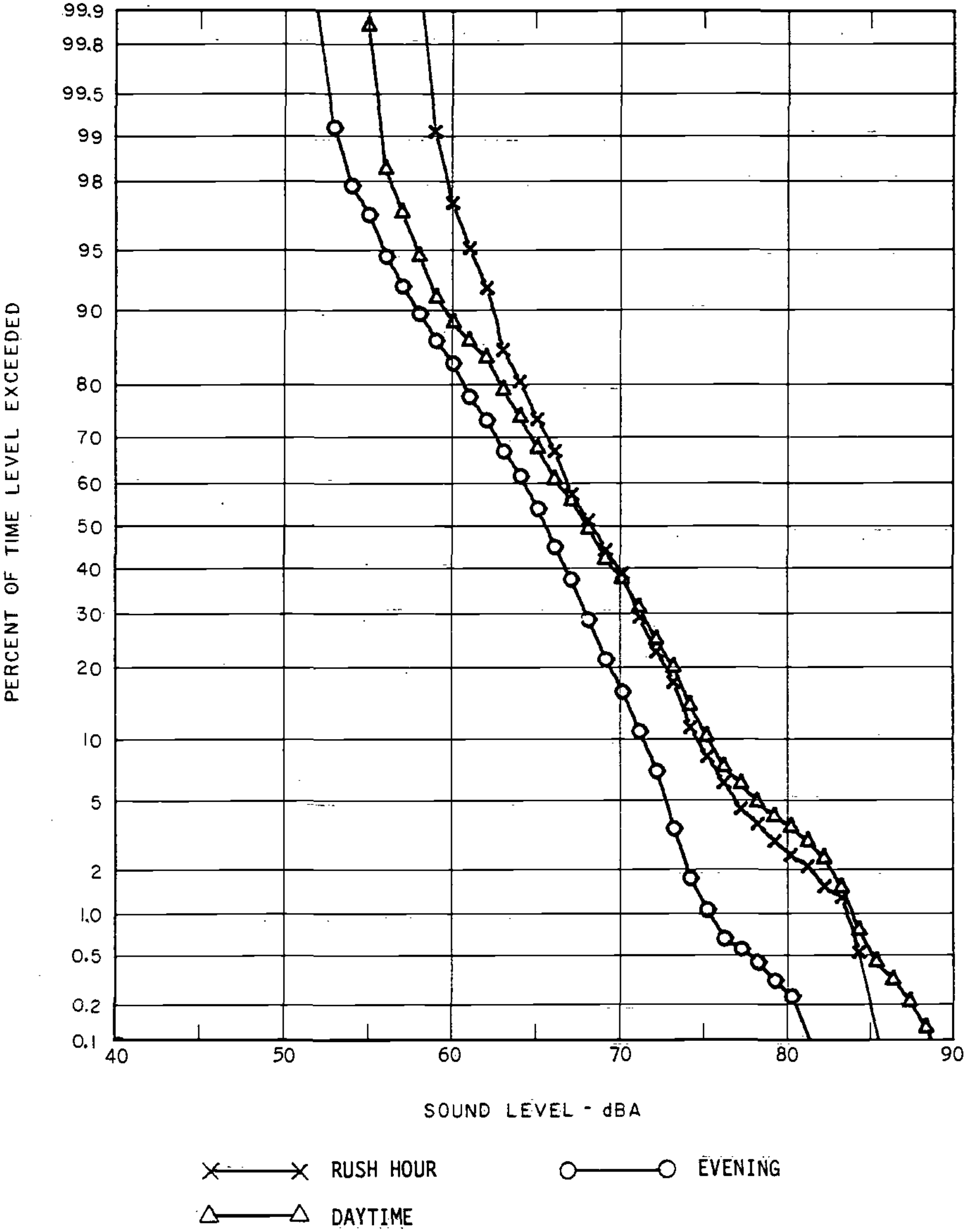

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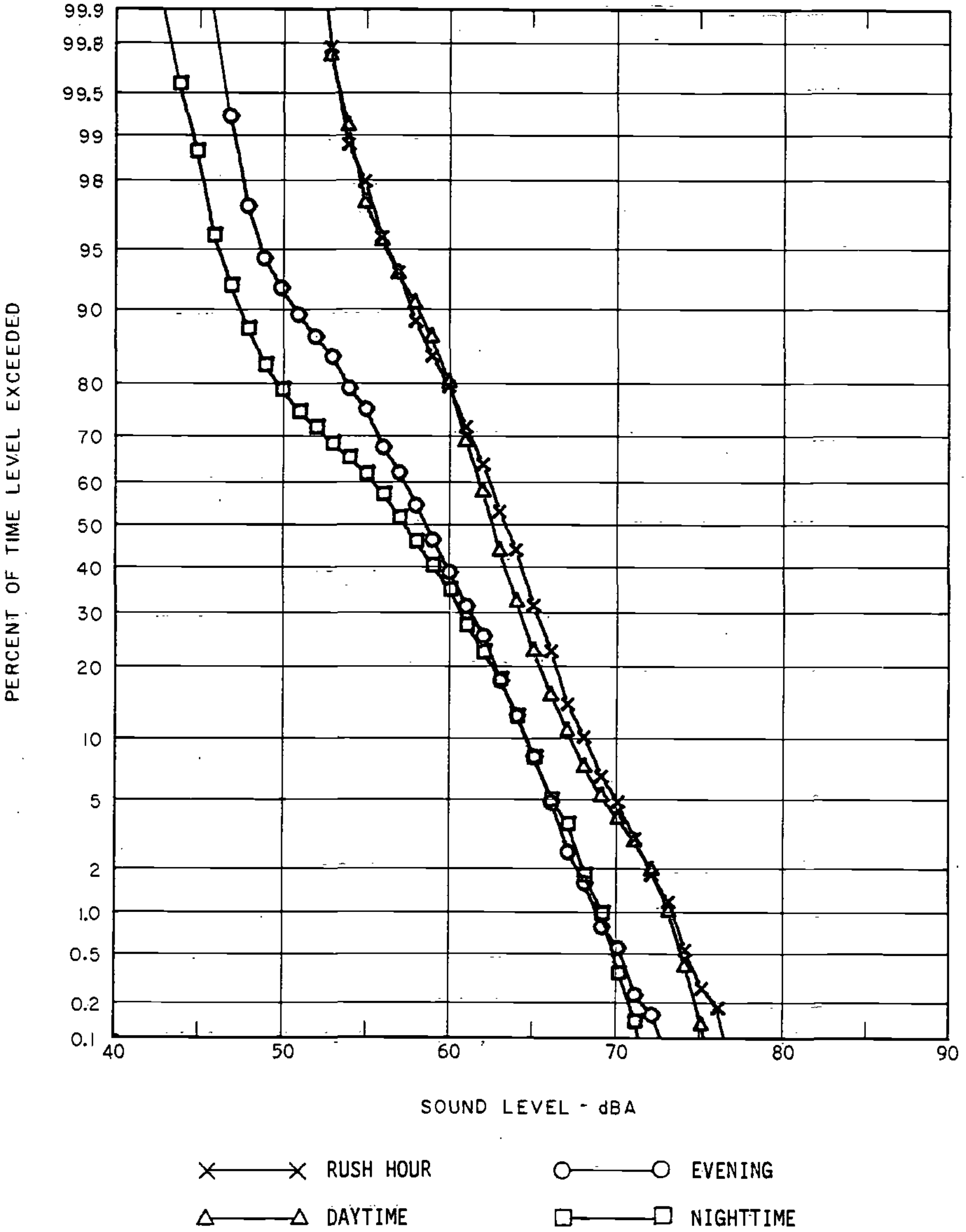

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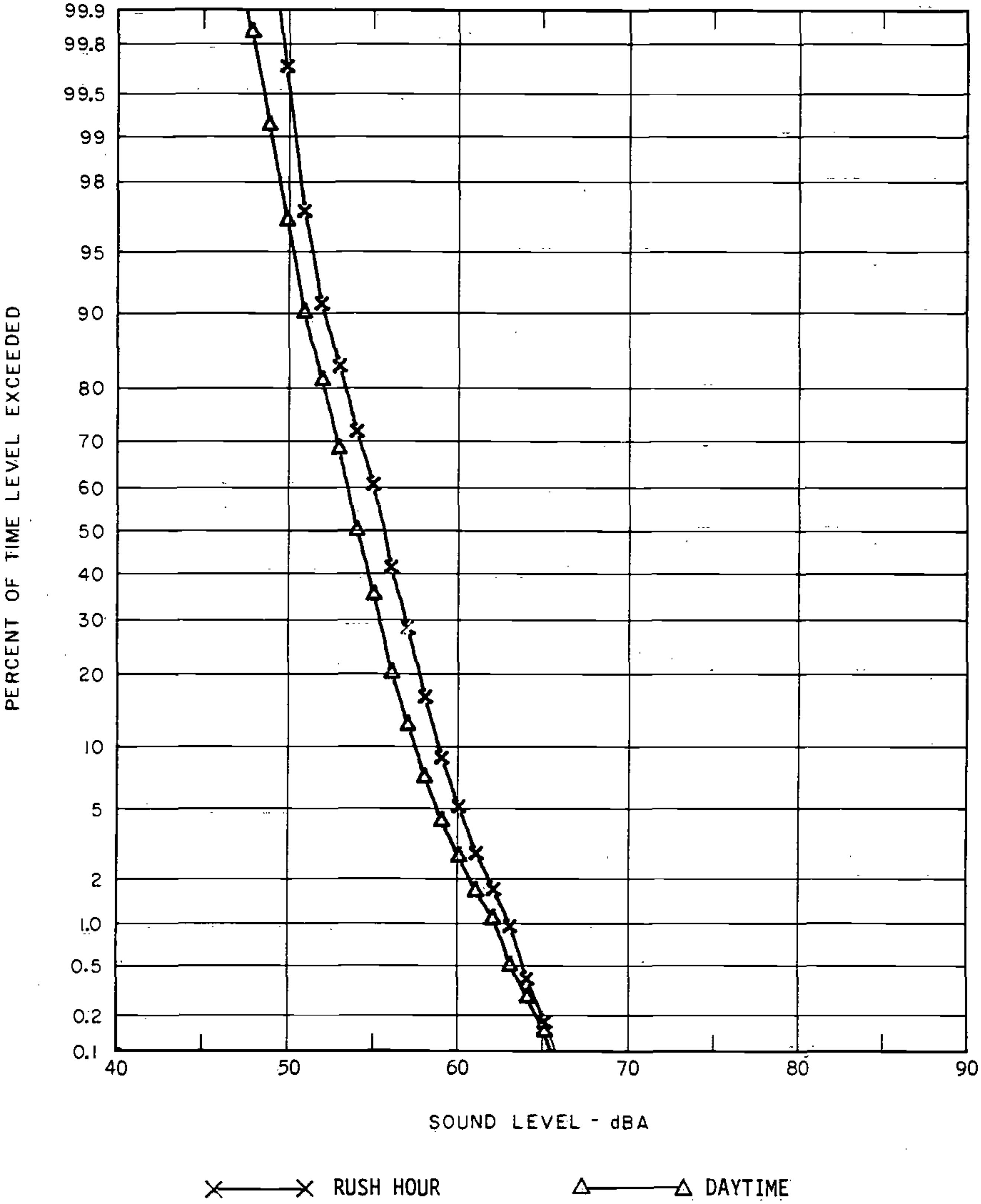

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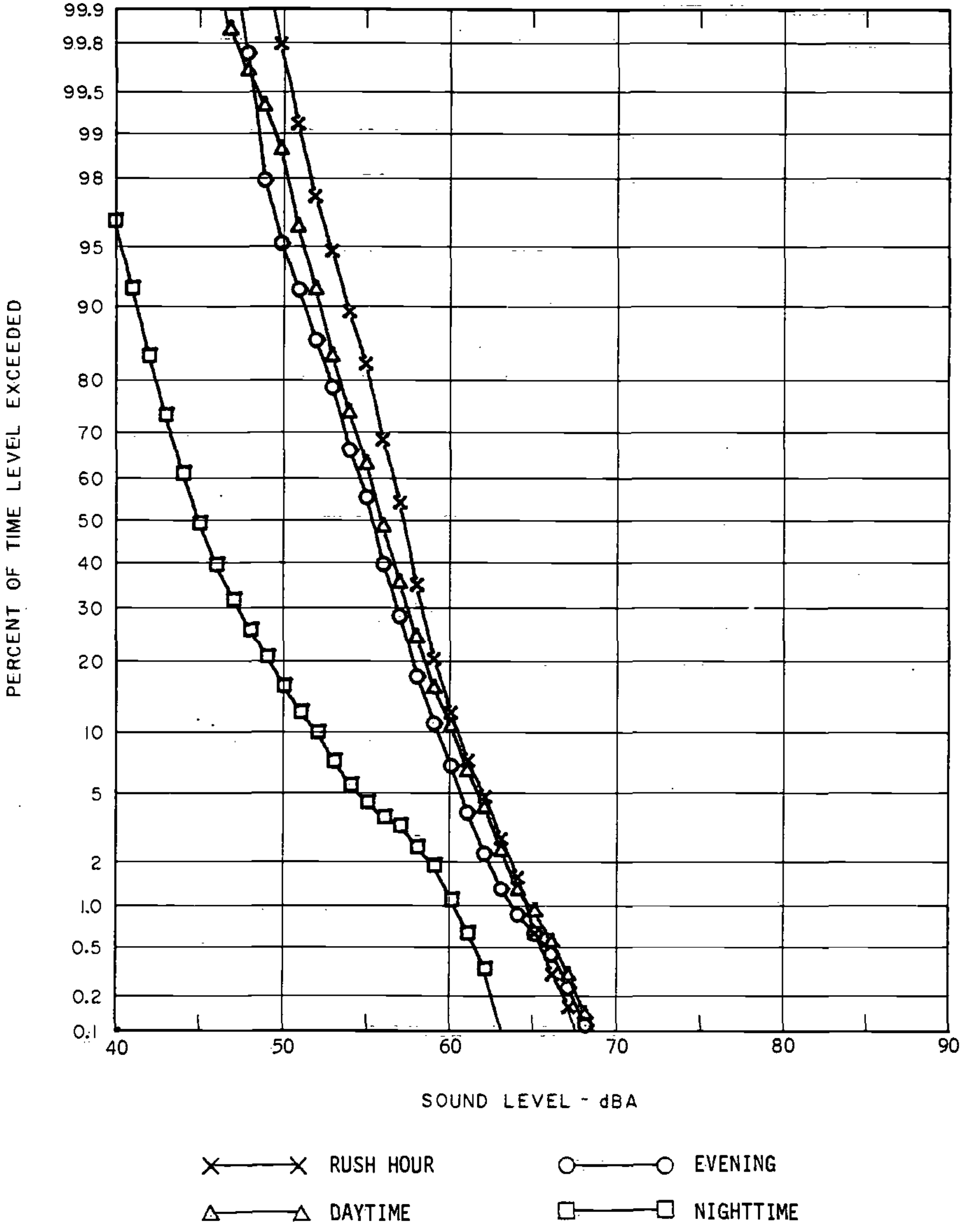

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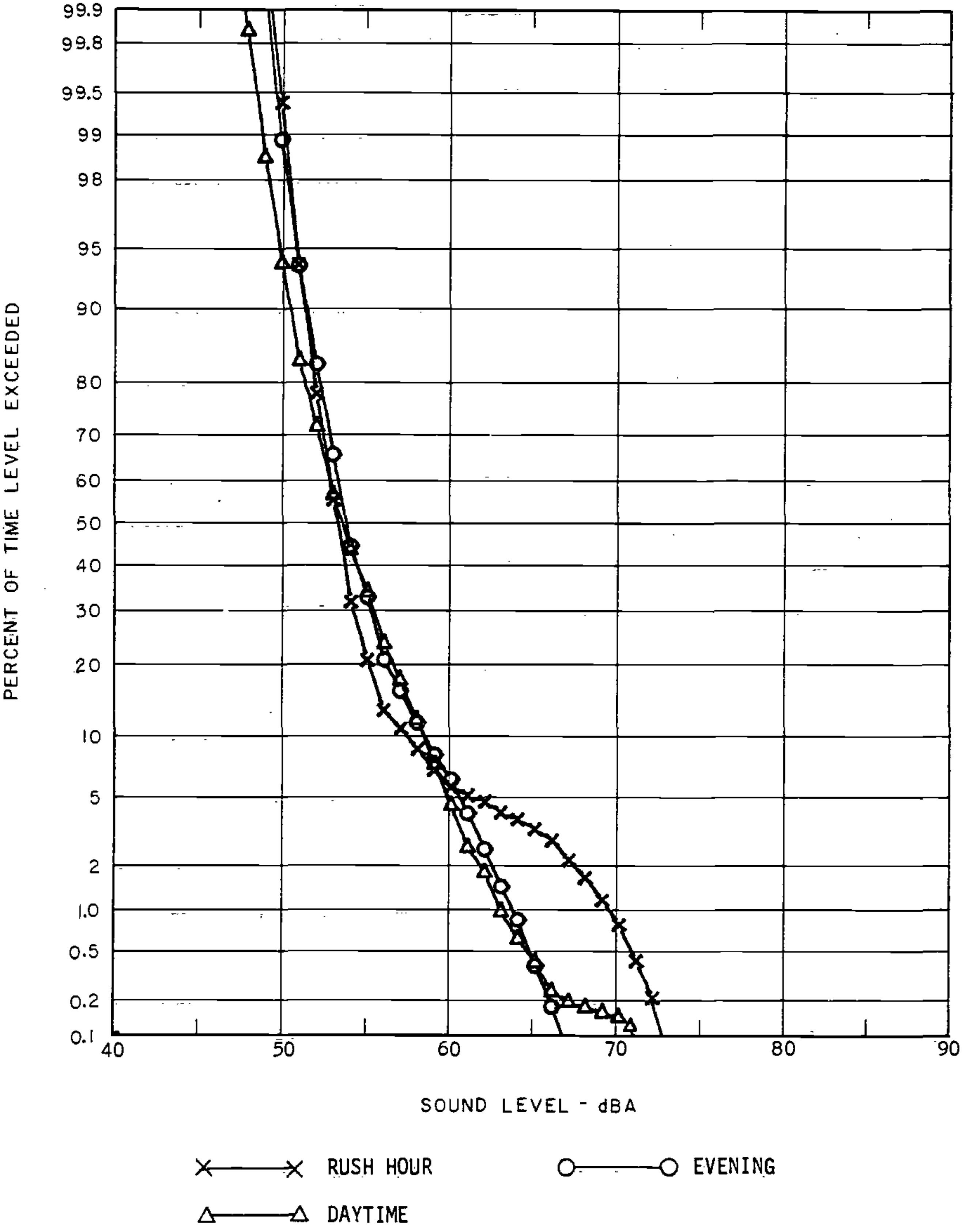

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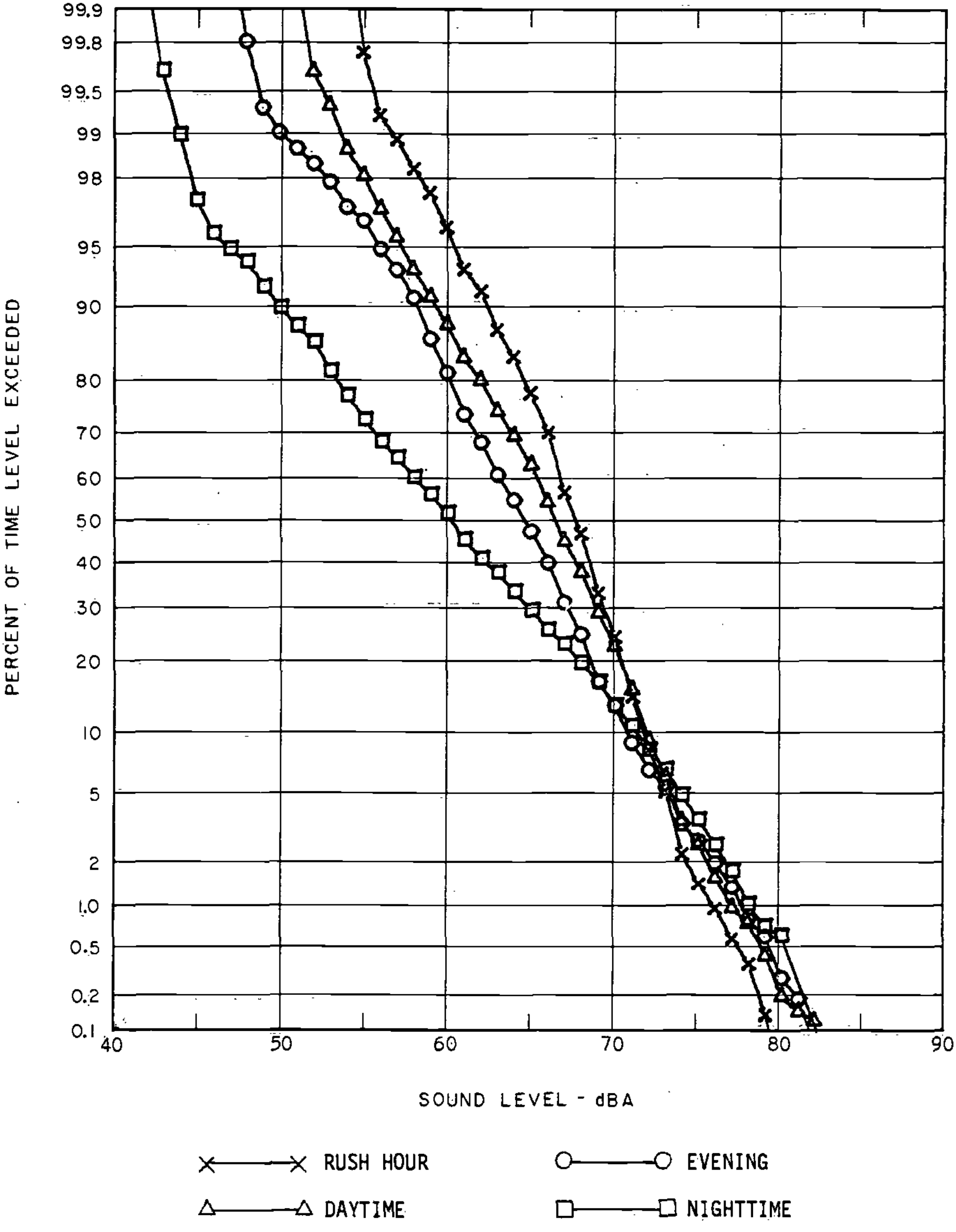

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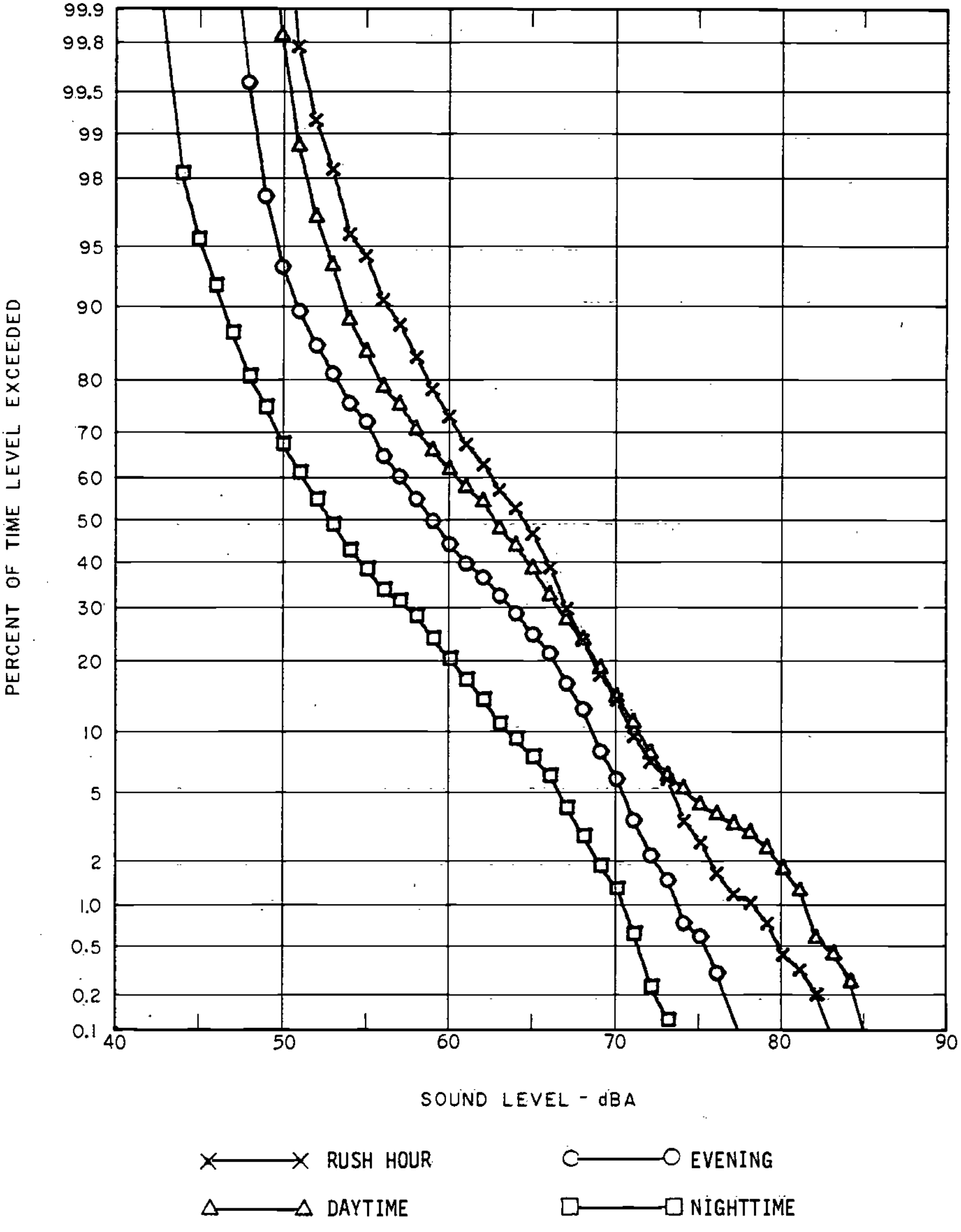

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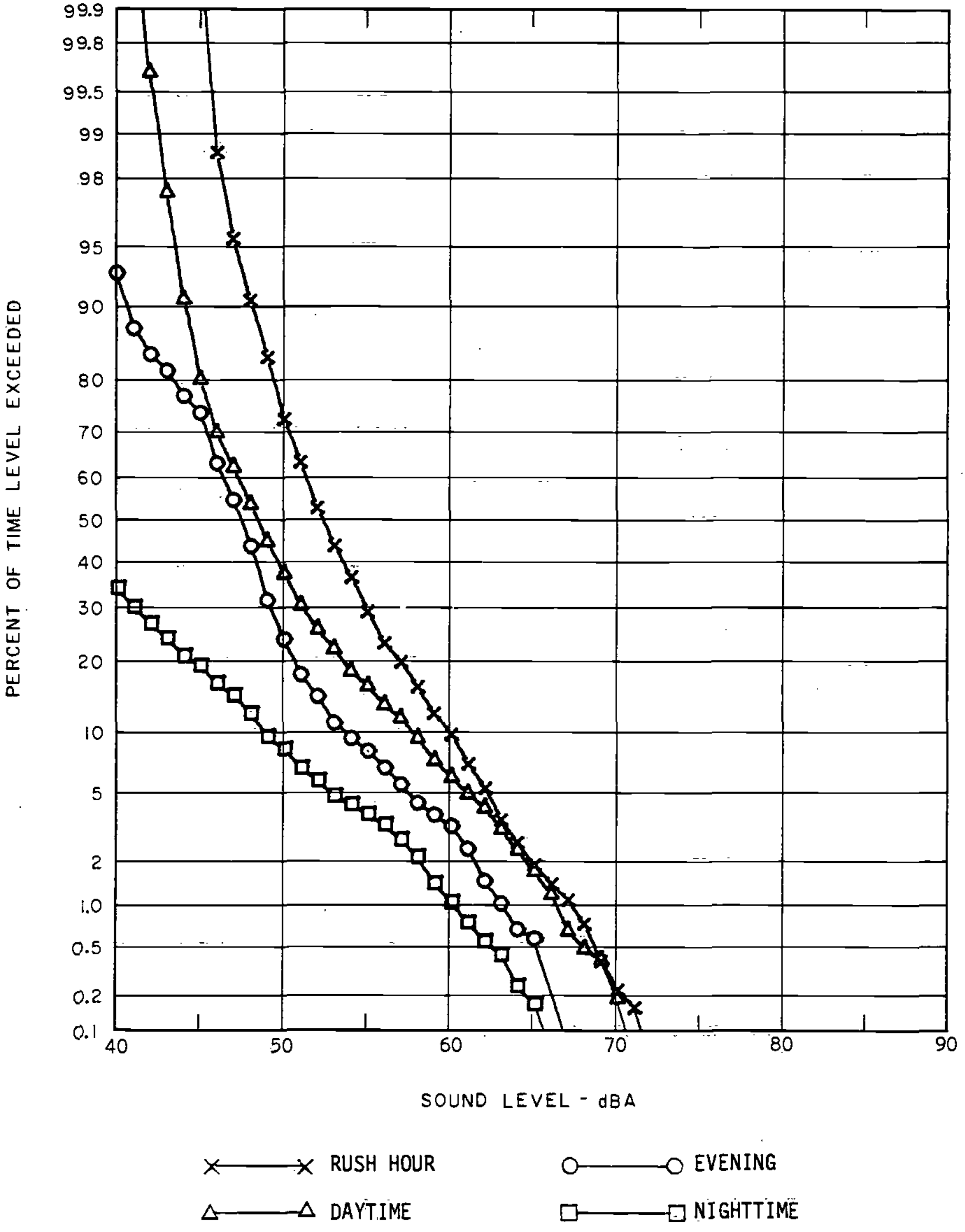

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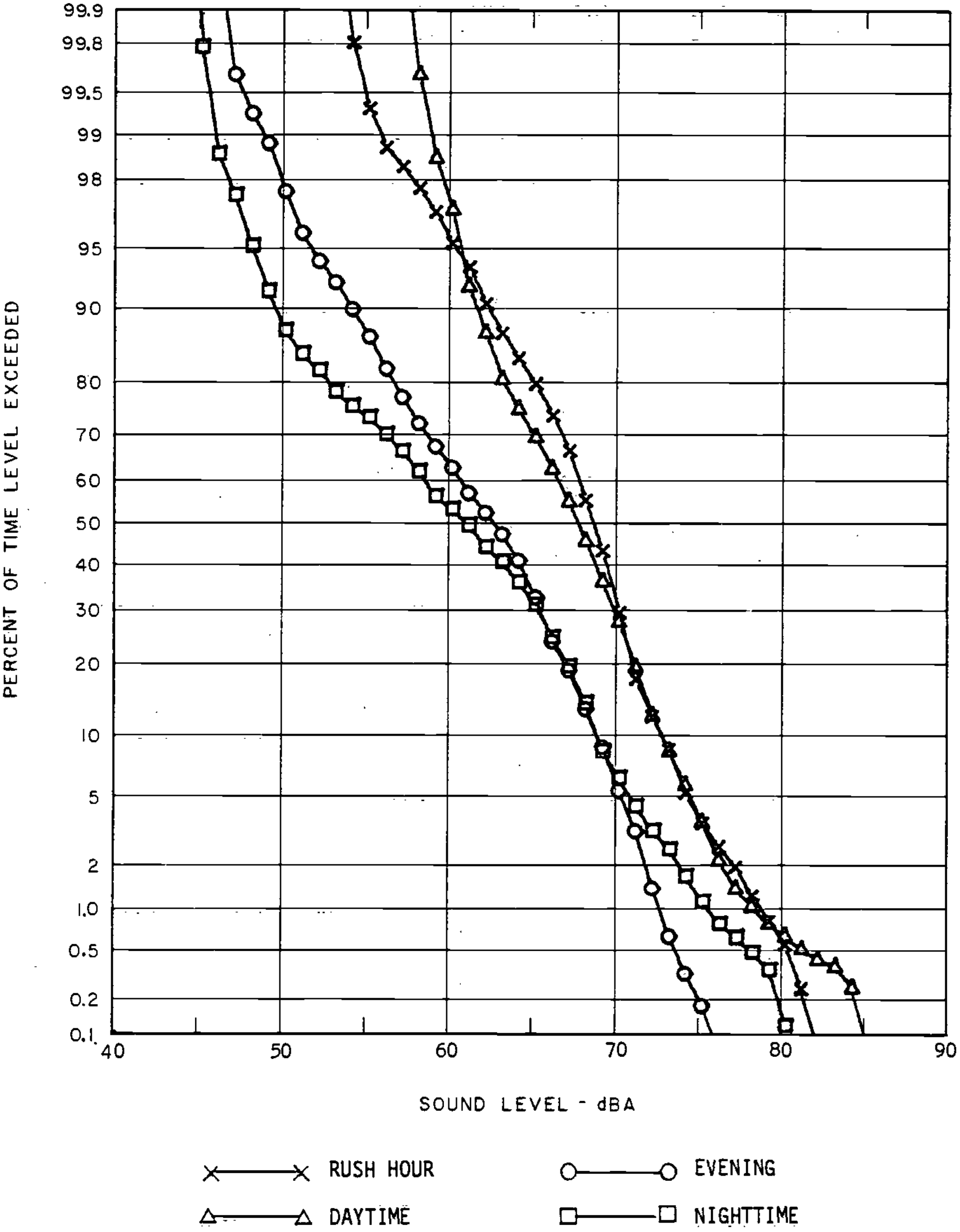

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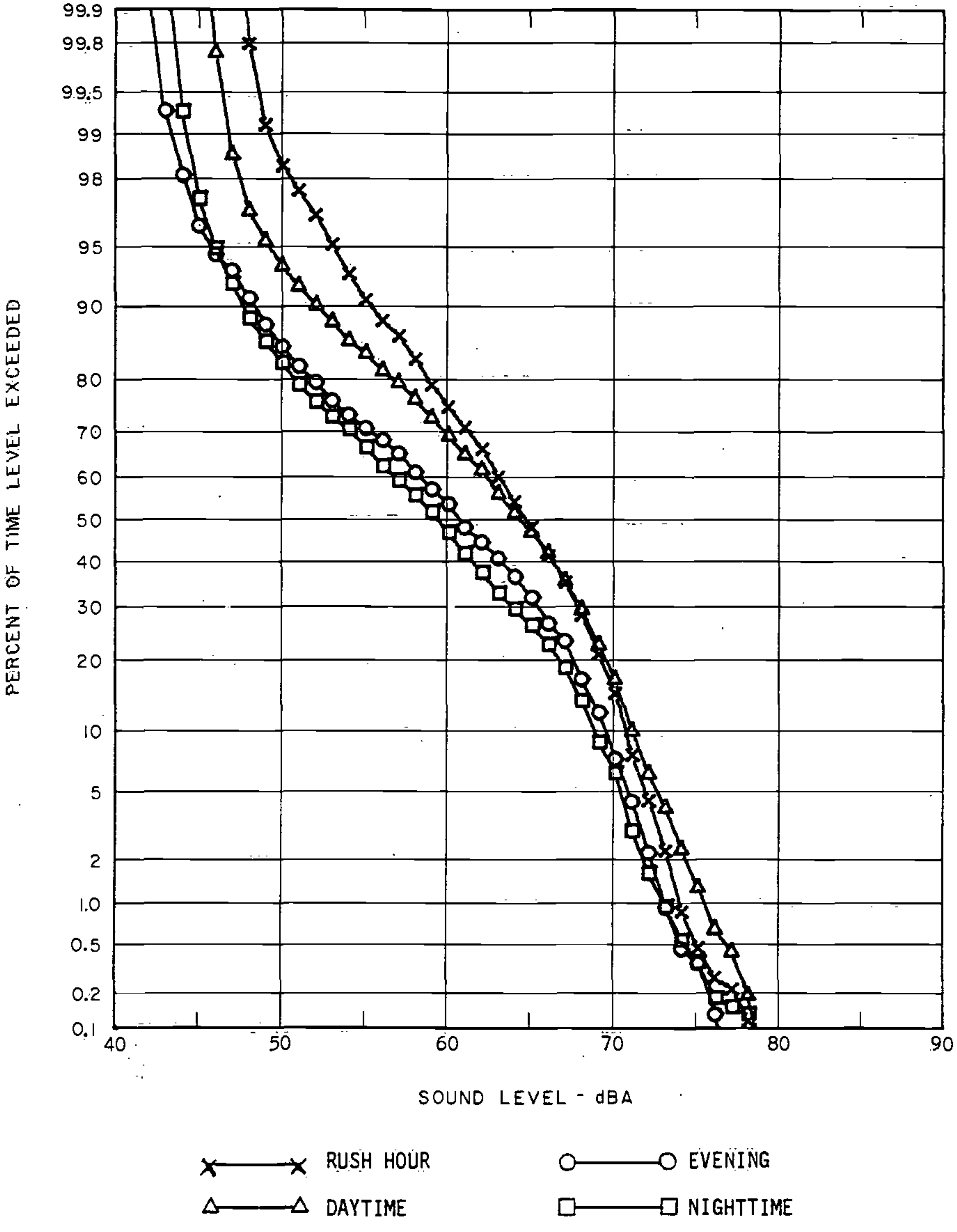

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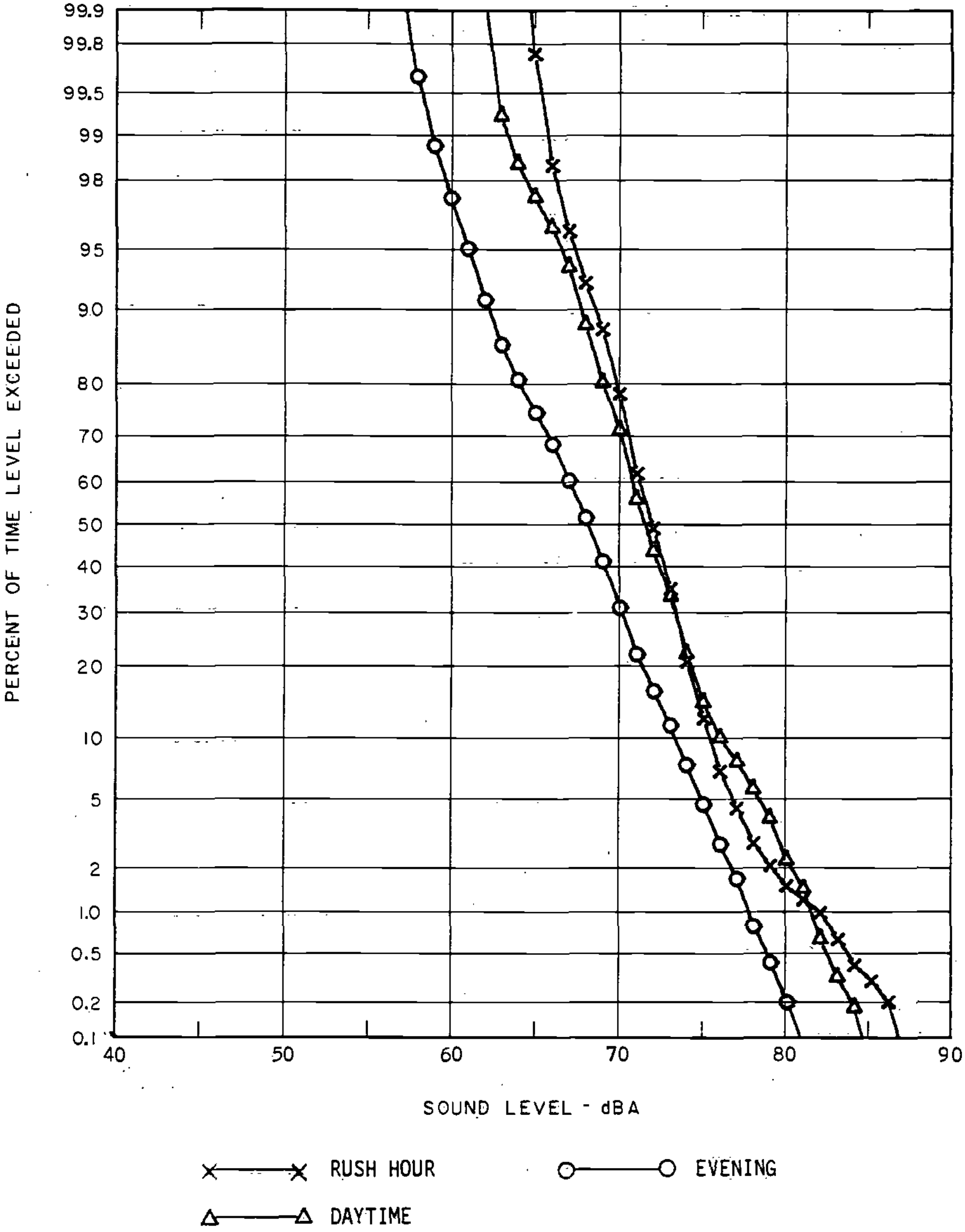

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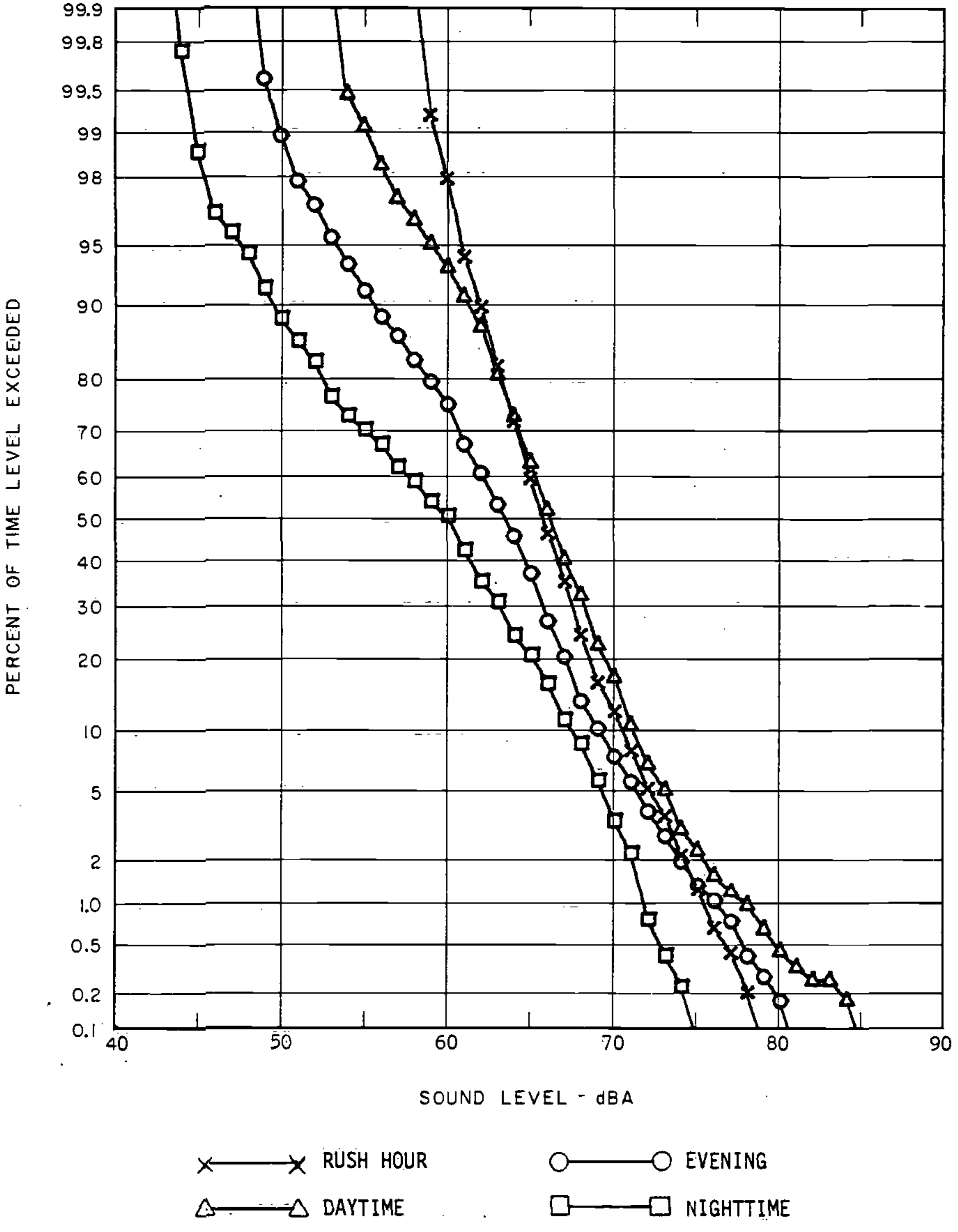

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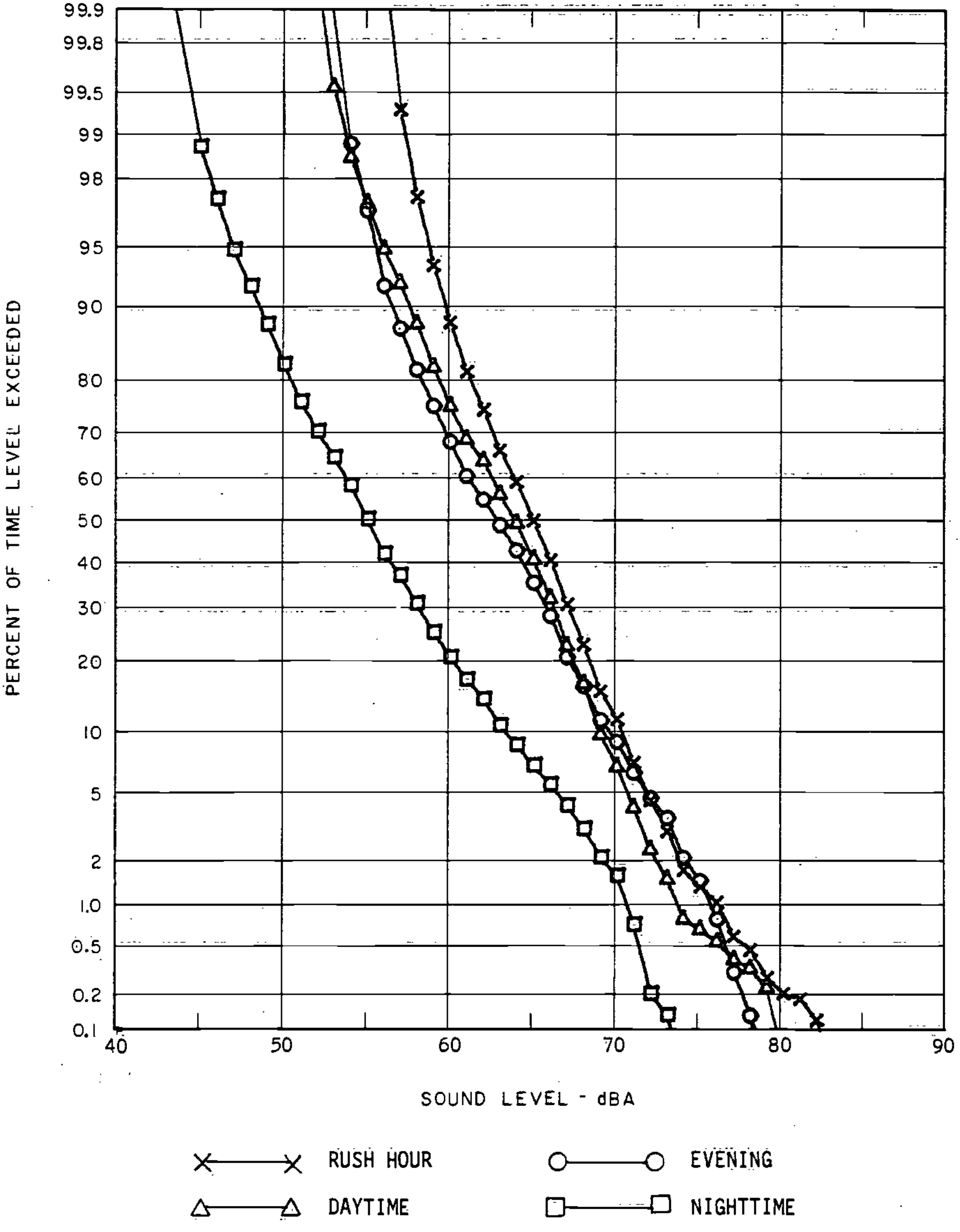

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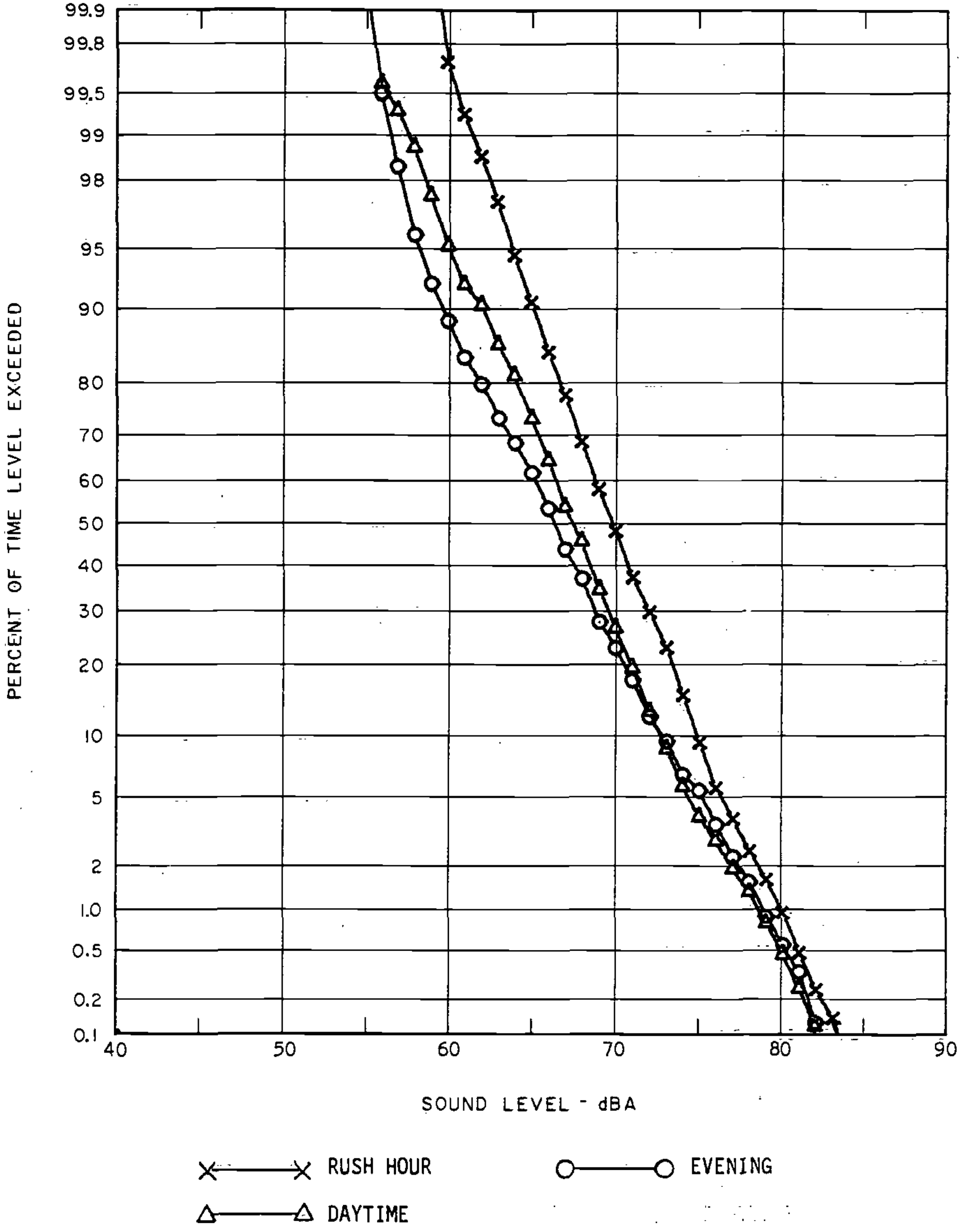

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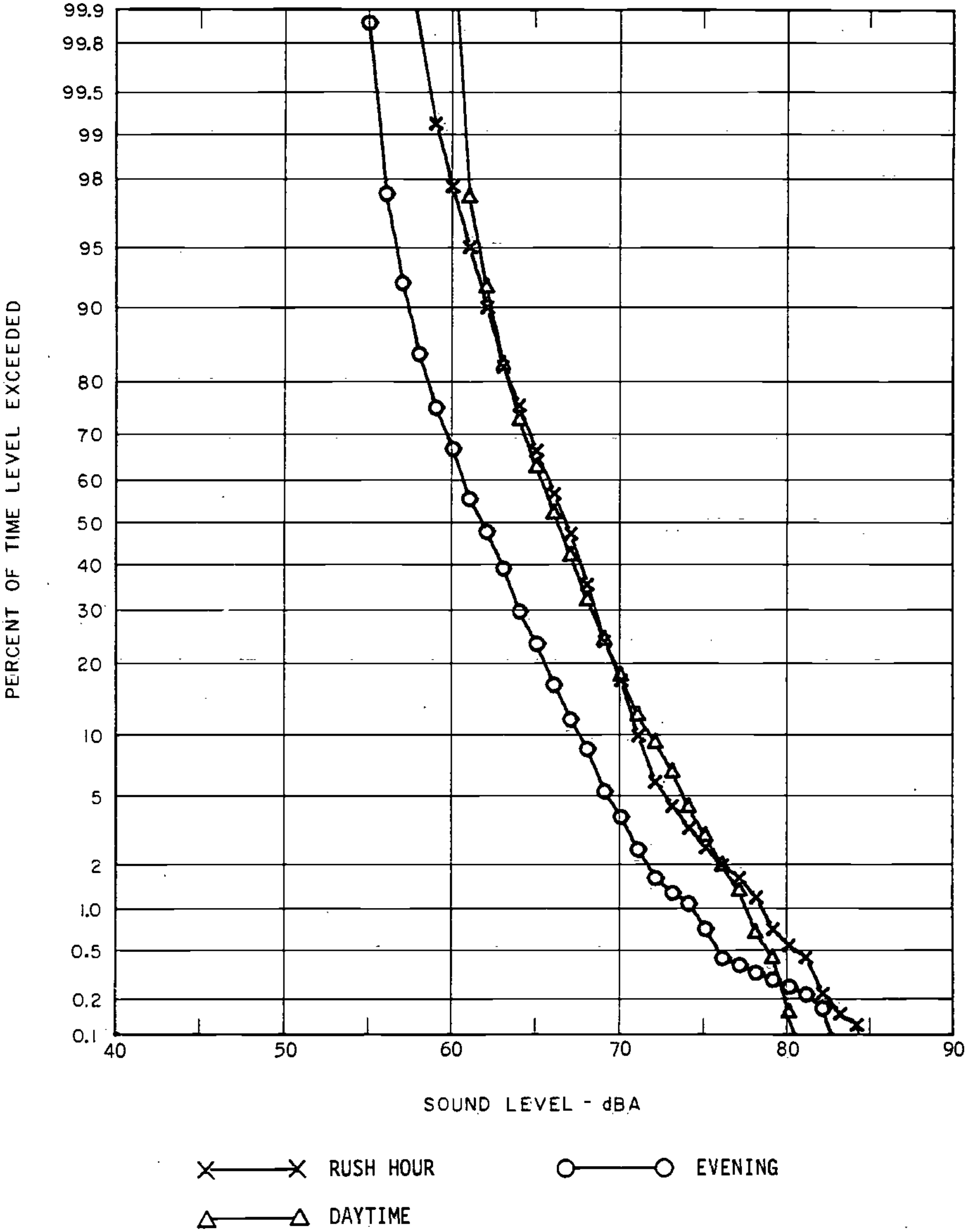

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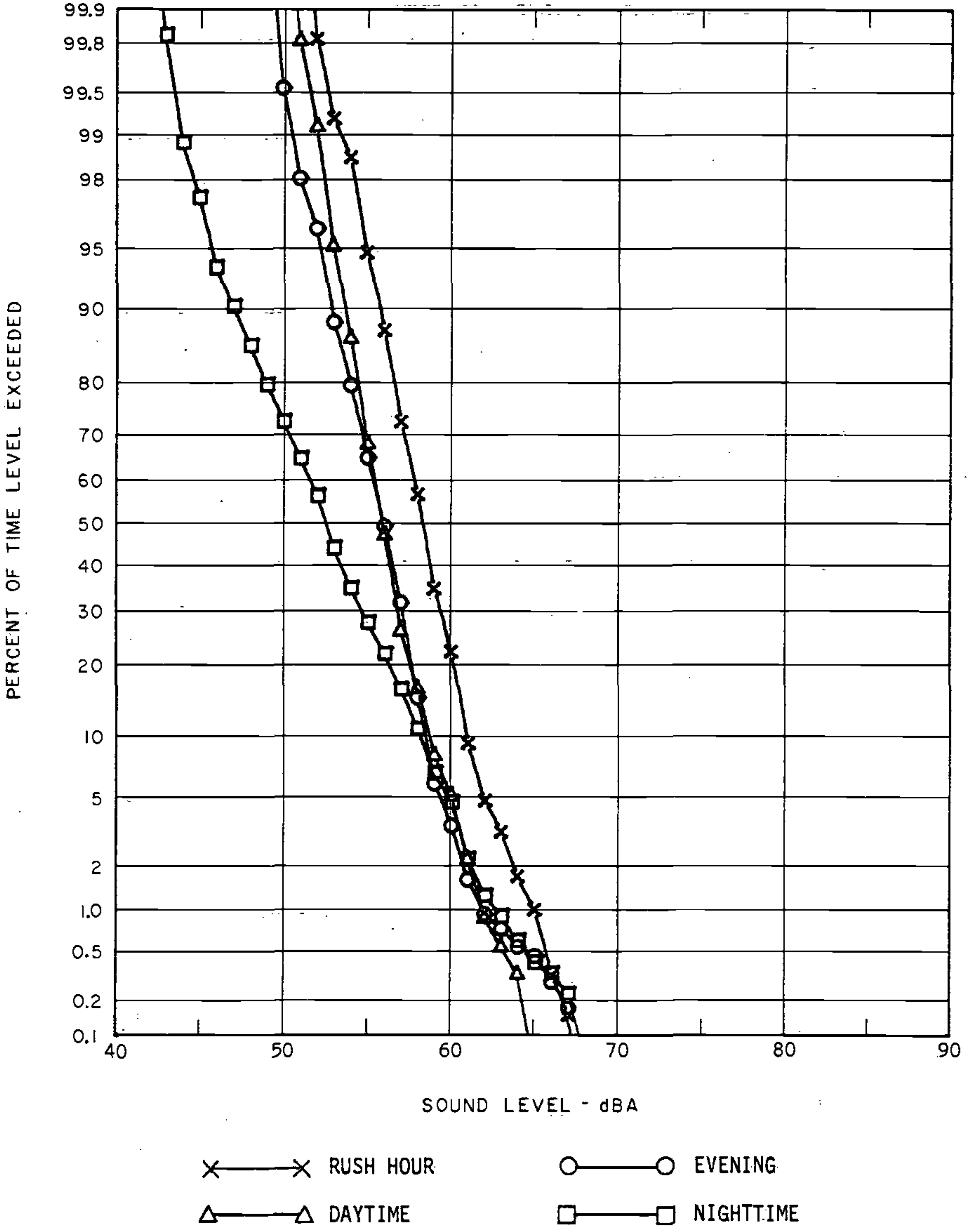

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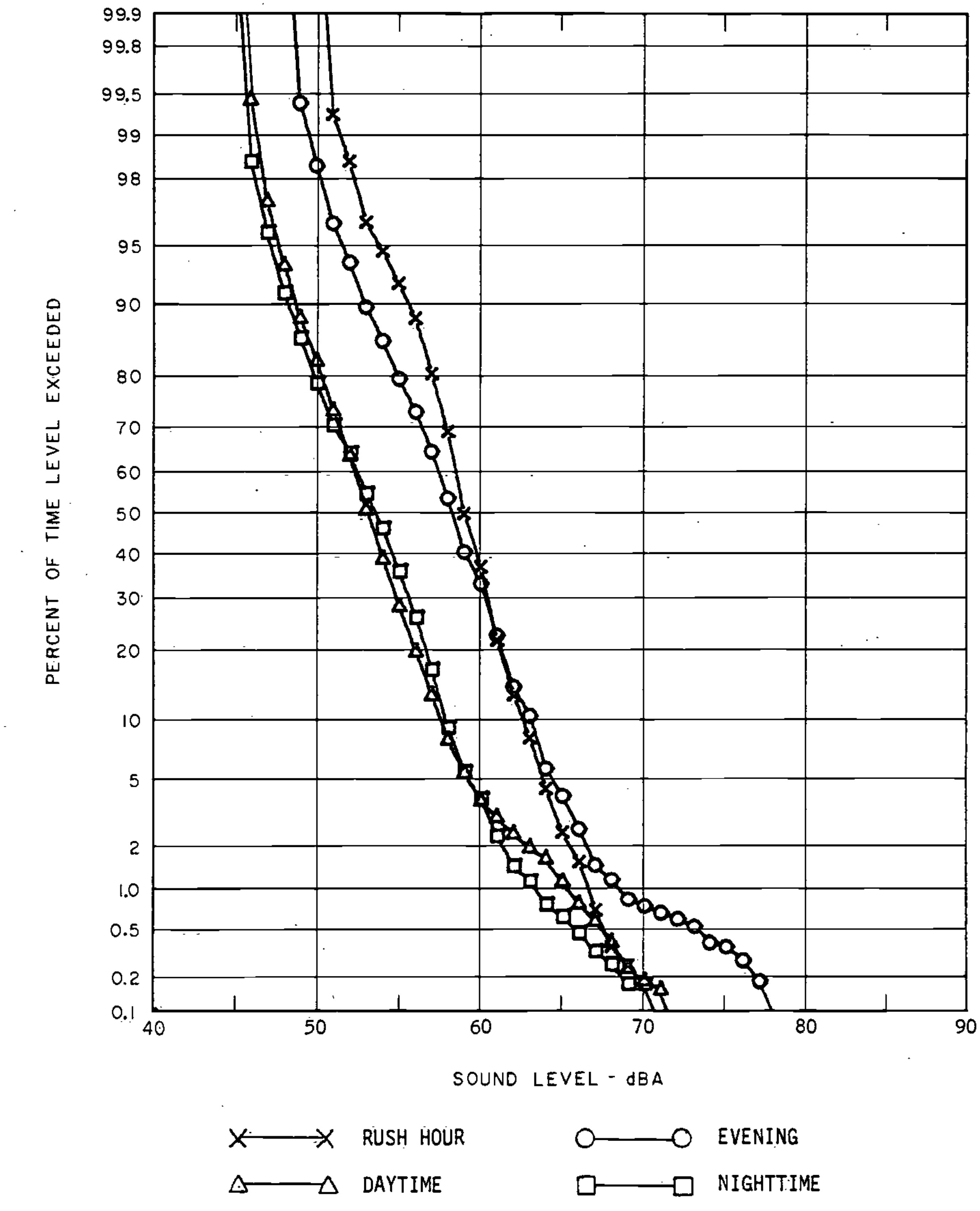

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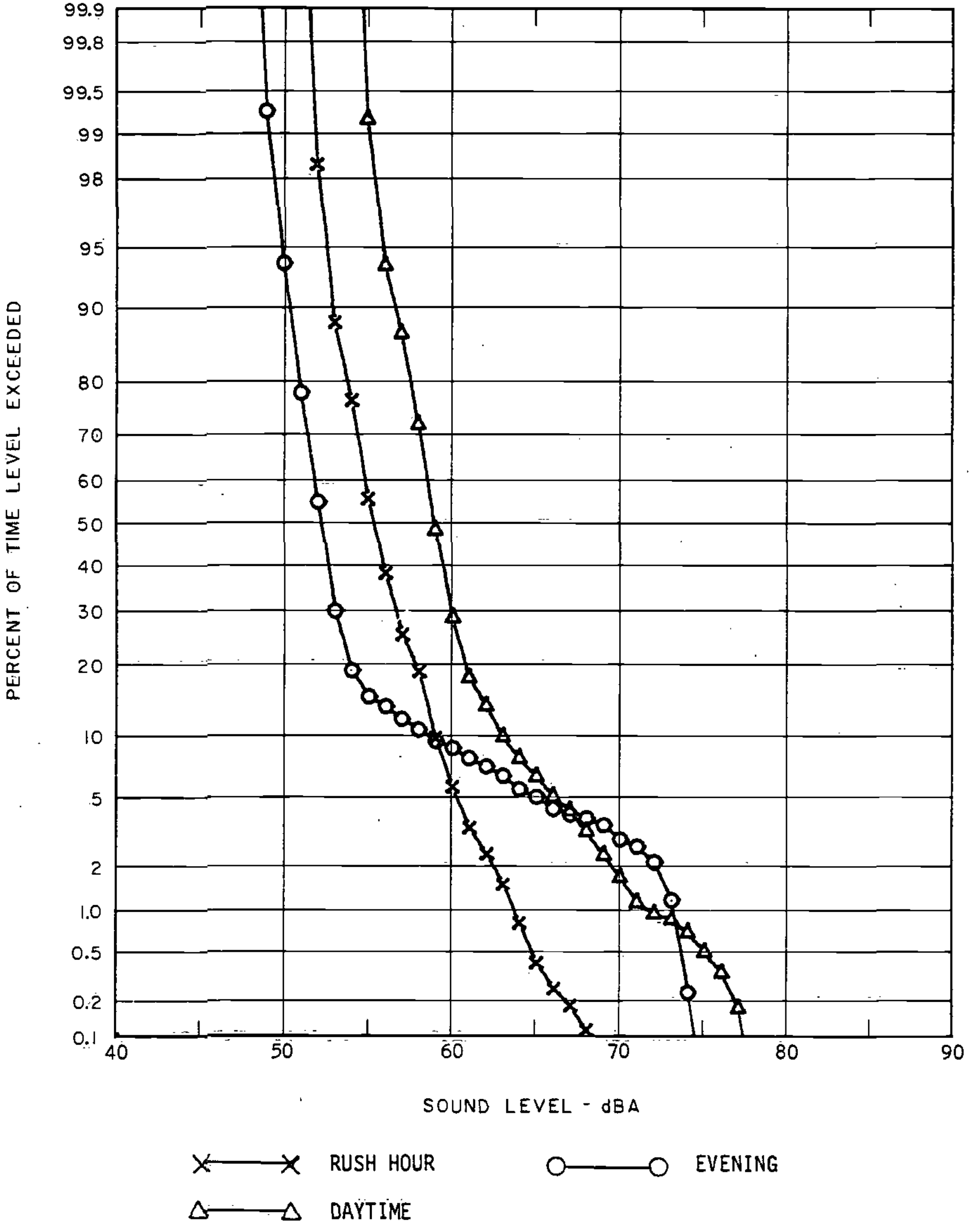

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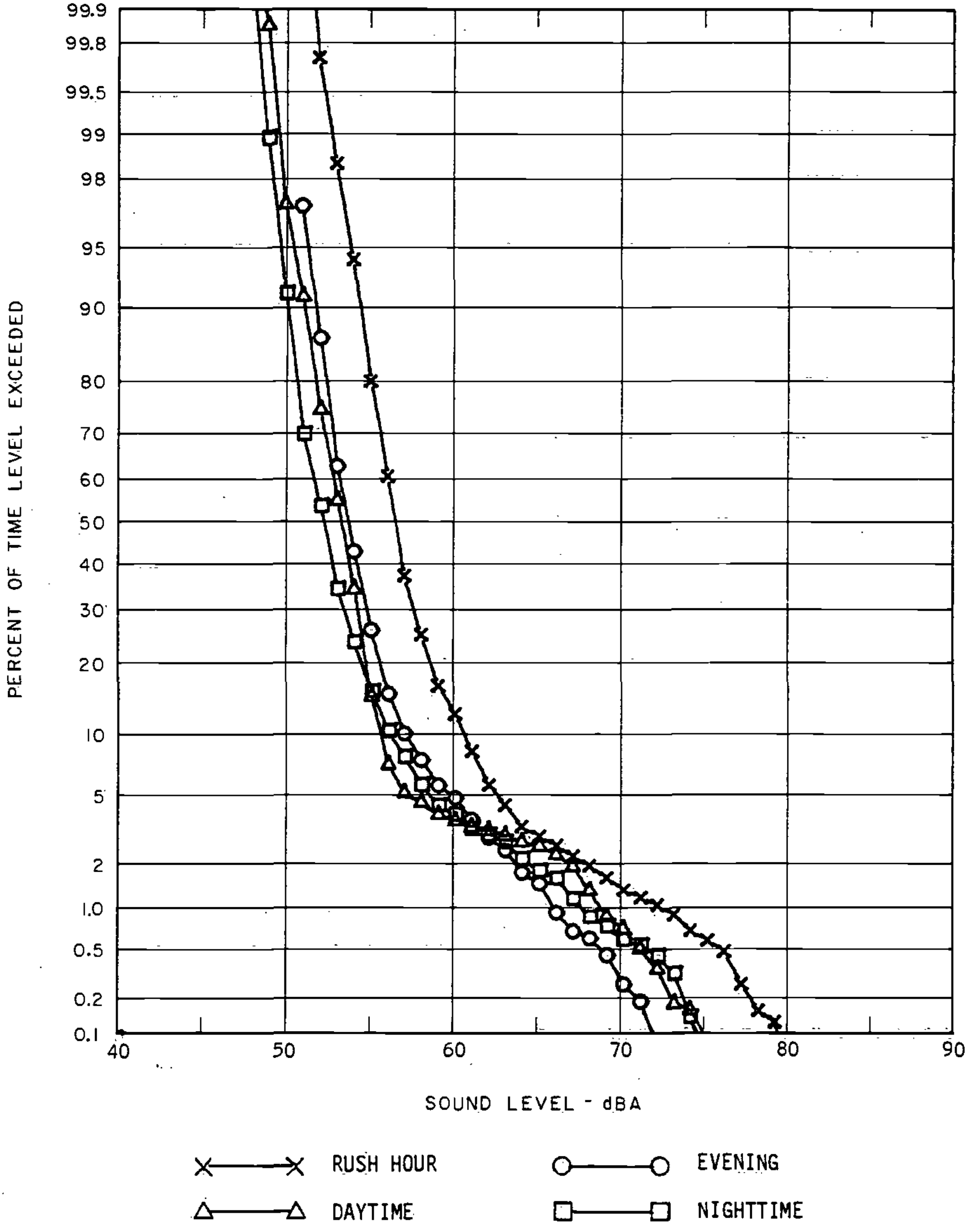

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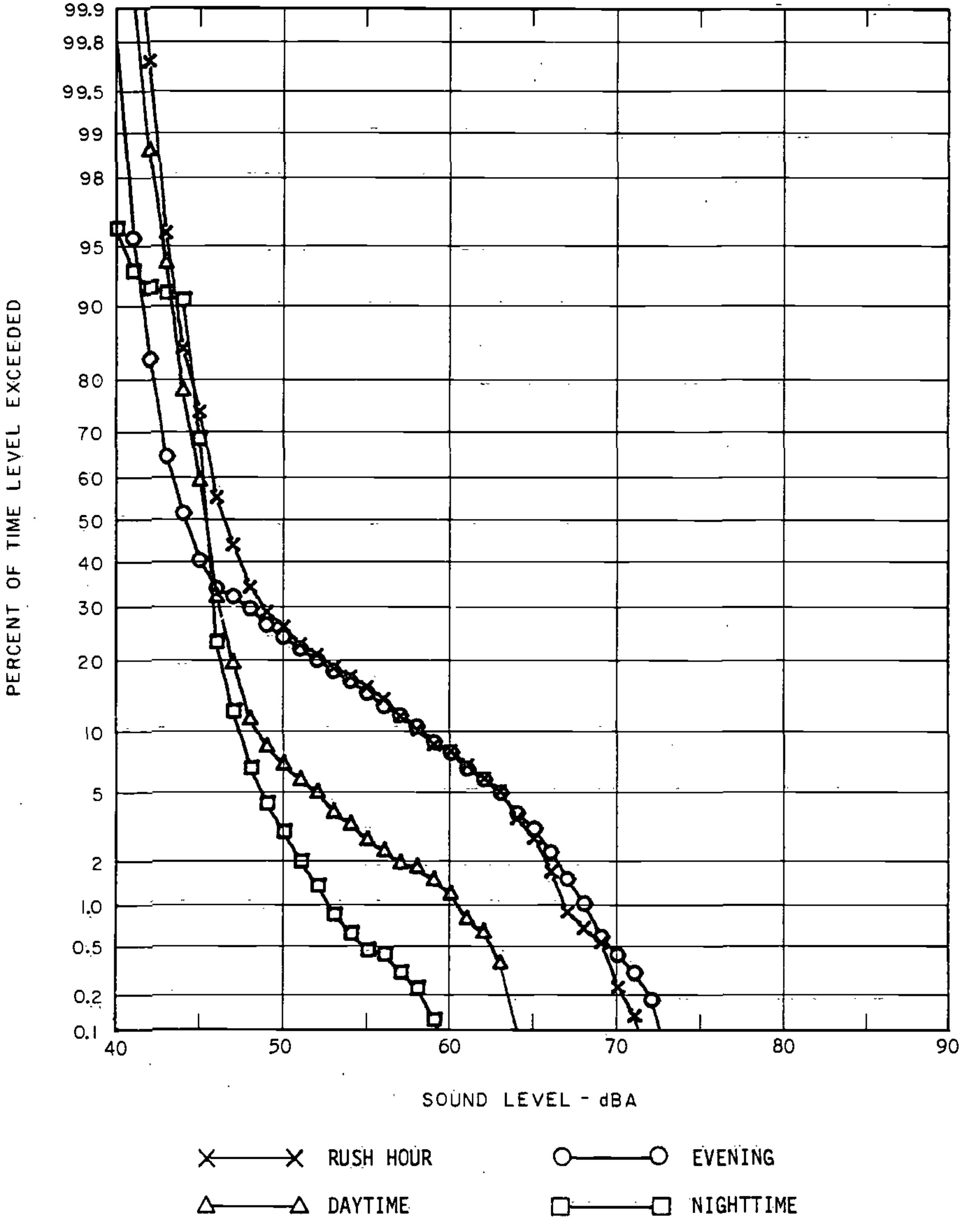

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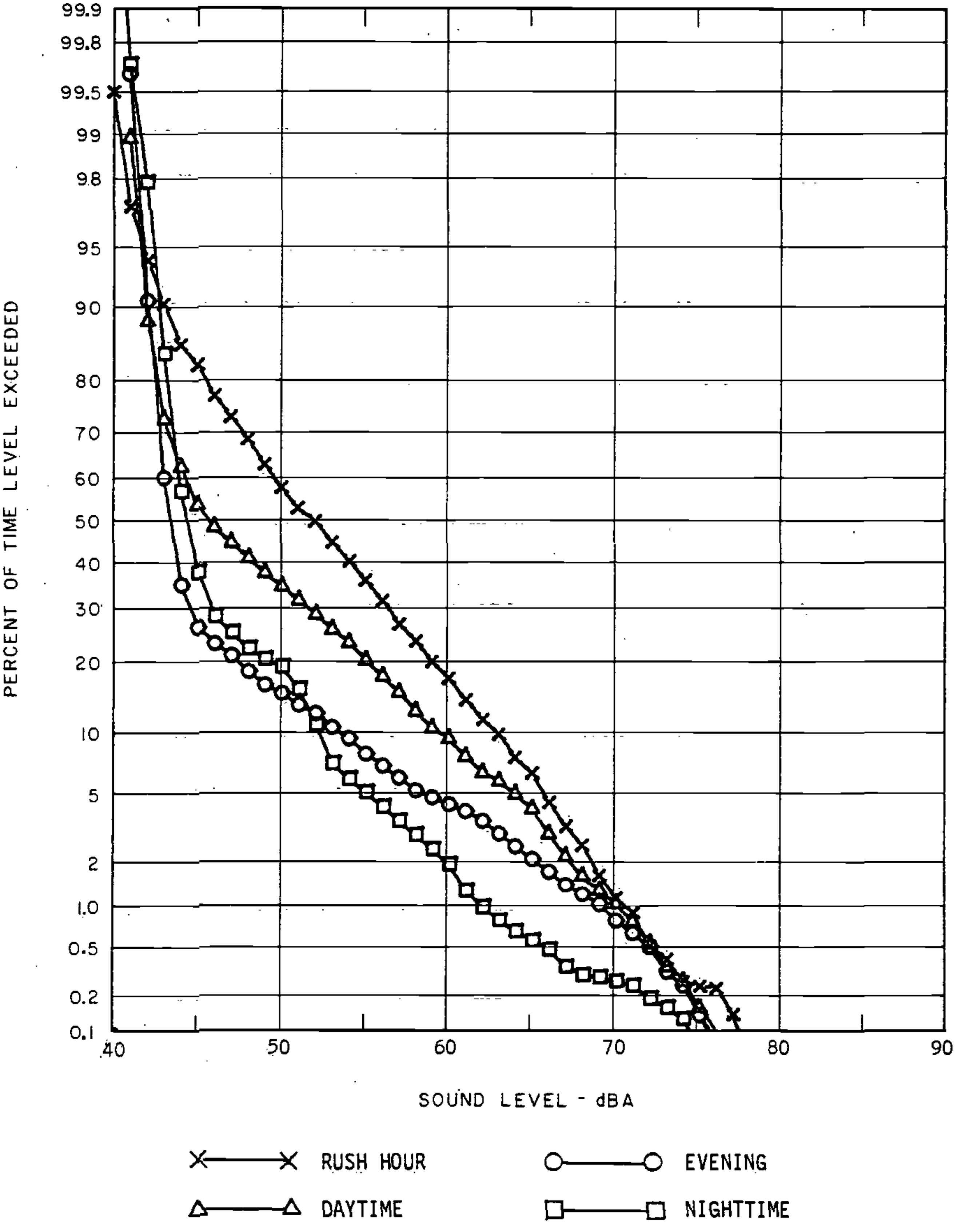

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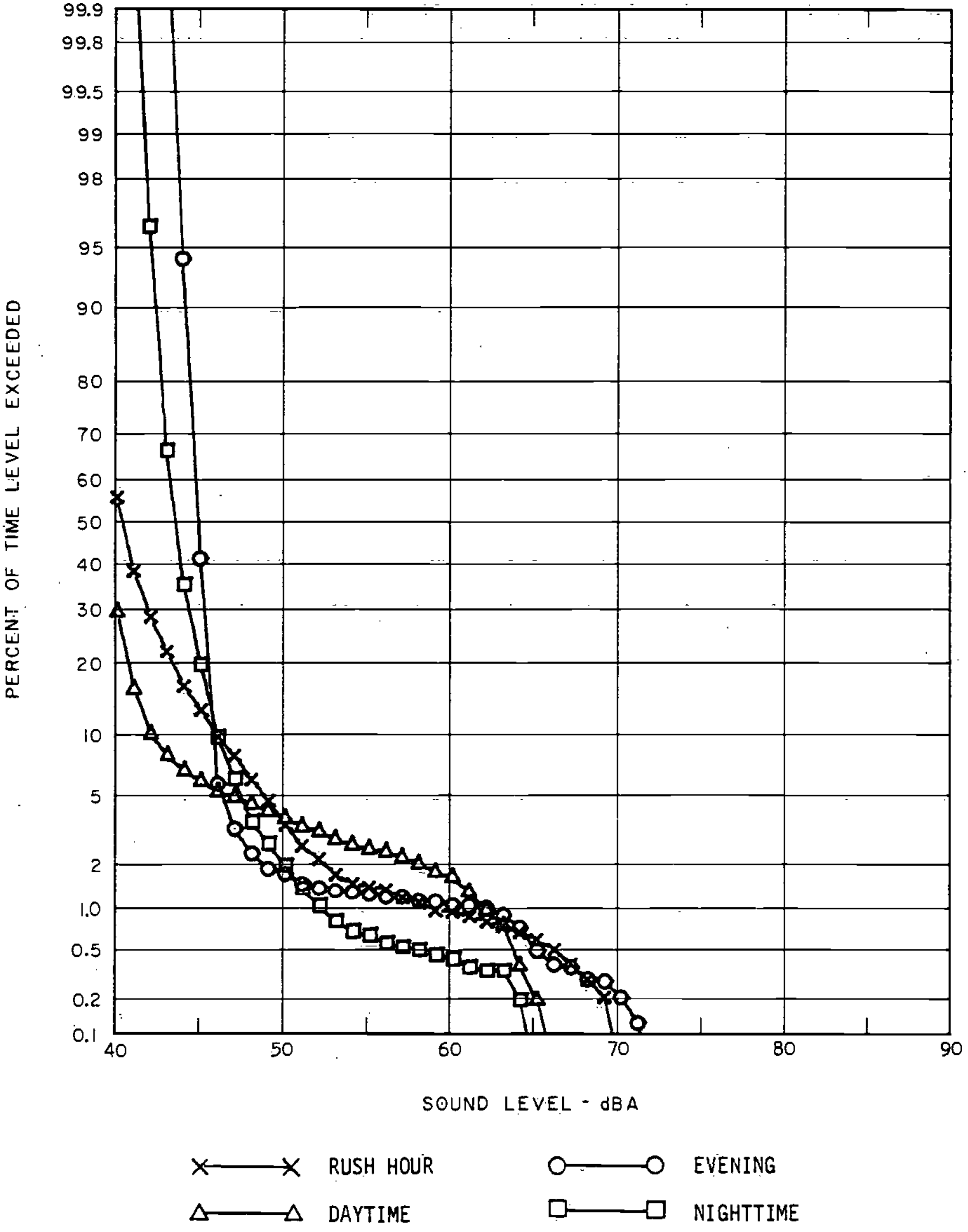

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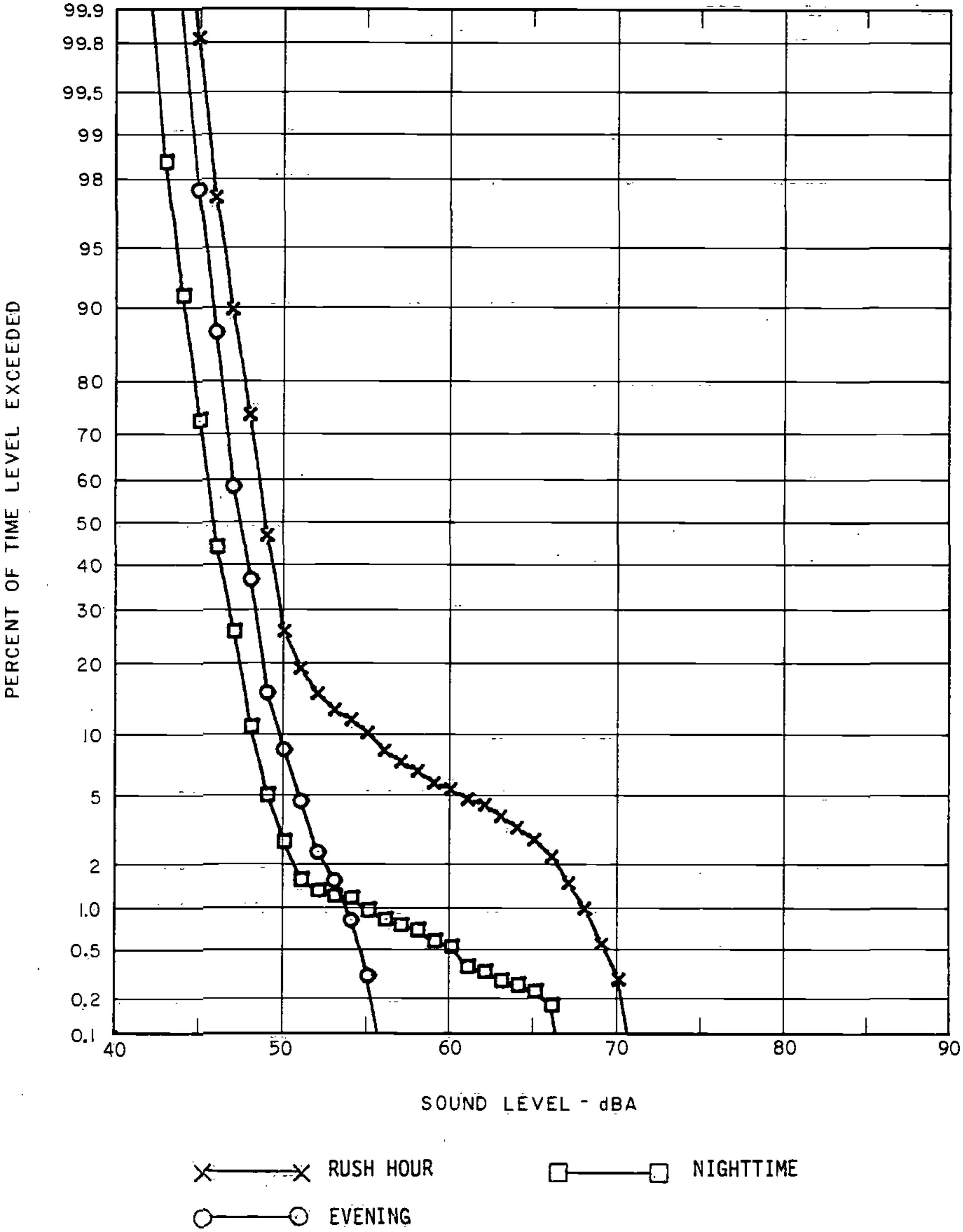

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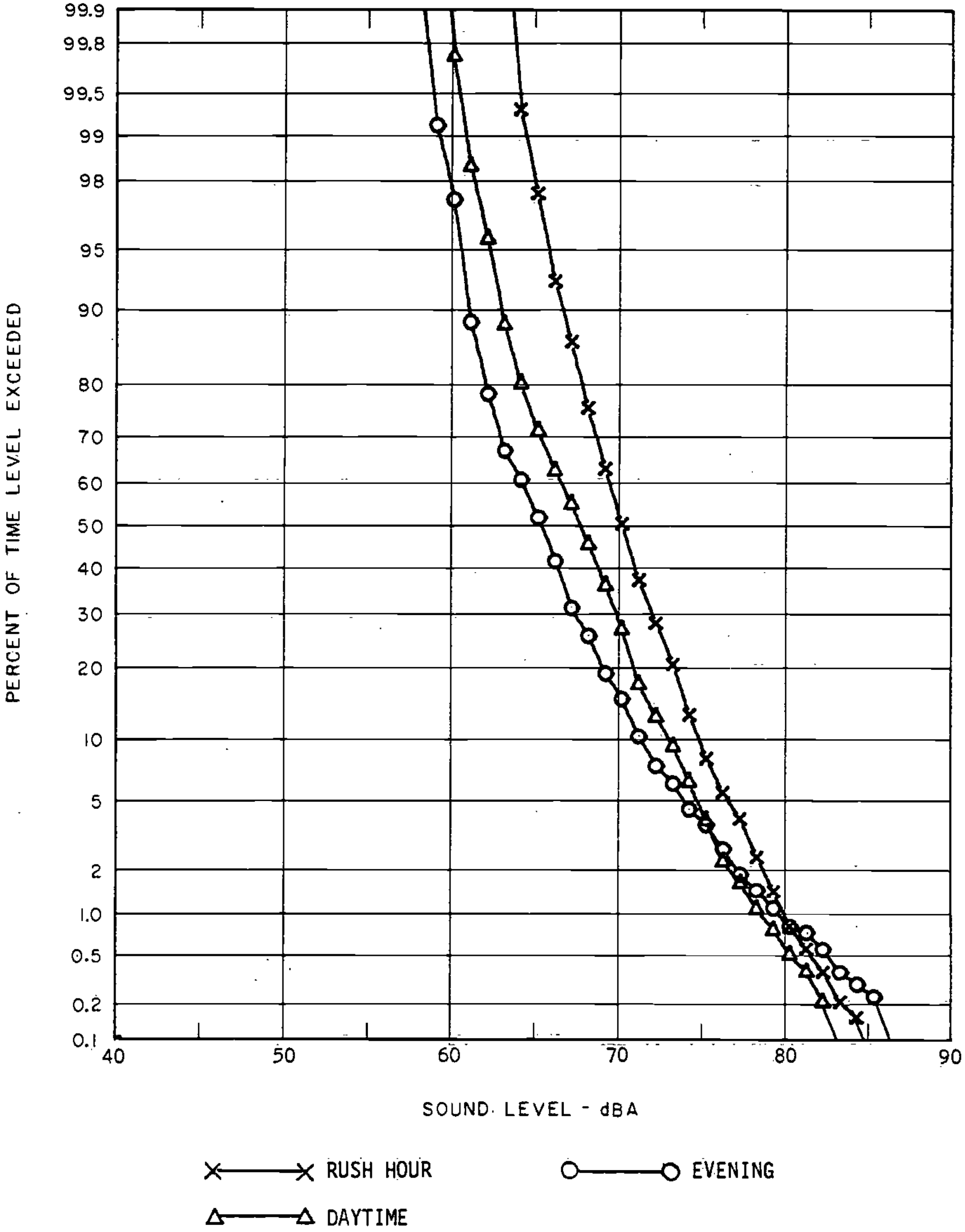

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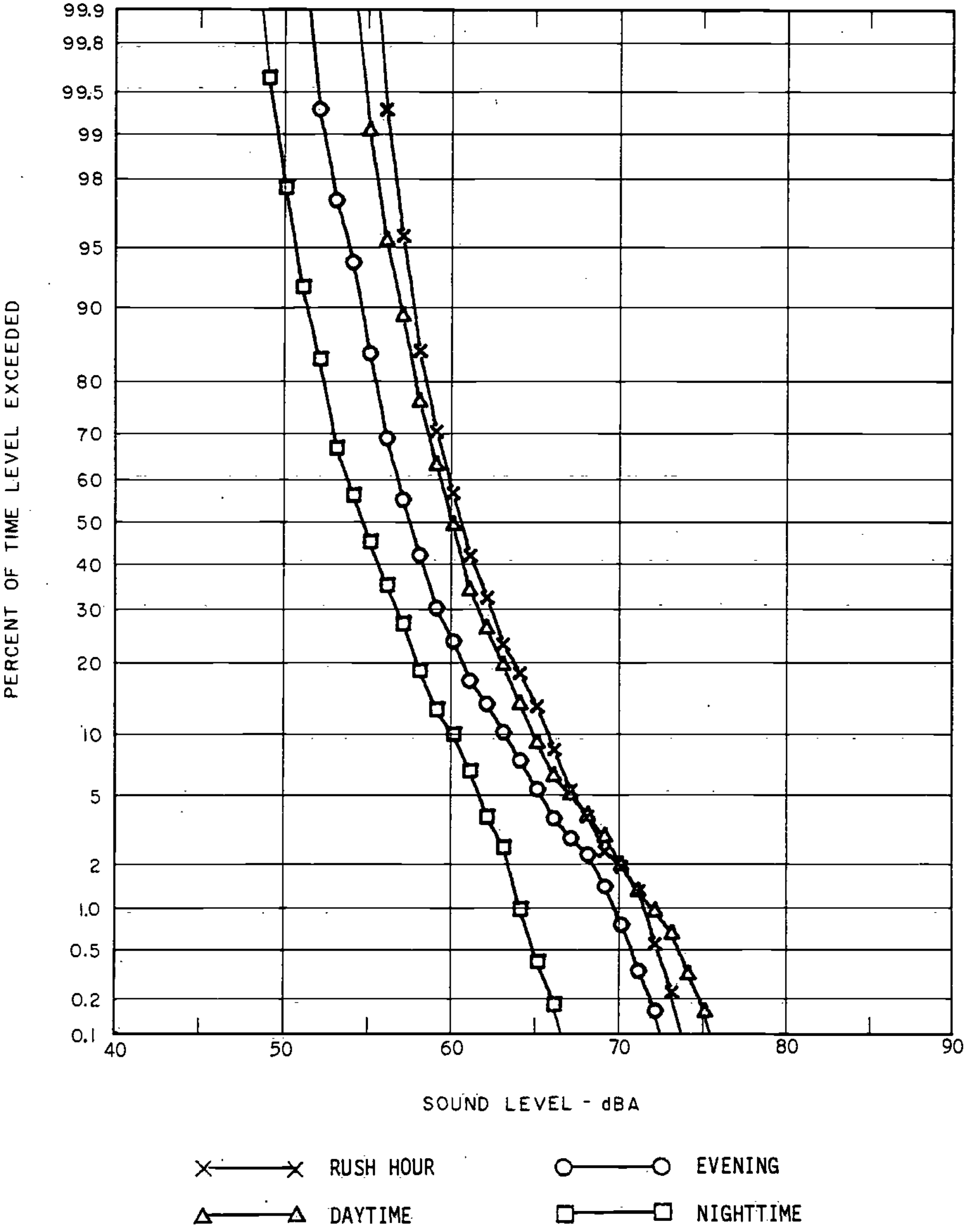

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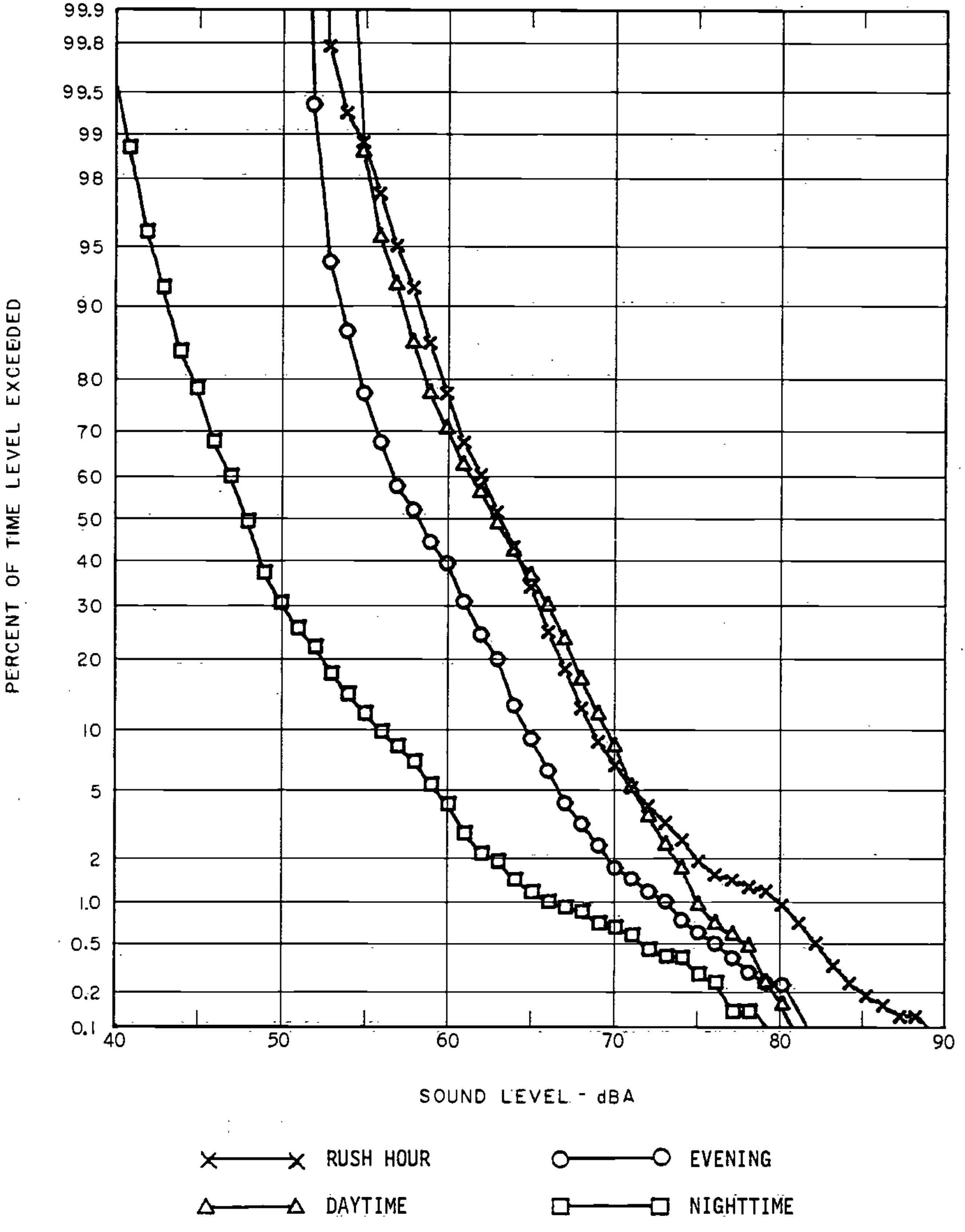

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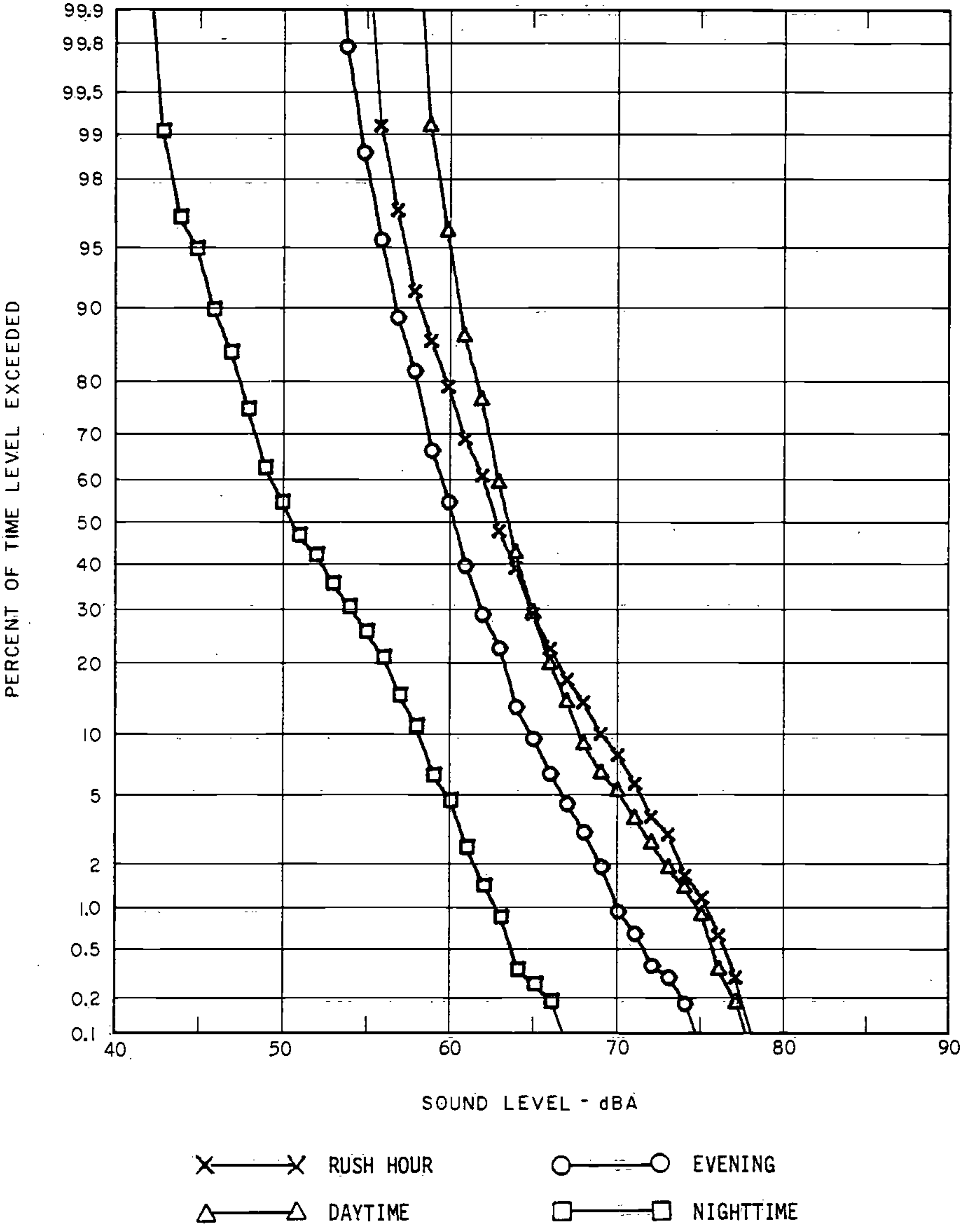

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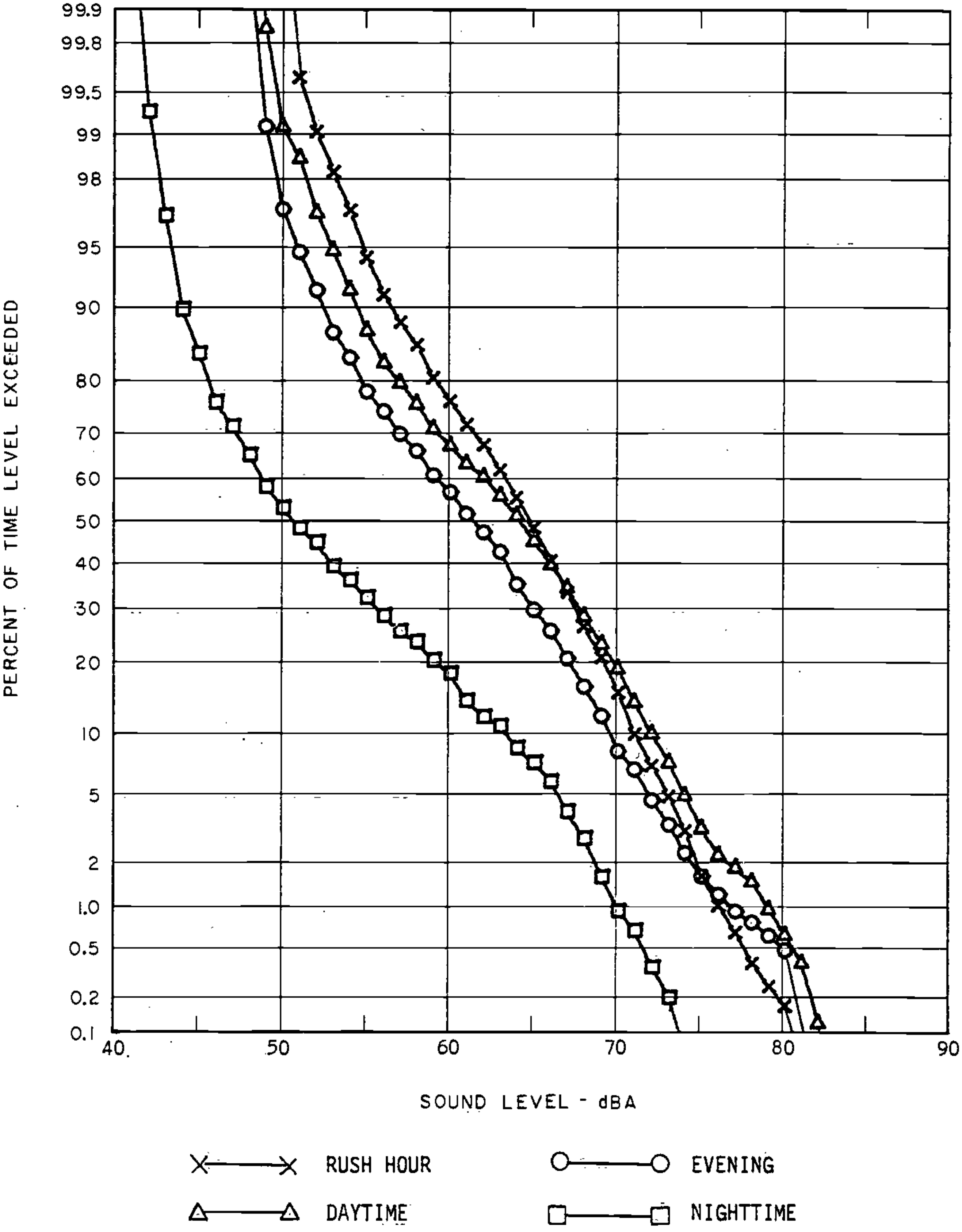

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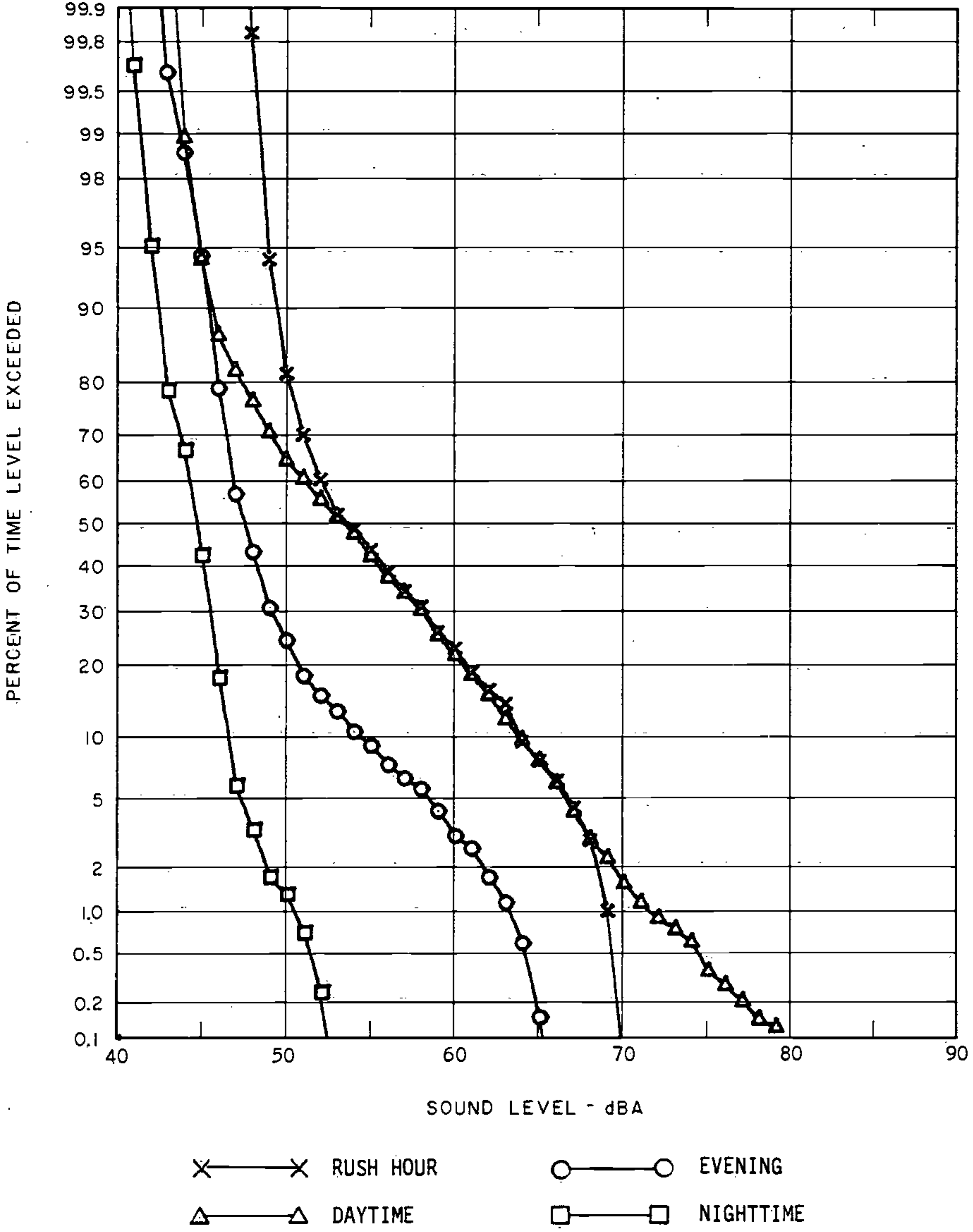

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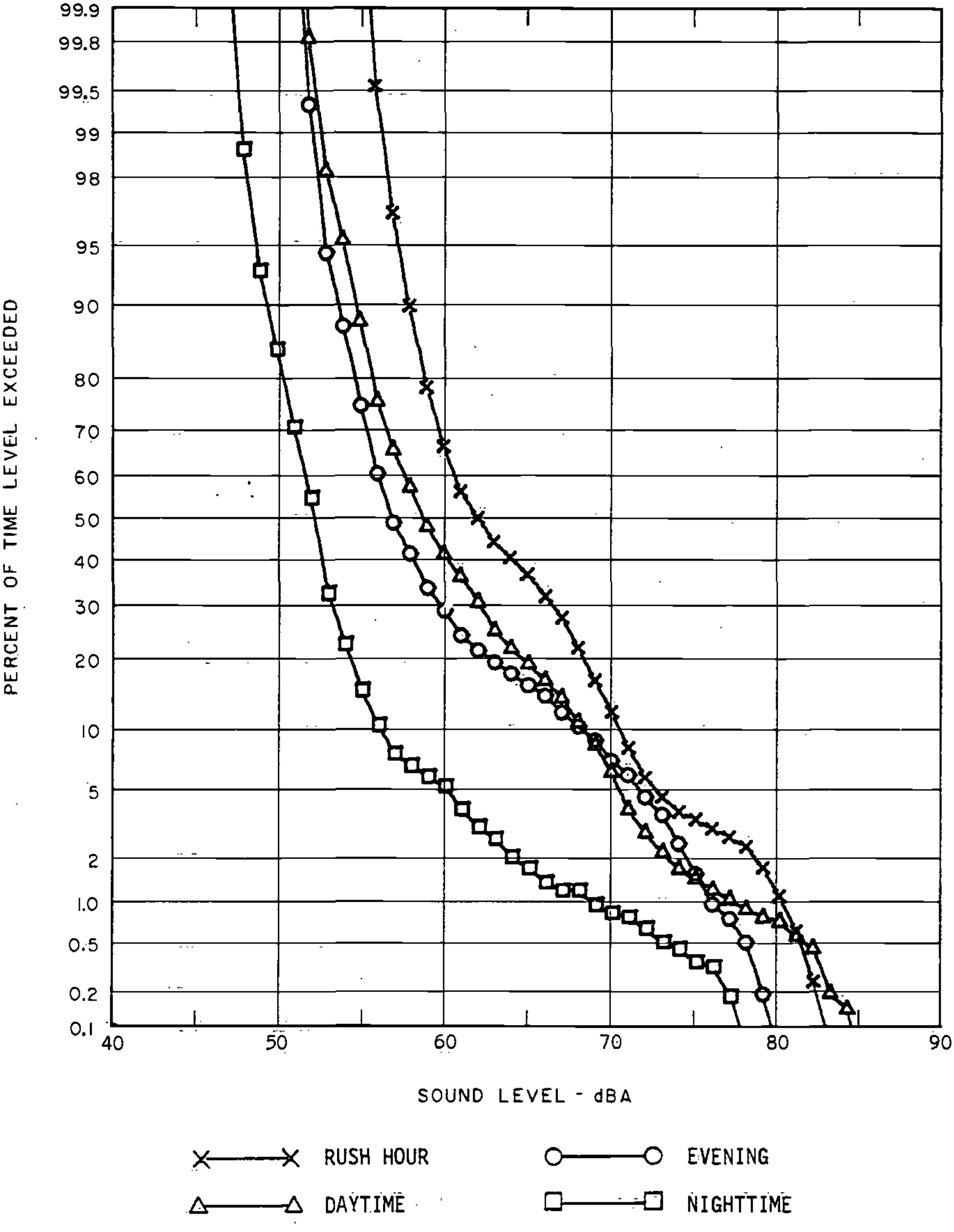

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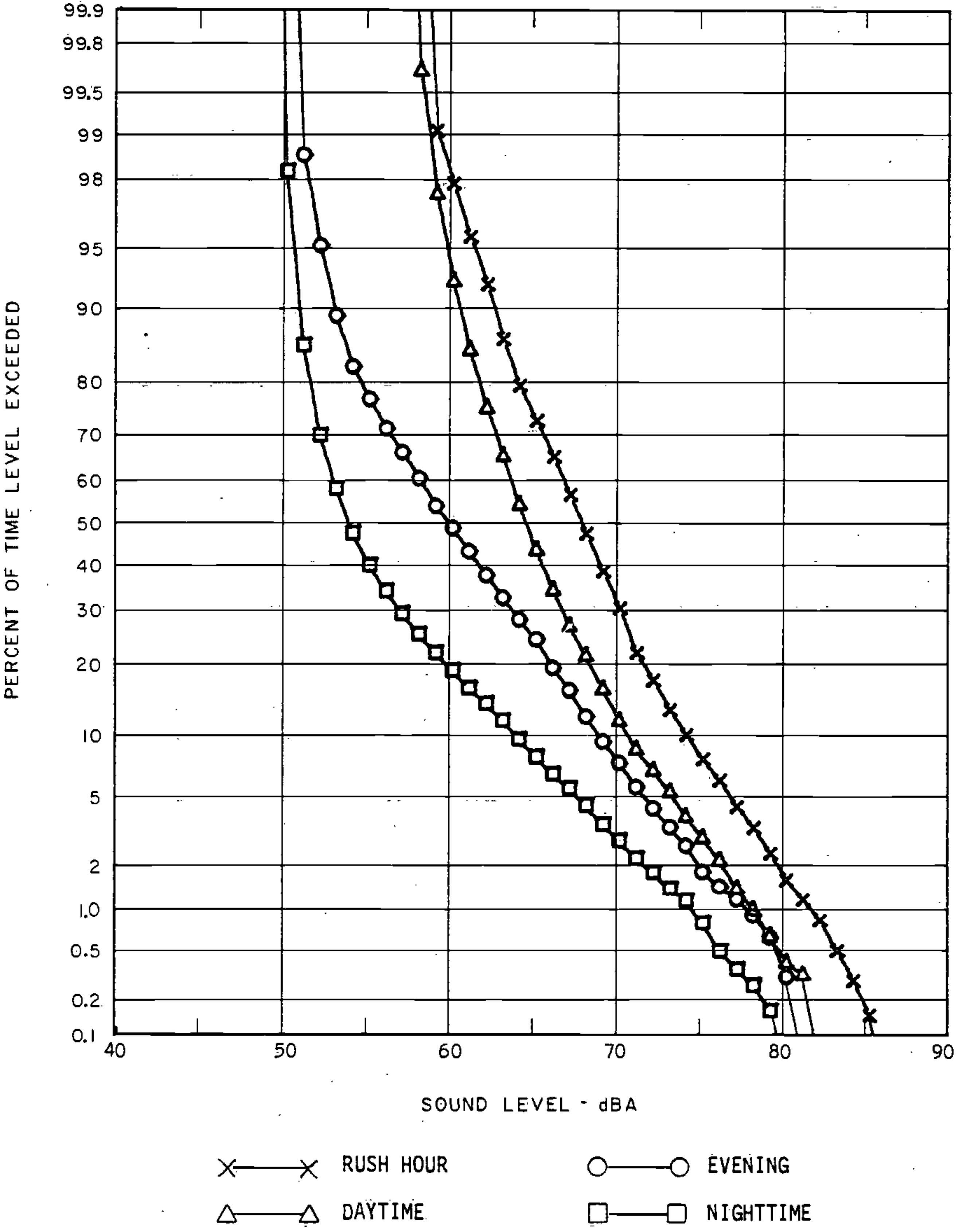

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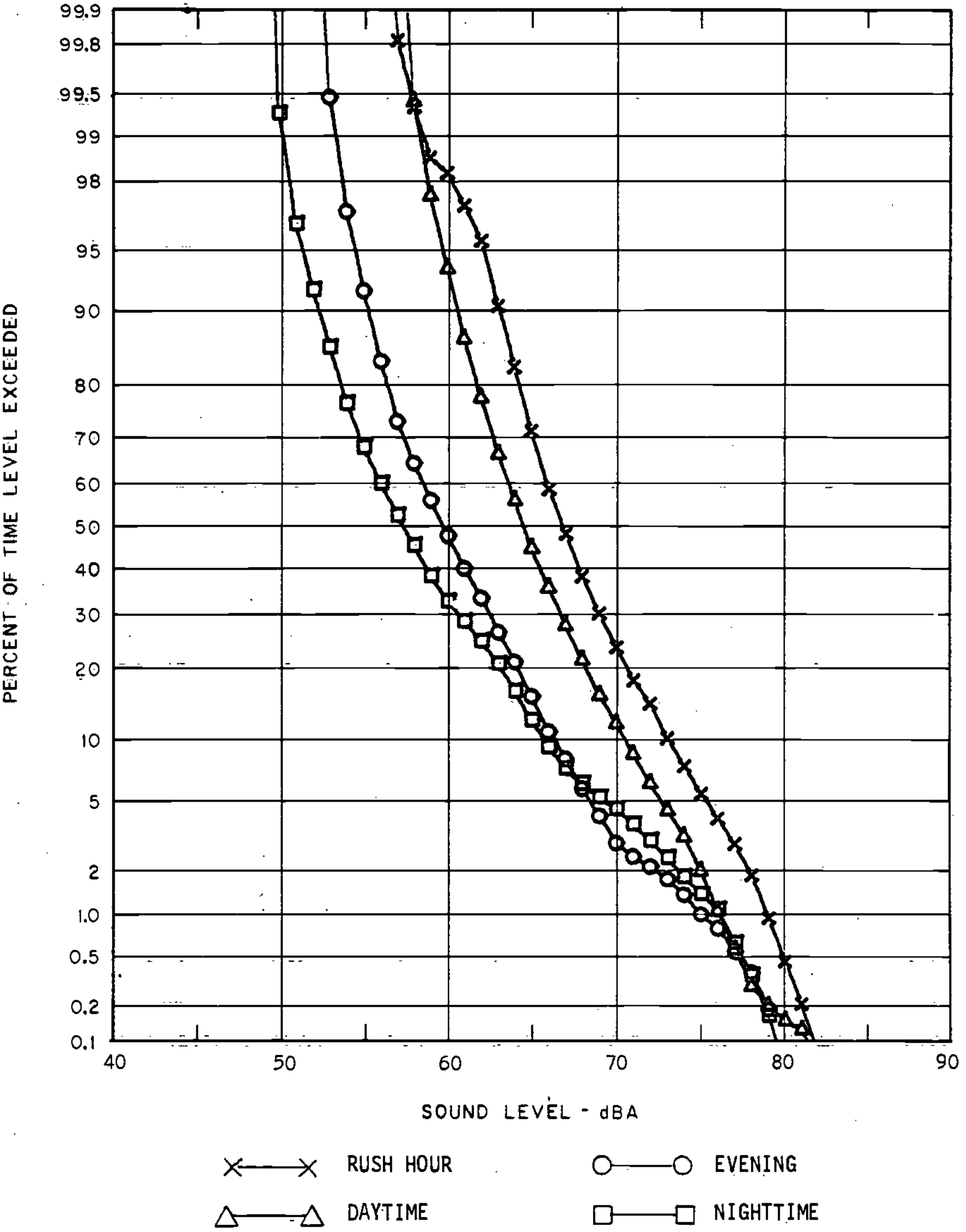

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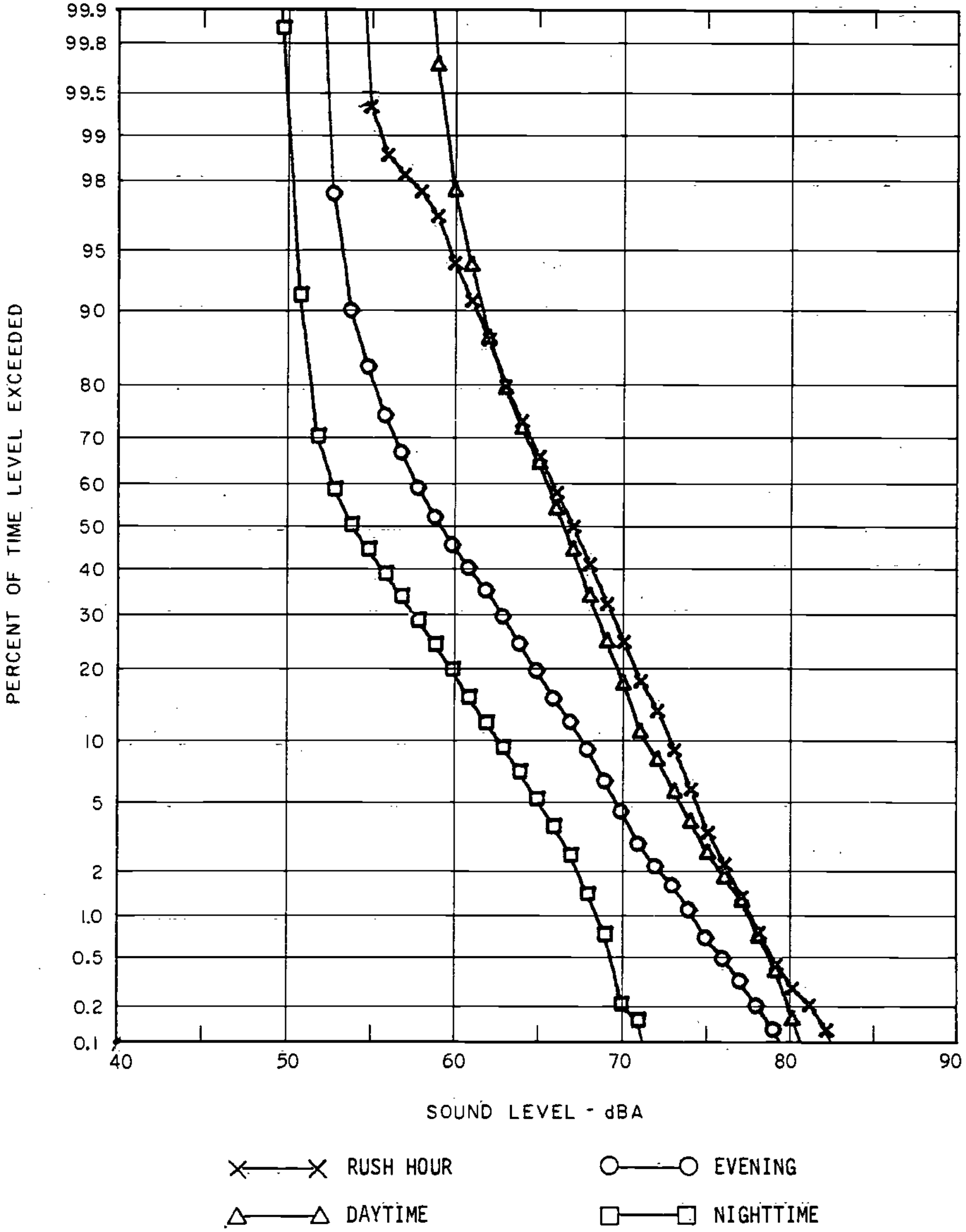

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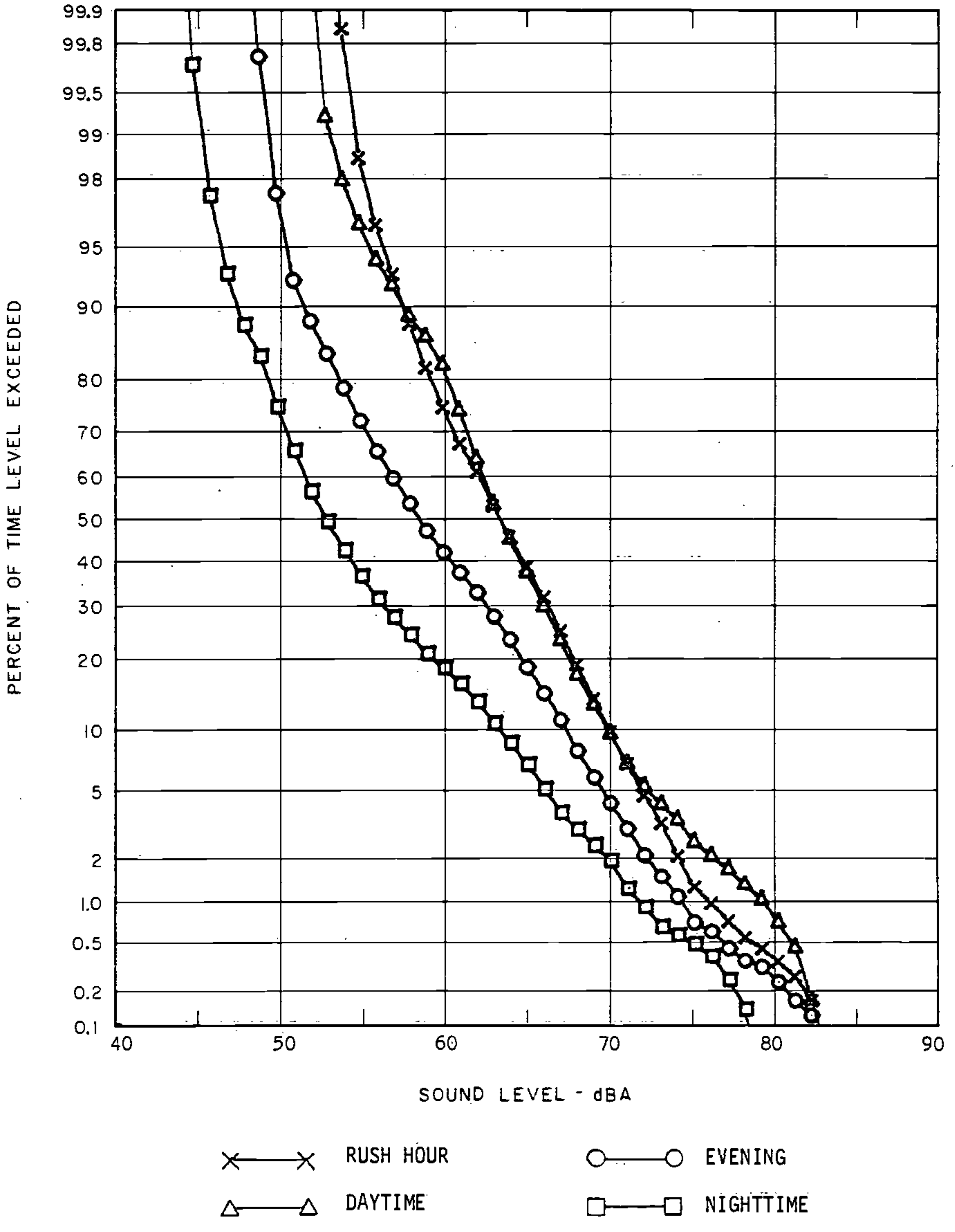

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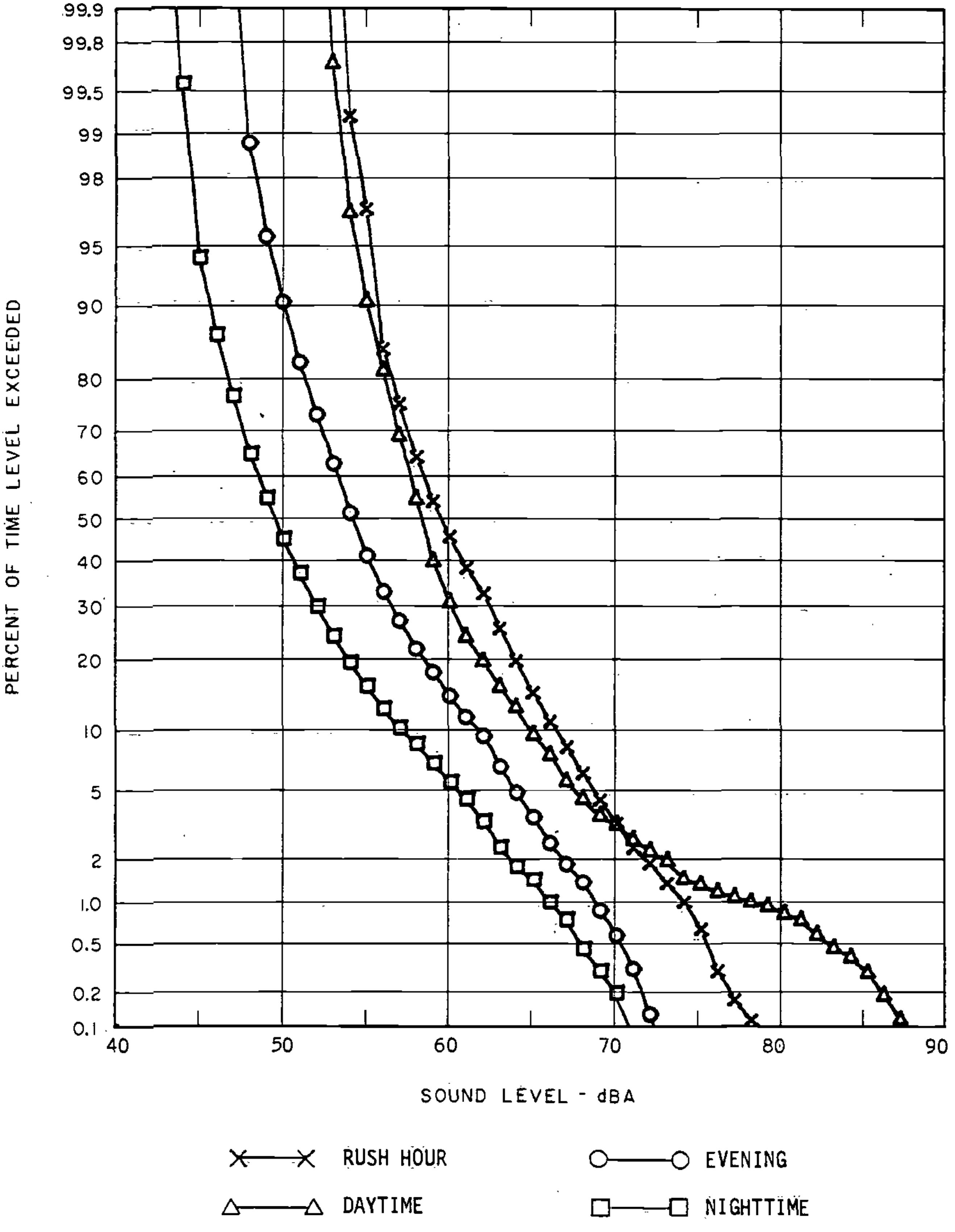

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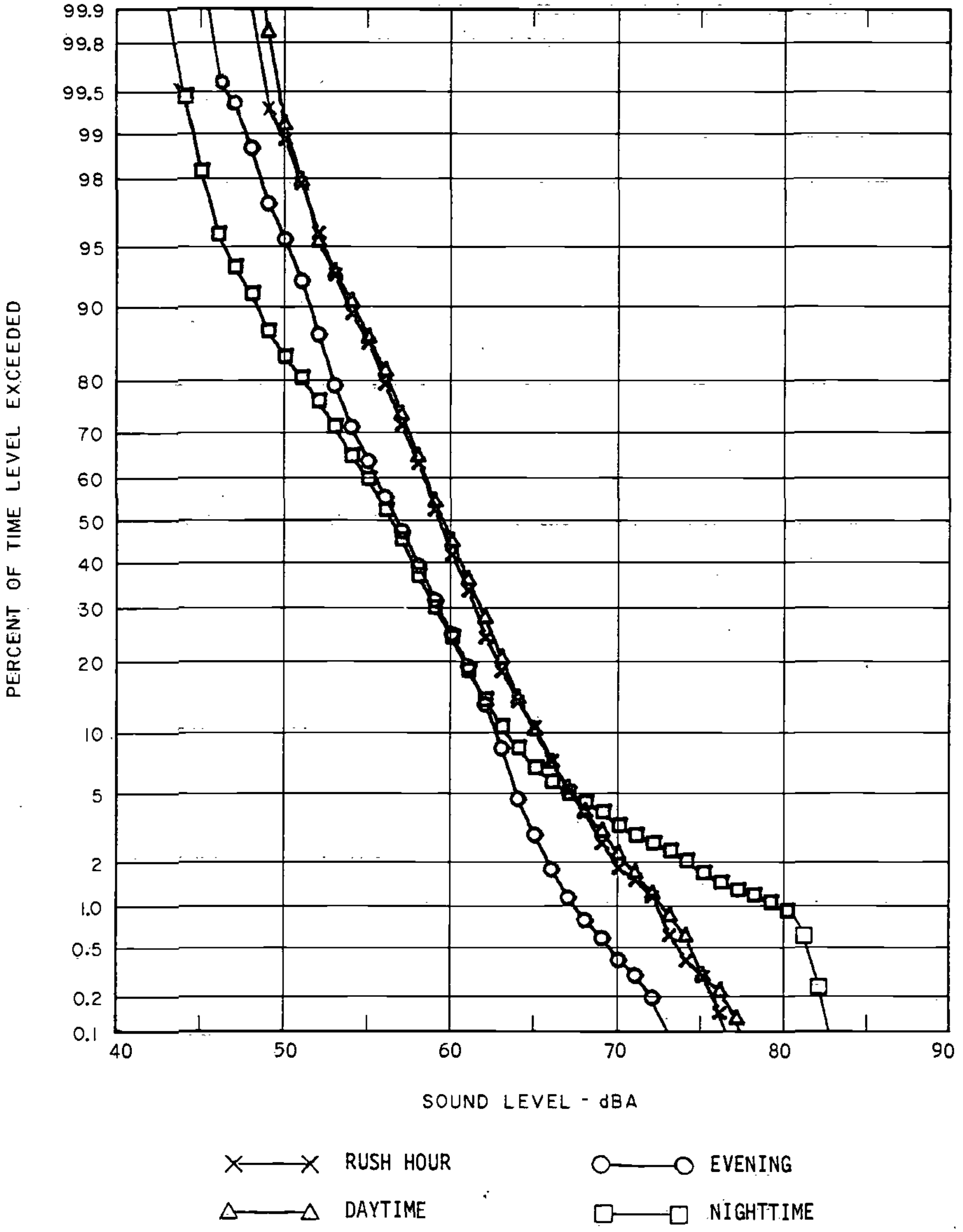

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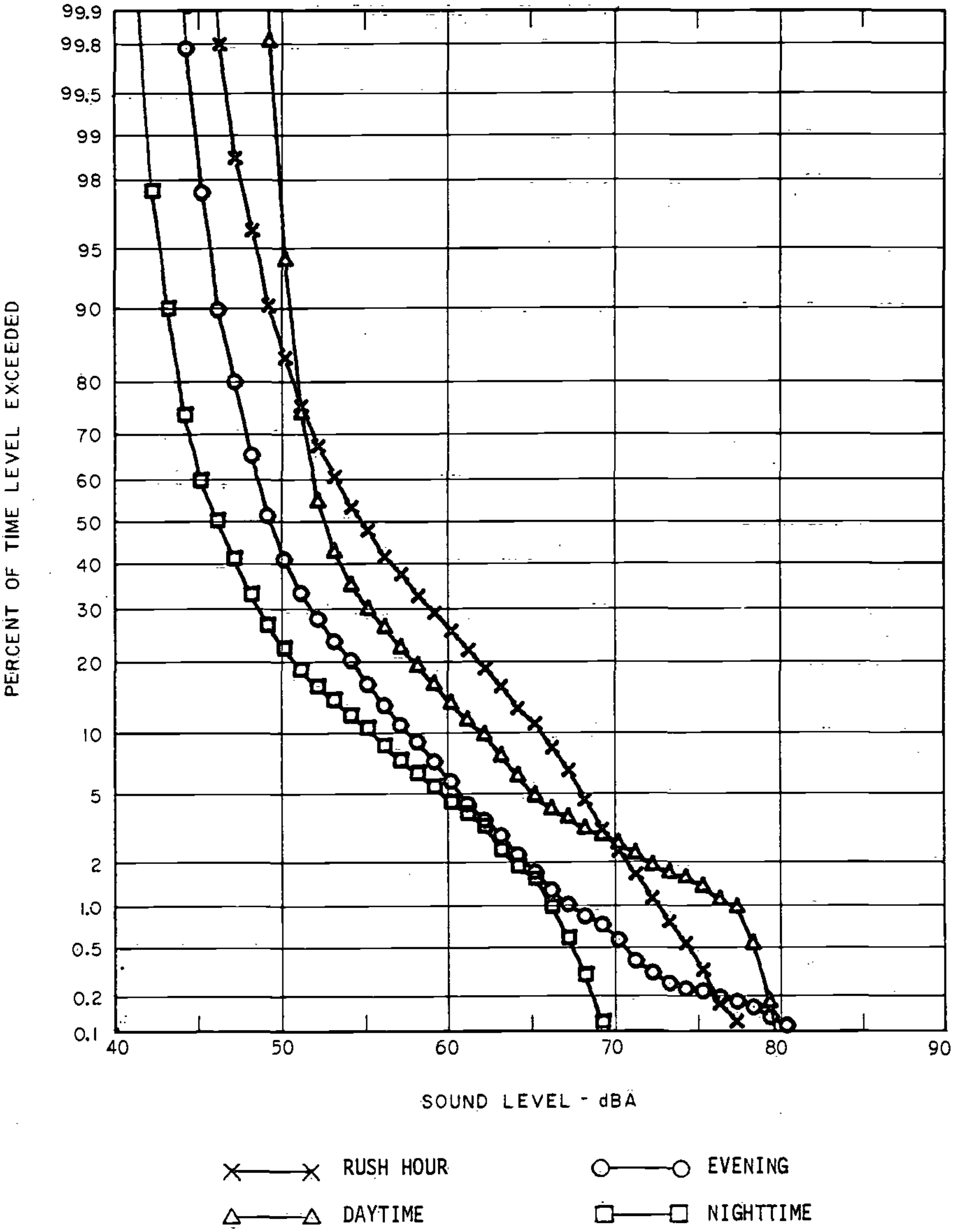

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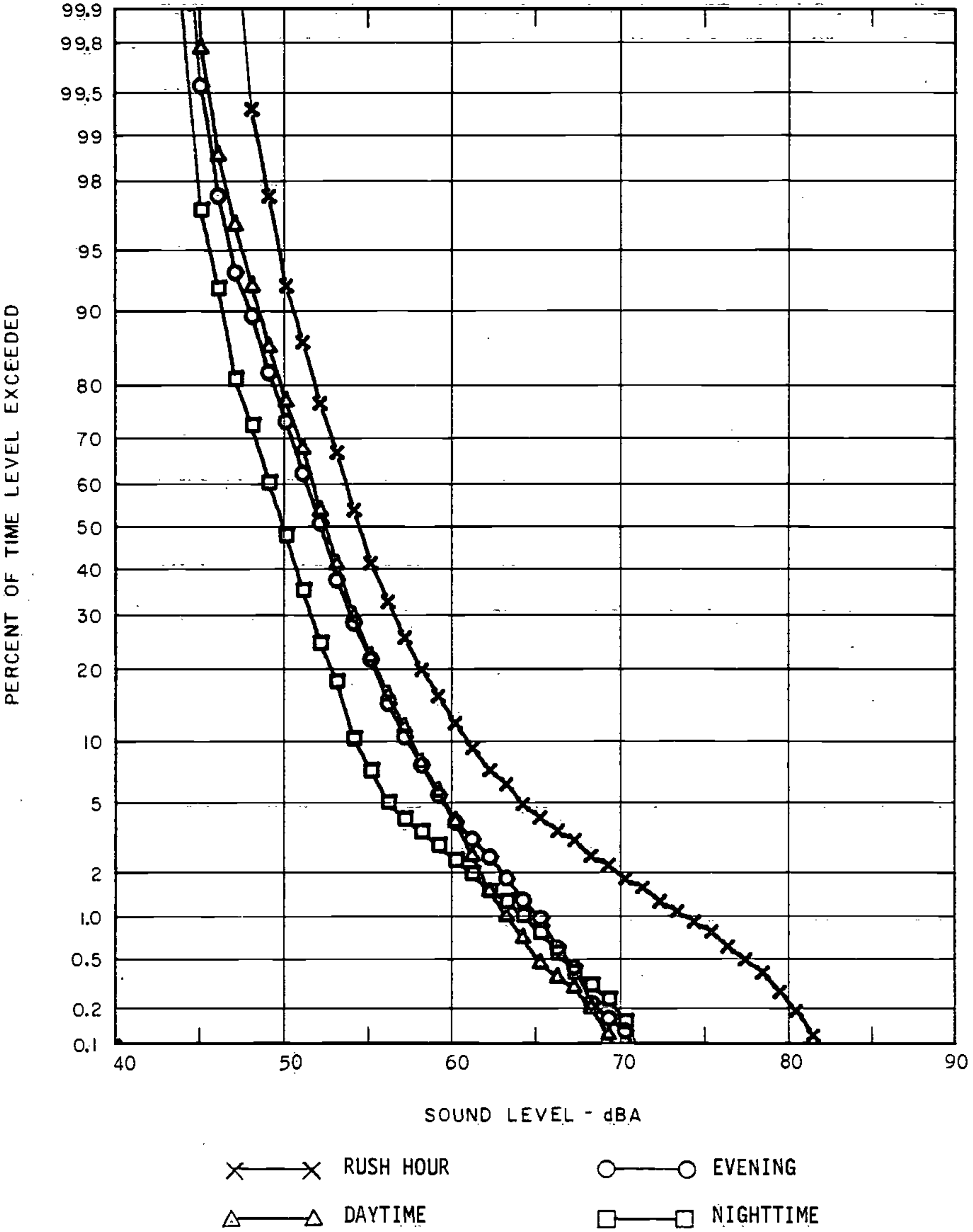

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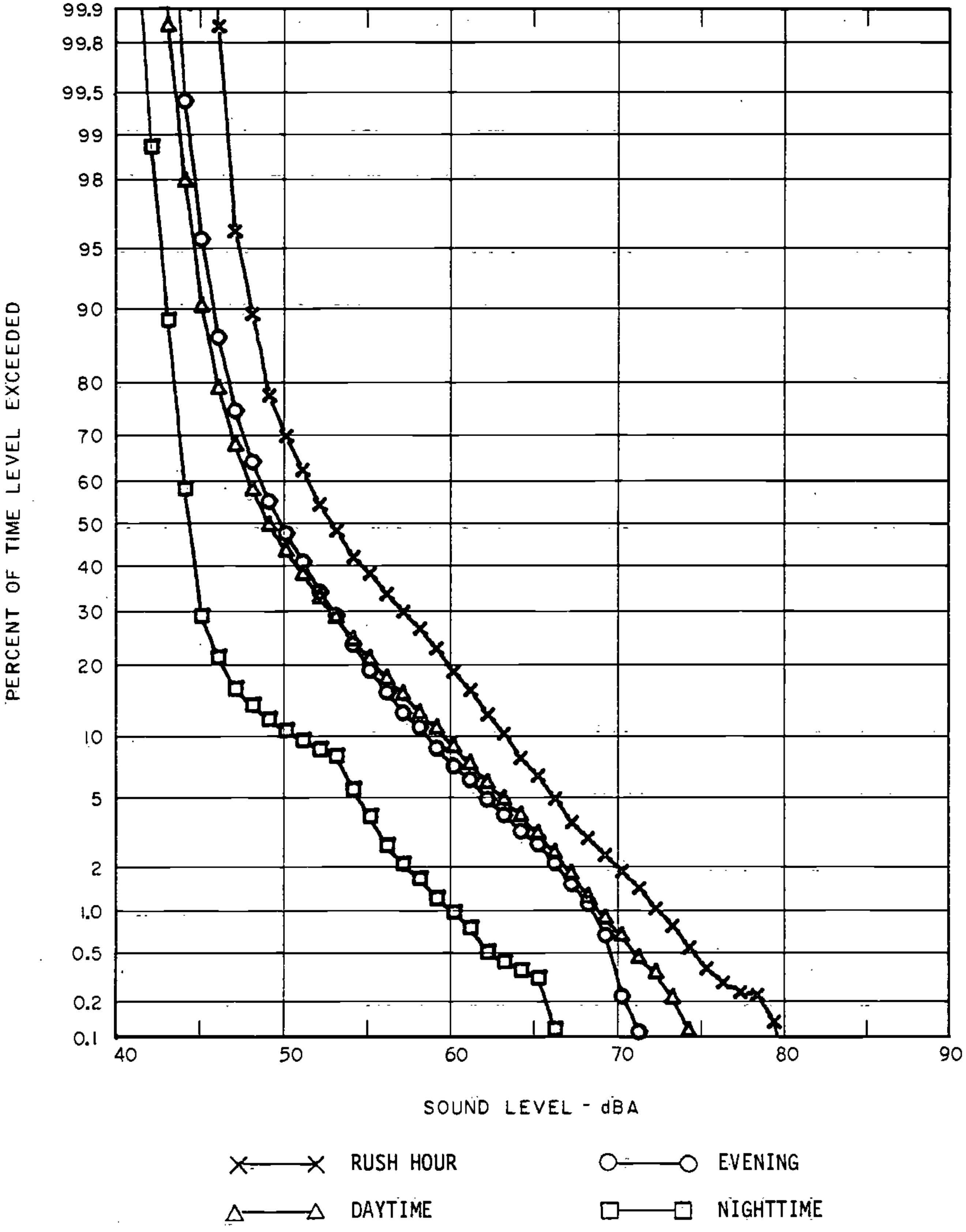

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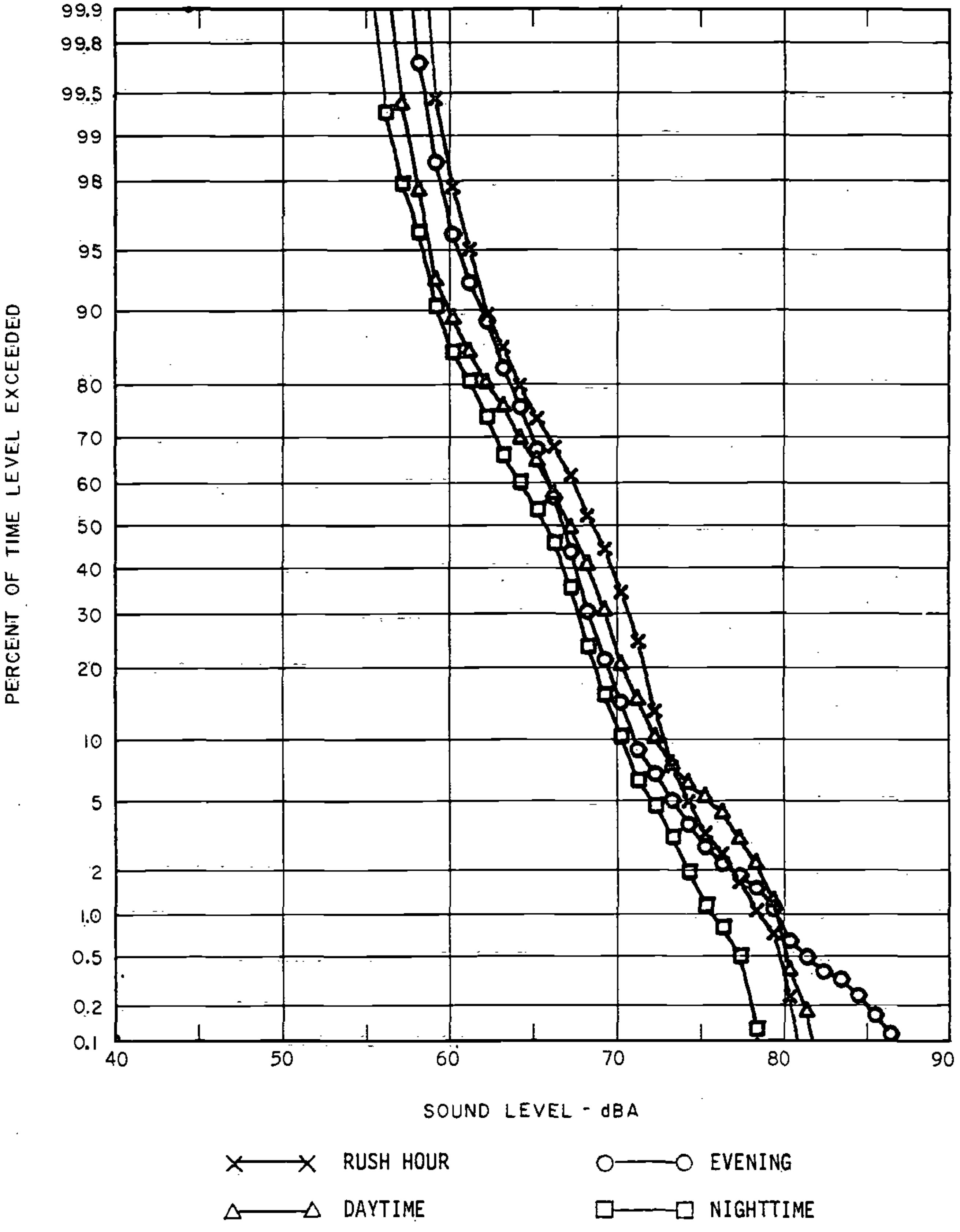

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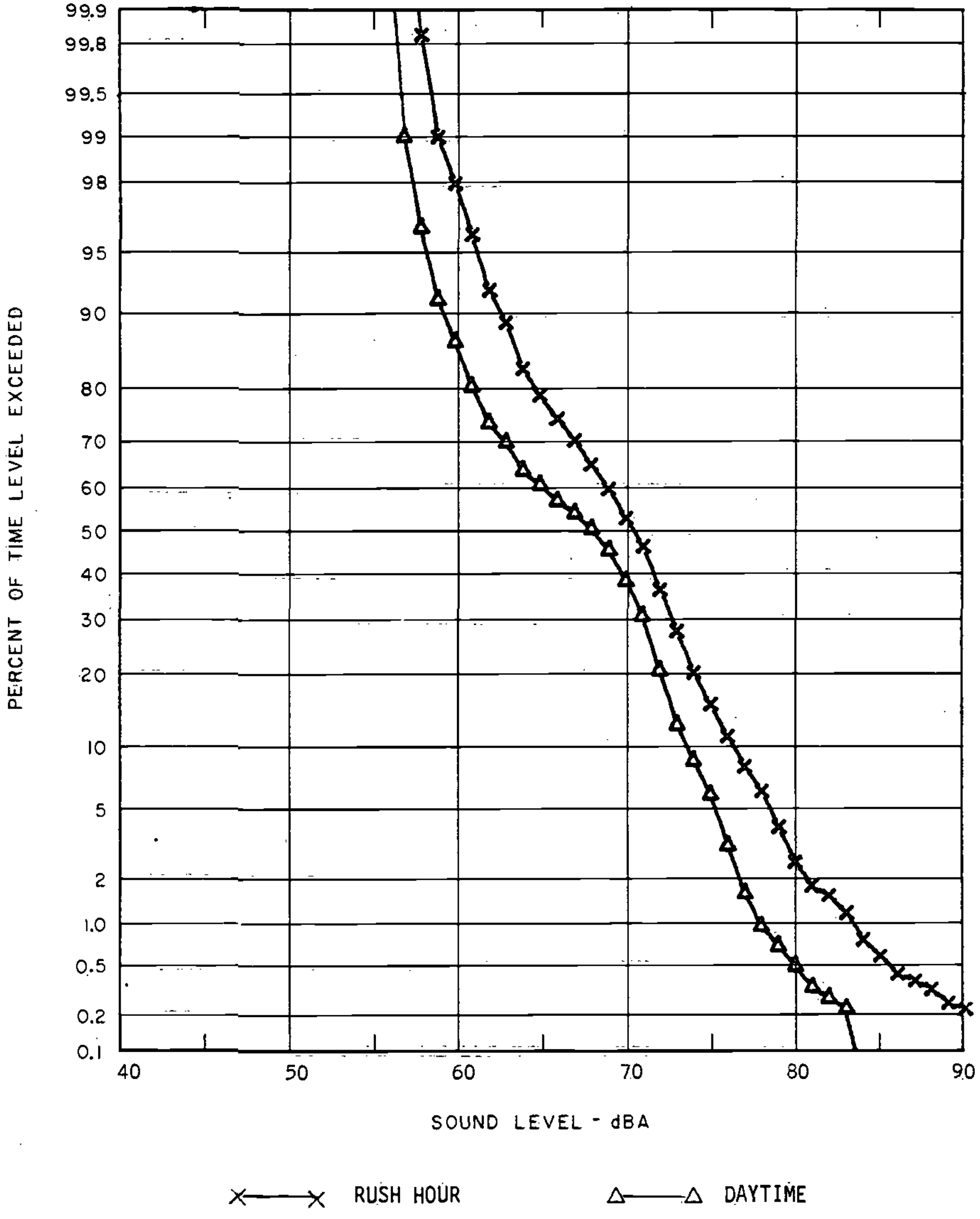
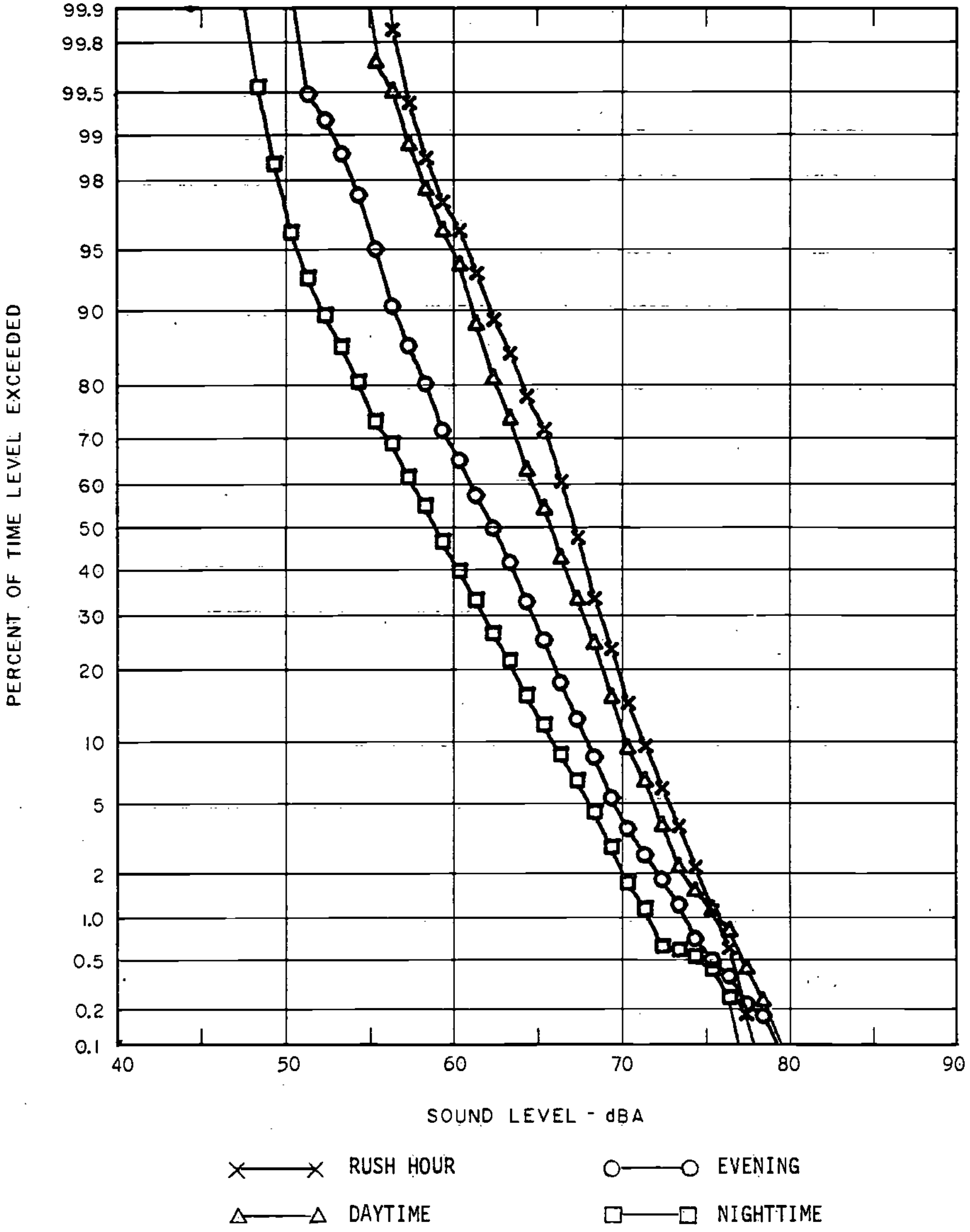


FIGURE A-56 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 111



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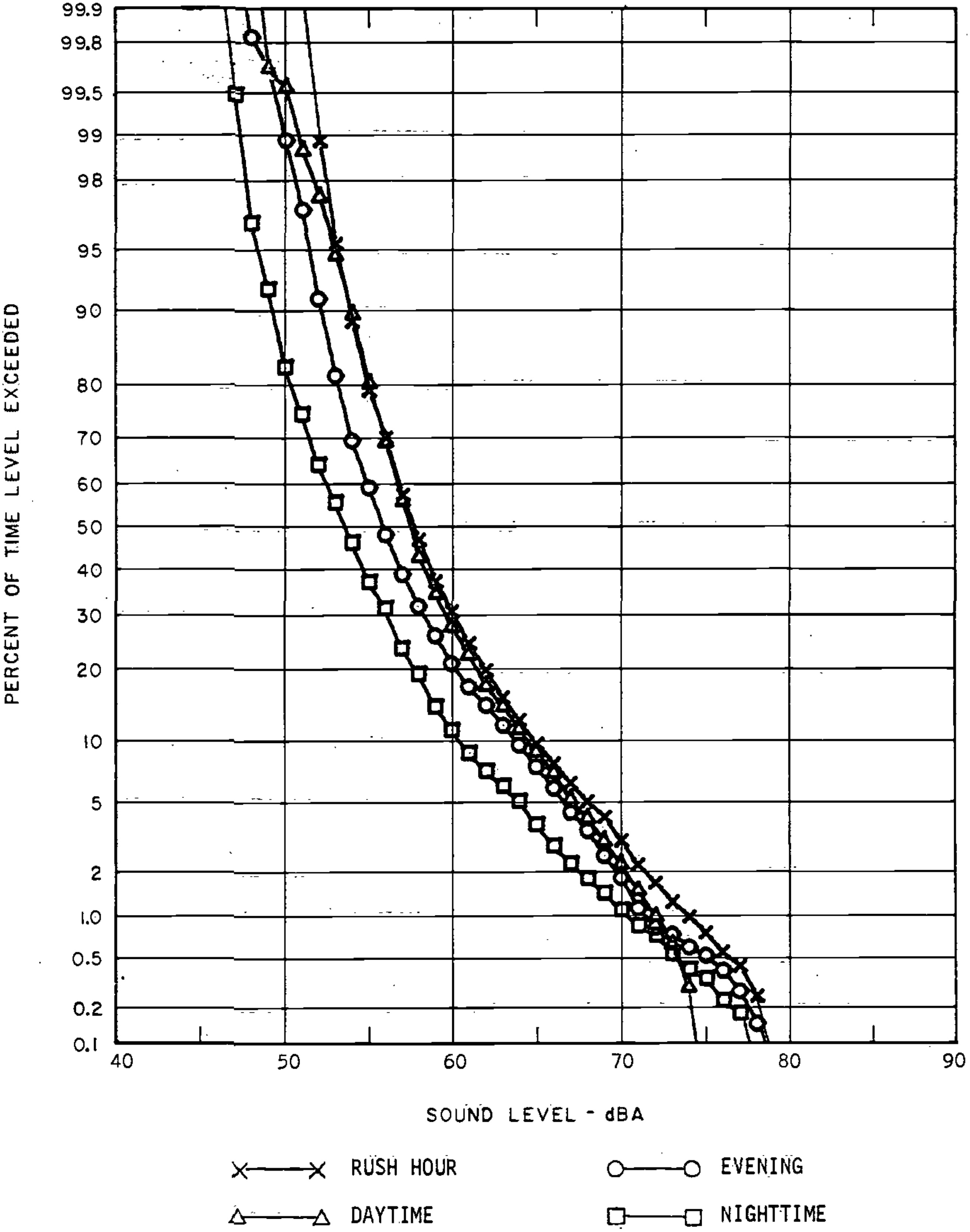


FIGURE A-58 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 113

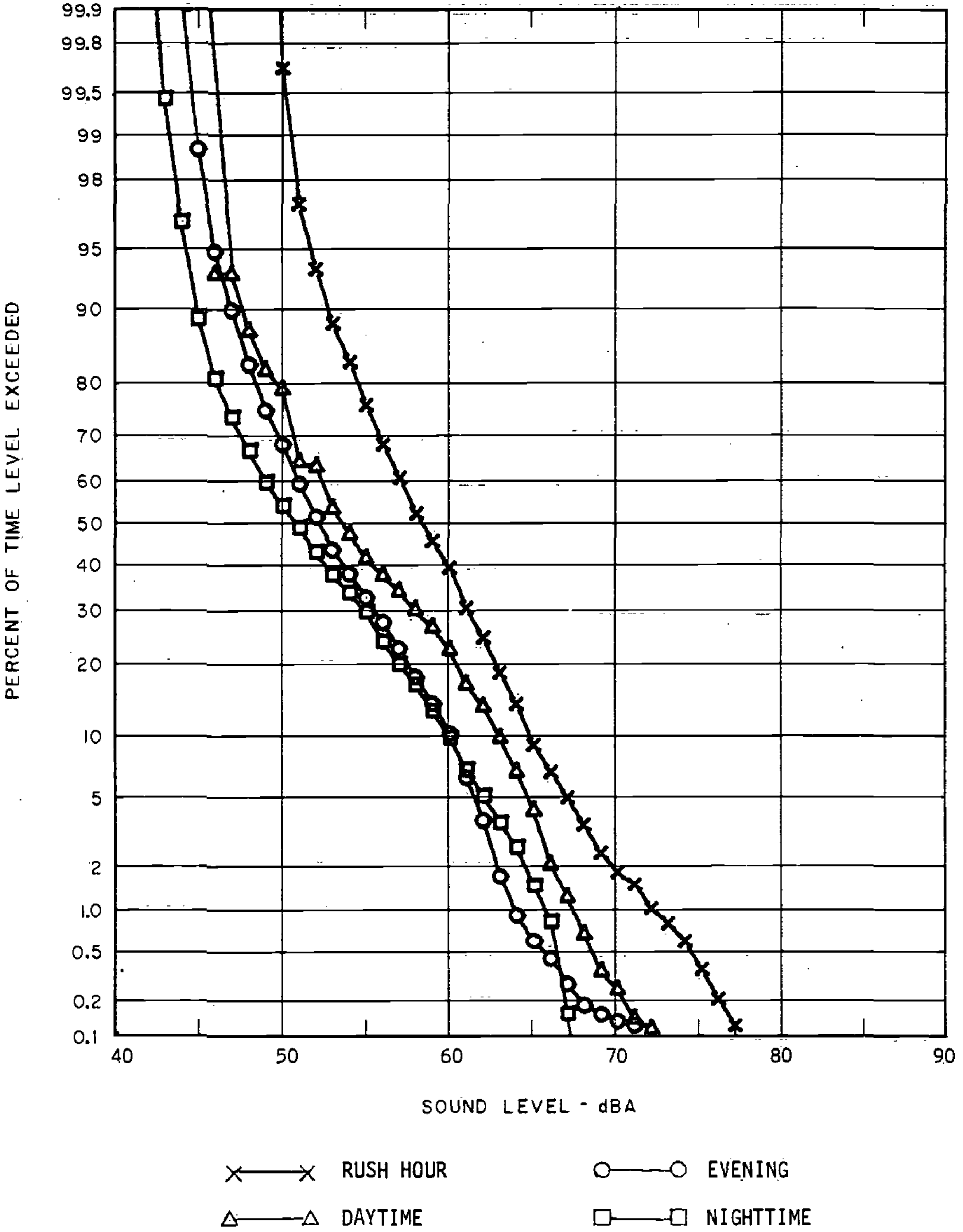


FIGURE A-59 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 114

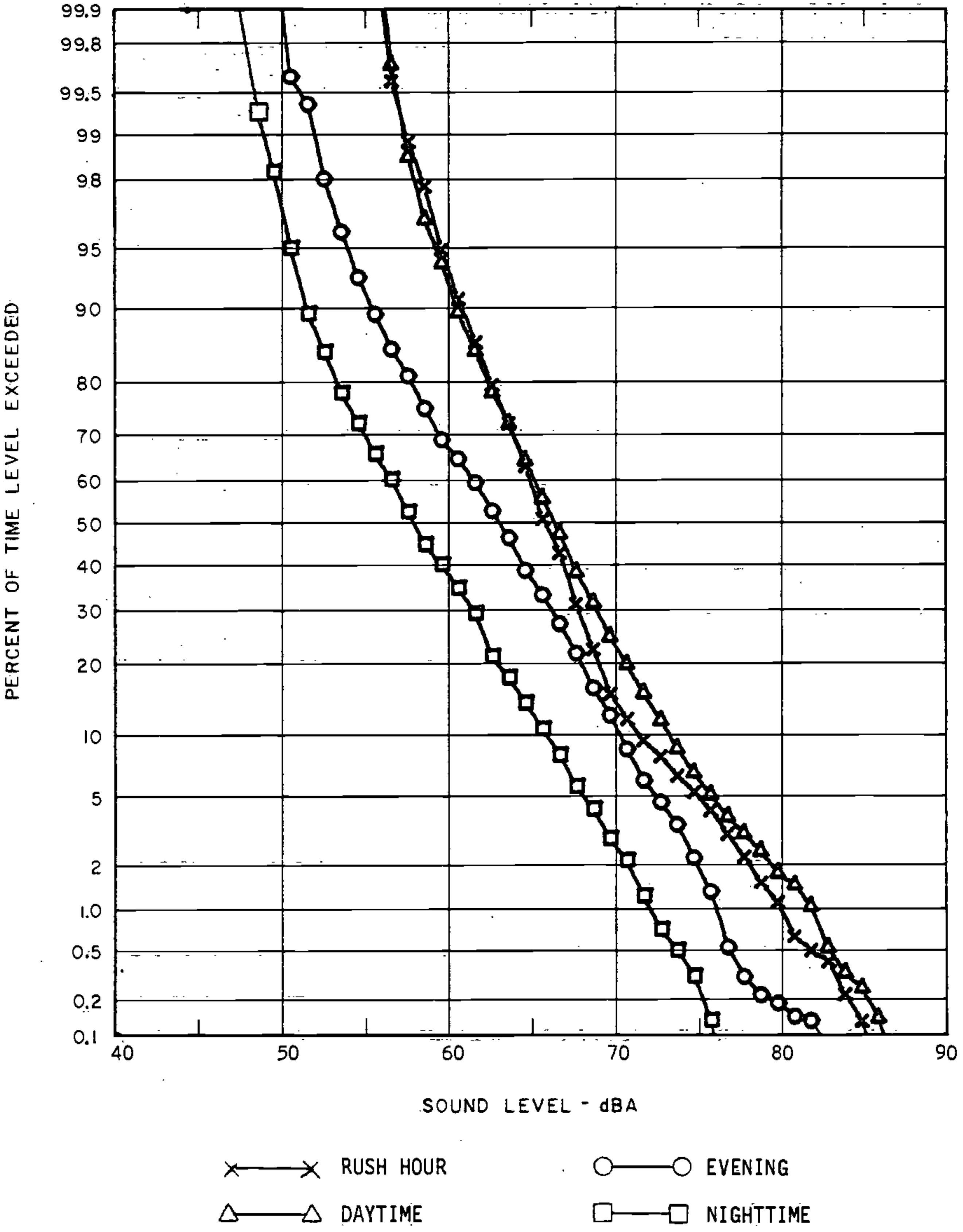


FIGURE A-60 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 115

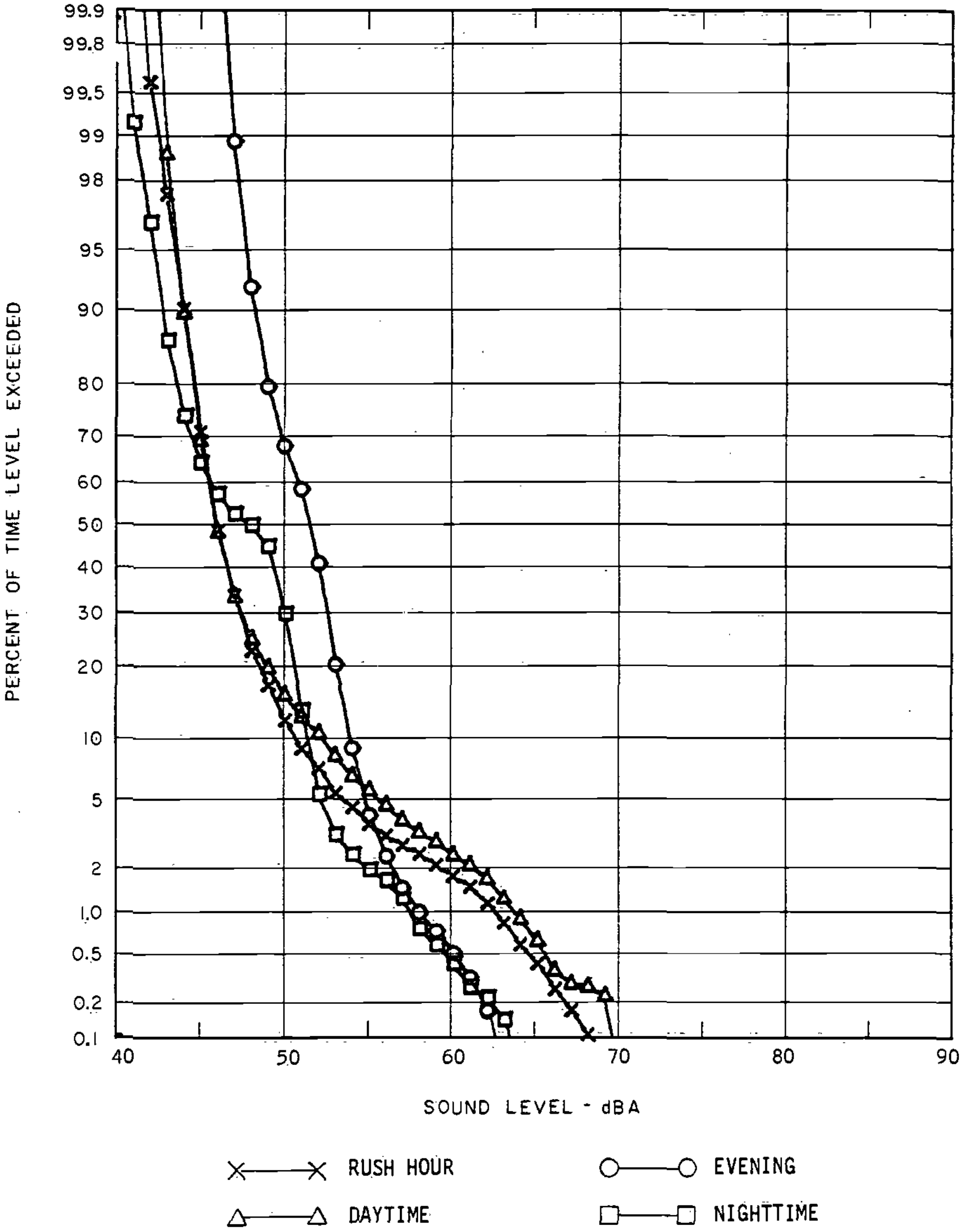


FIGURE A-61 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 116

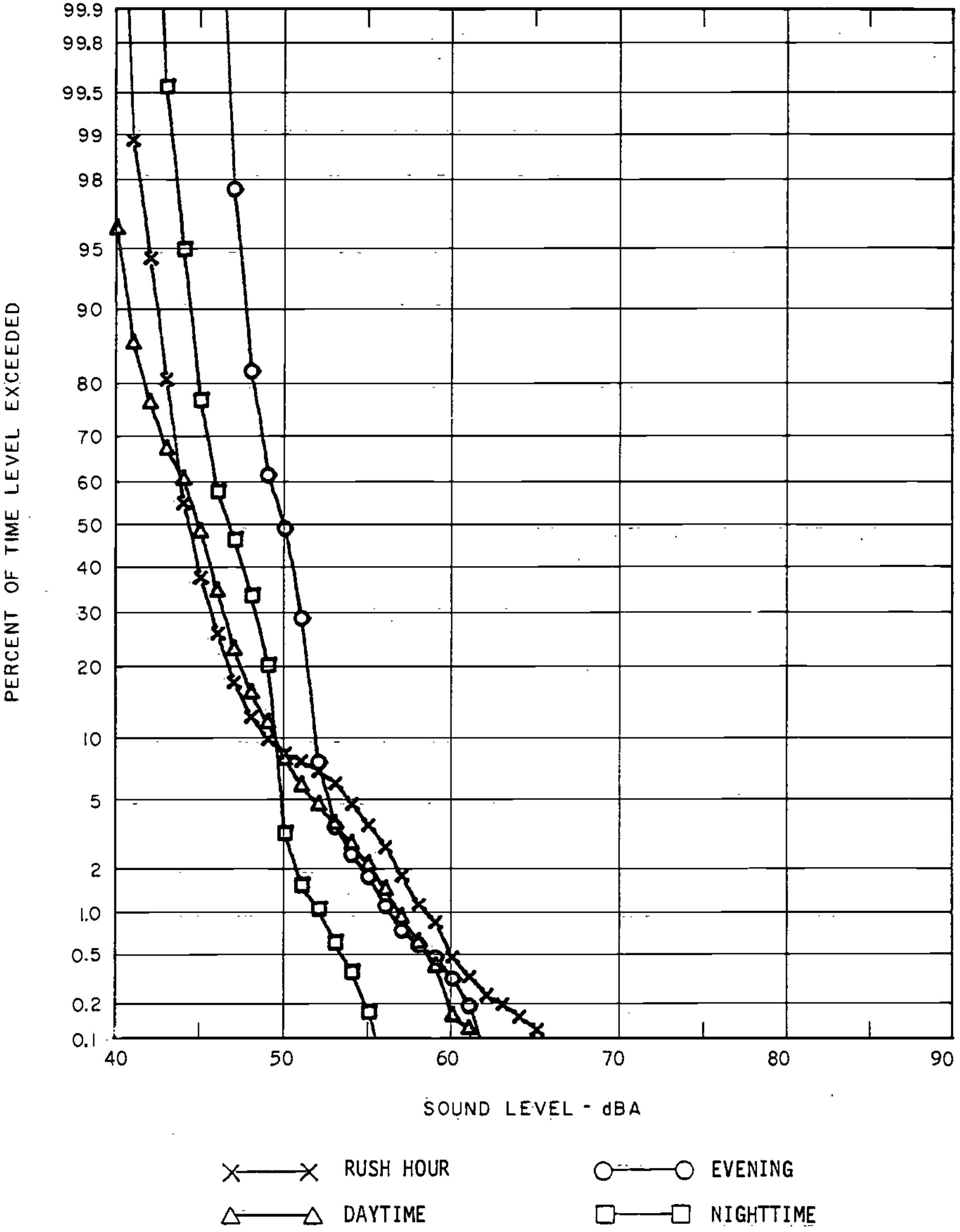


FIGURE A-62 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 117

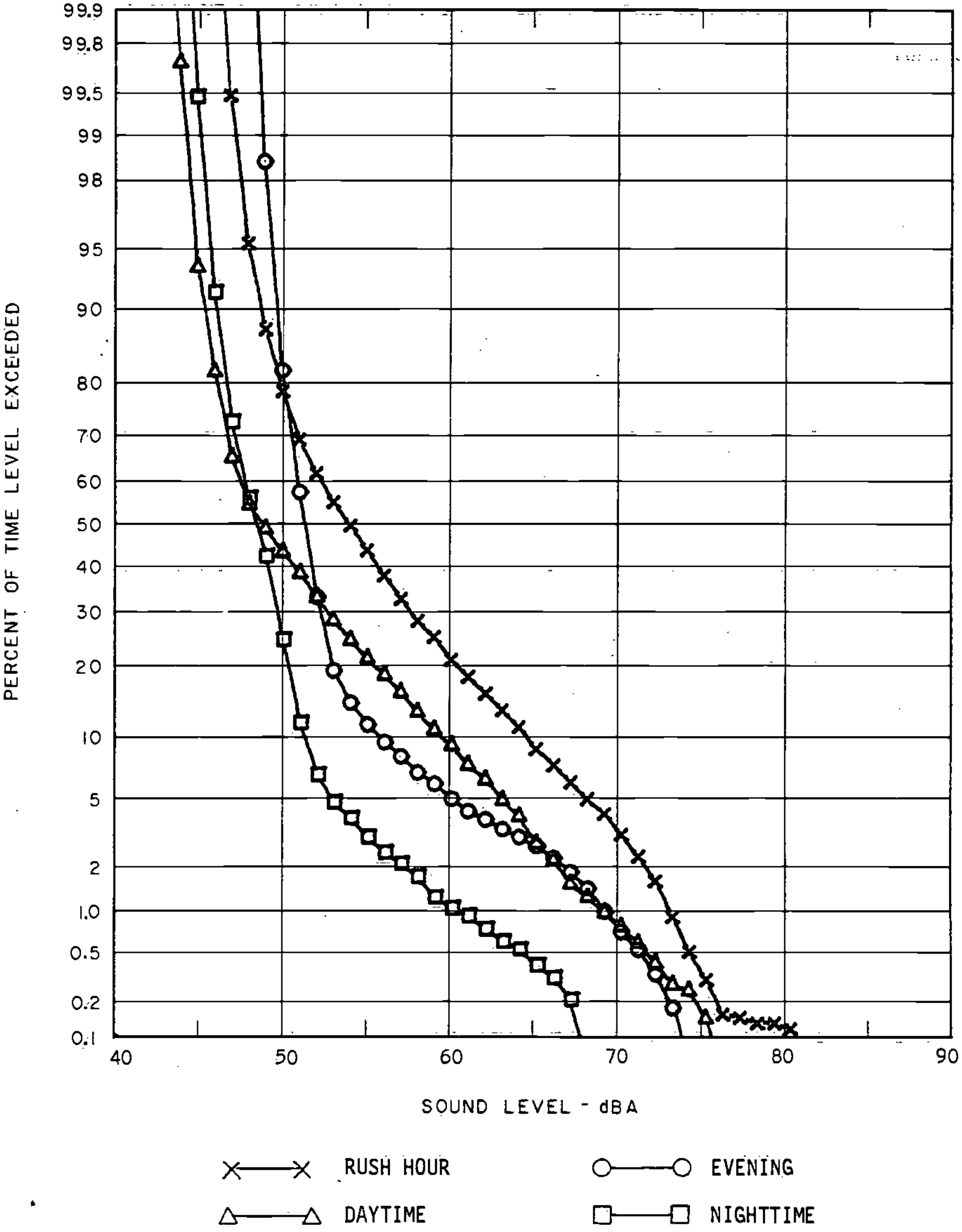


FIGURE A-63 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 118

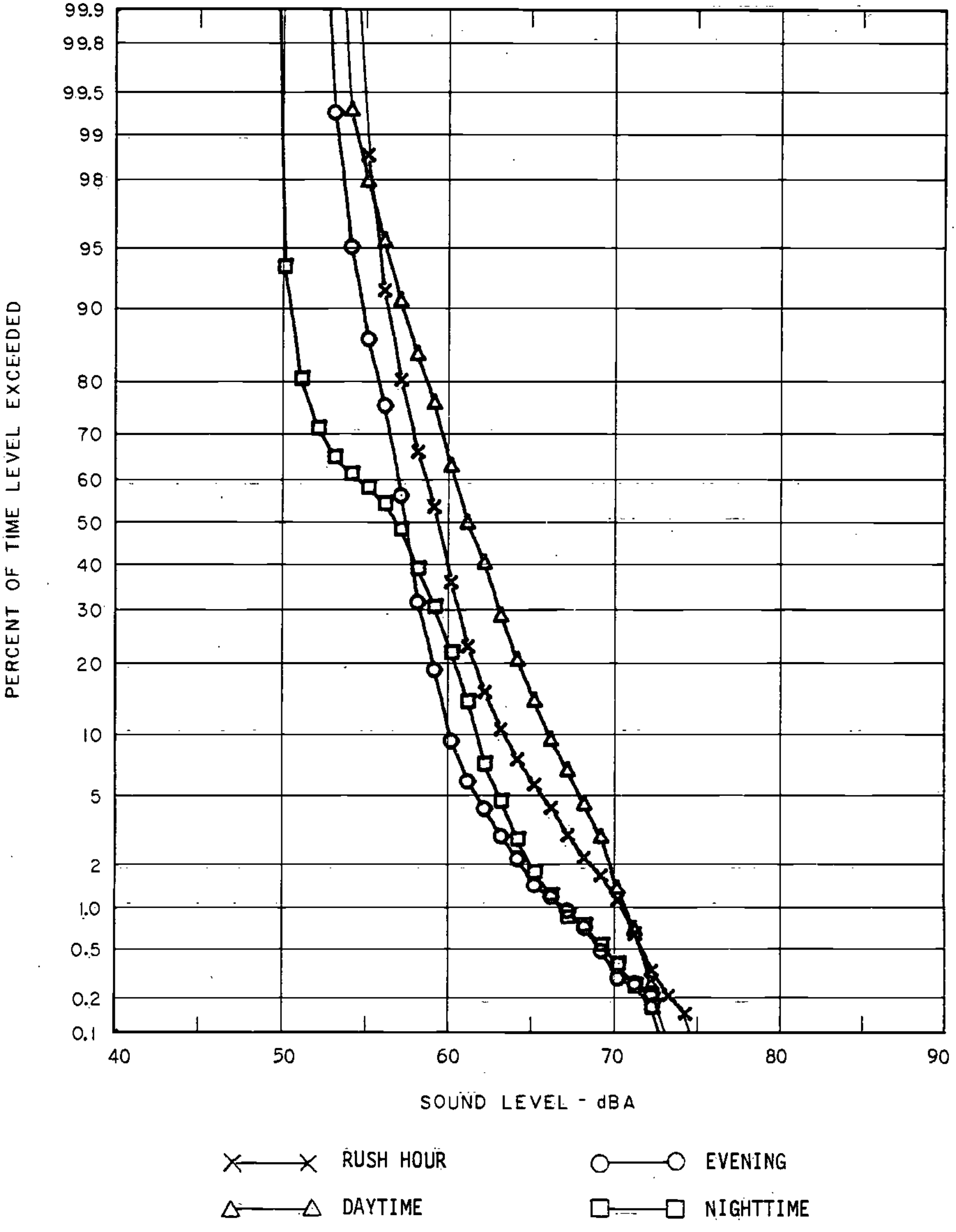


FIGURE A-64 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 119

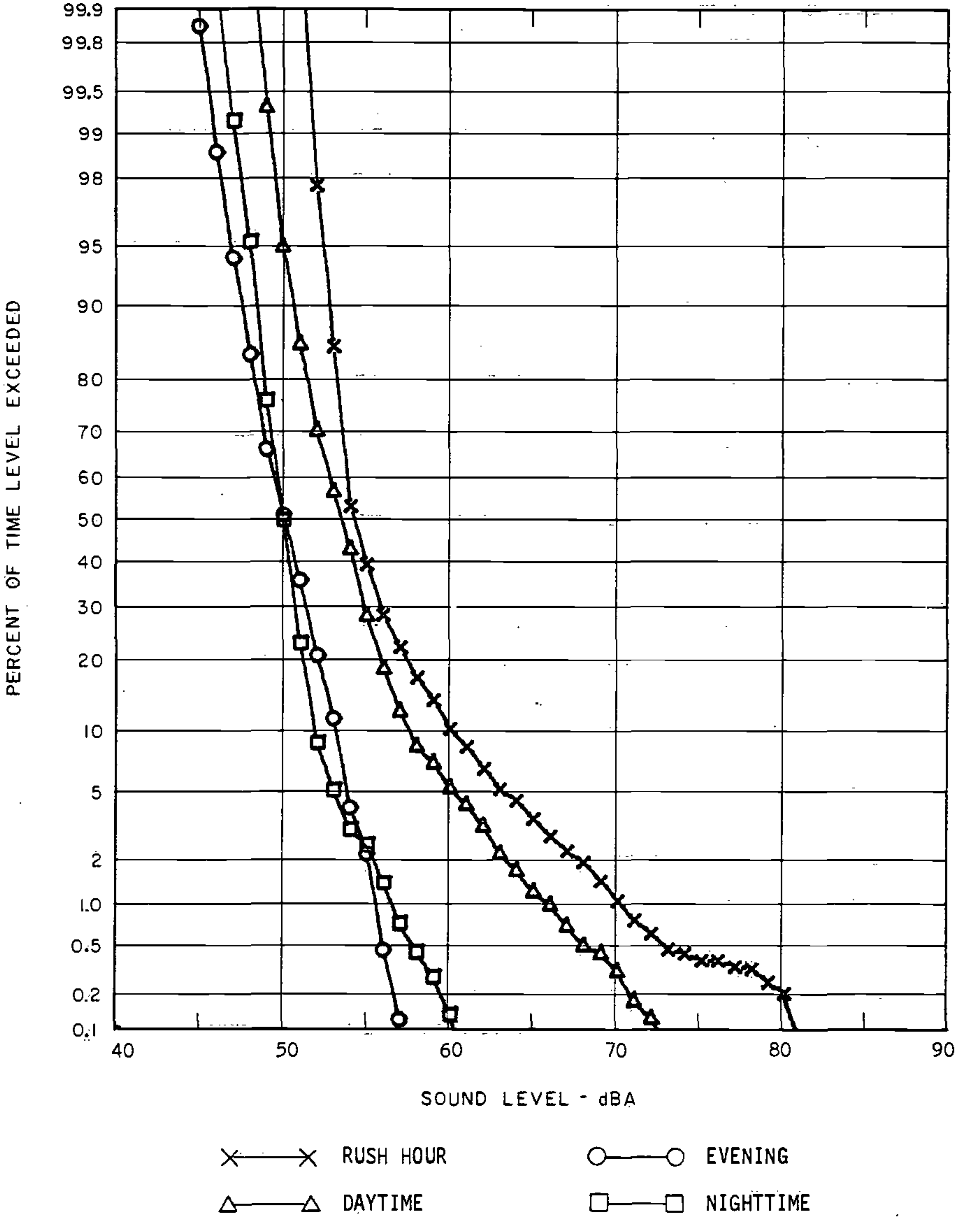


FIGURE A-65 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 120

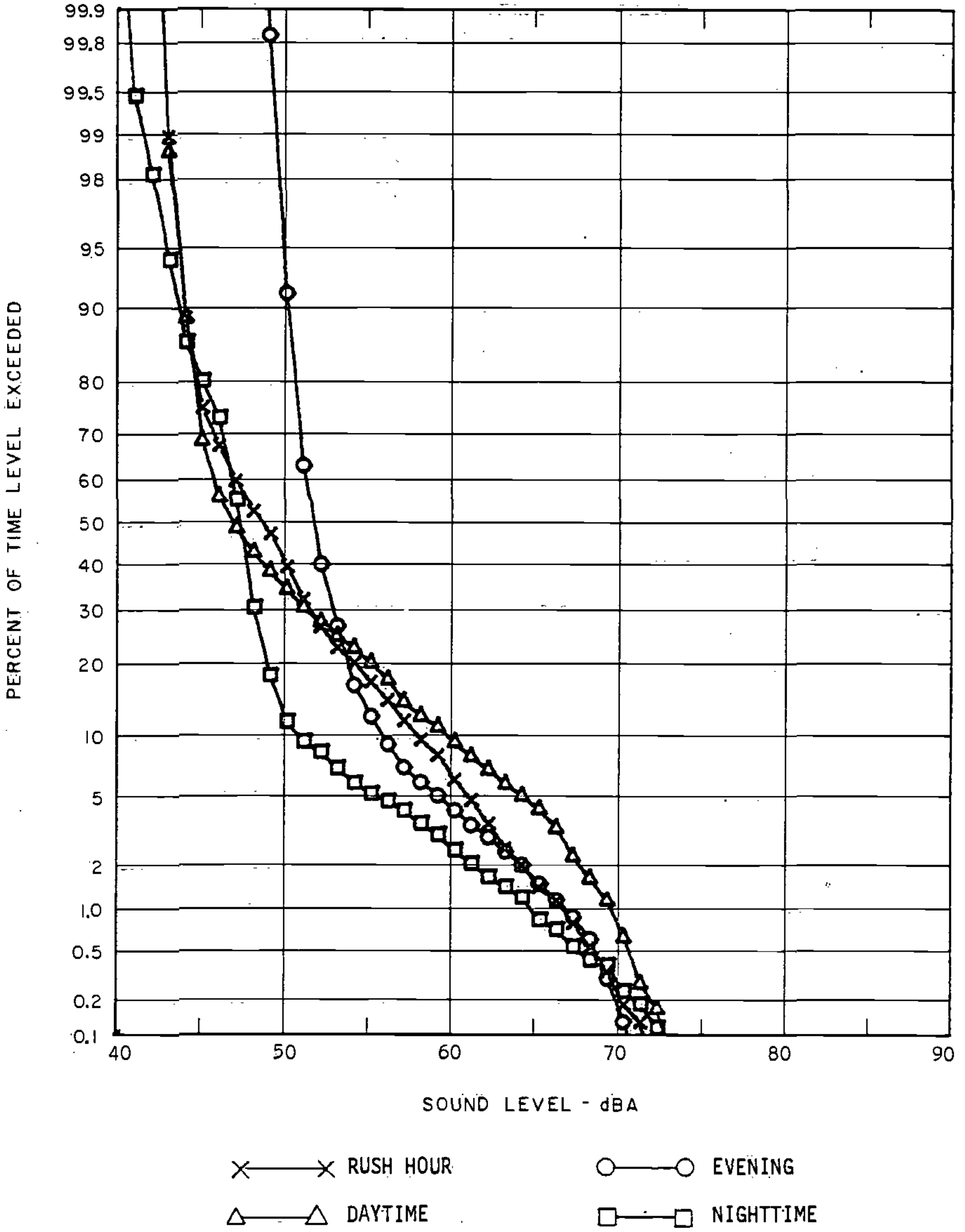


FIGURE A-66 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 121

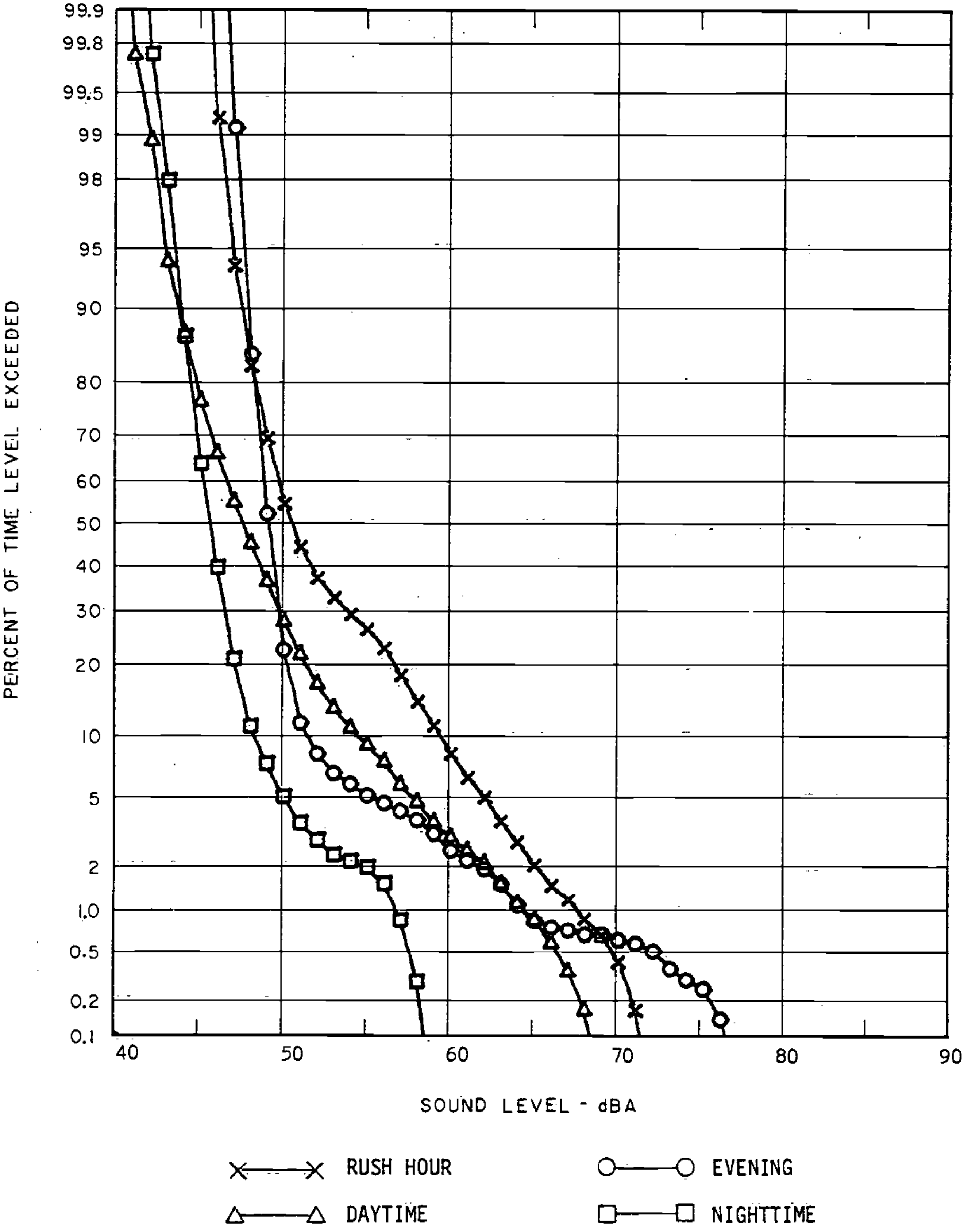


FIGURE A-67 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 122

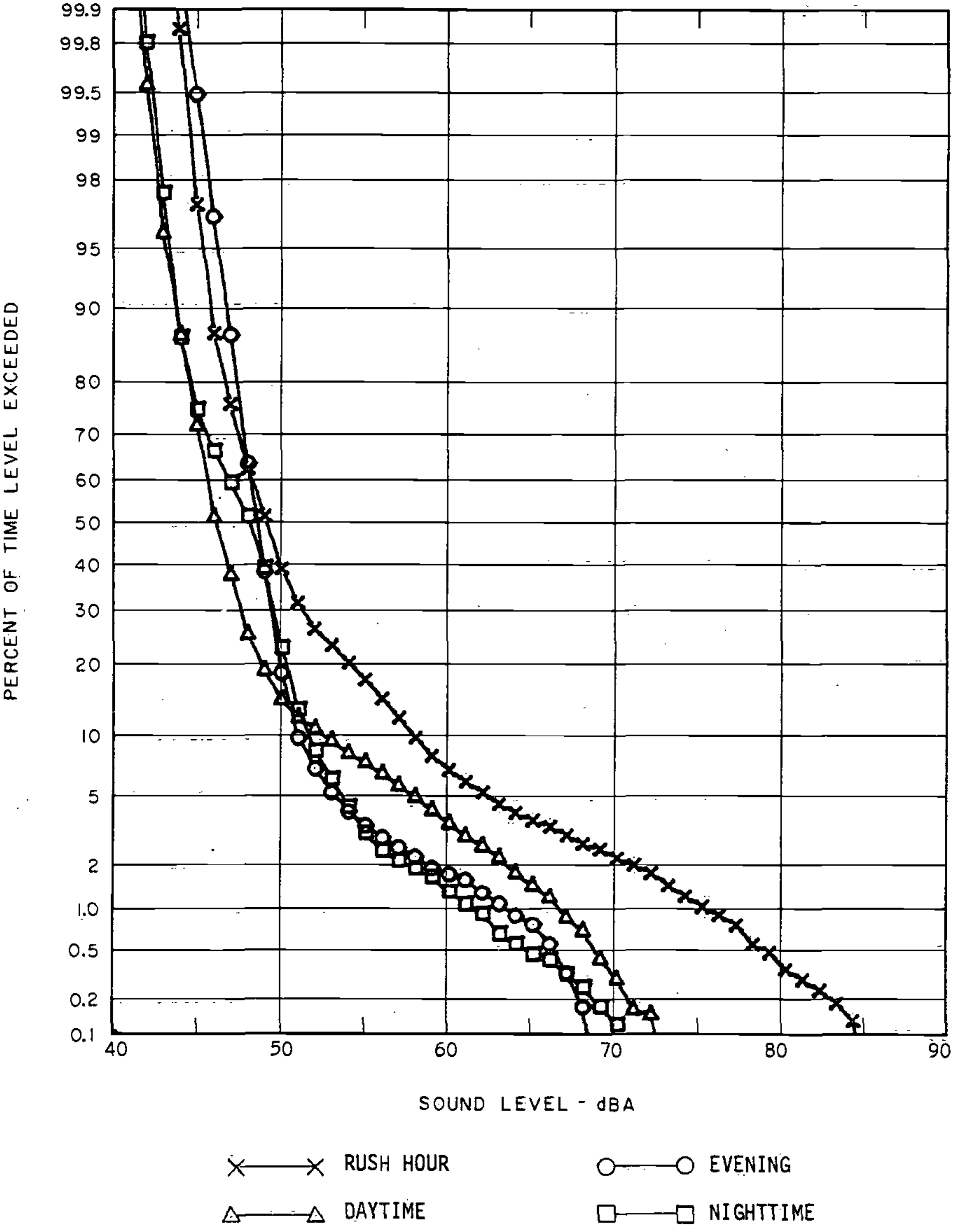


FIGURE A-68 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 123

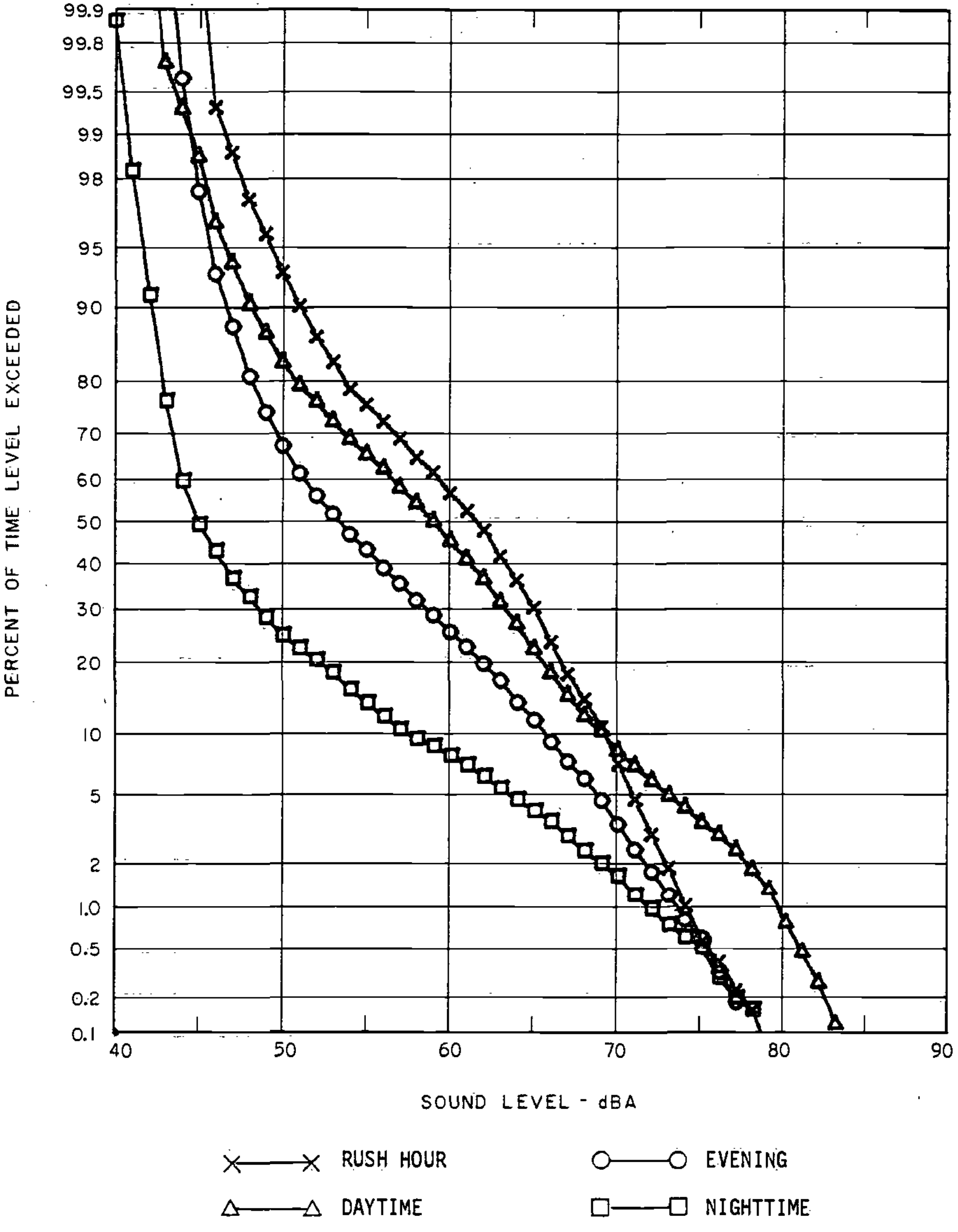


FIGURE A-69 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 124

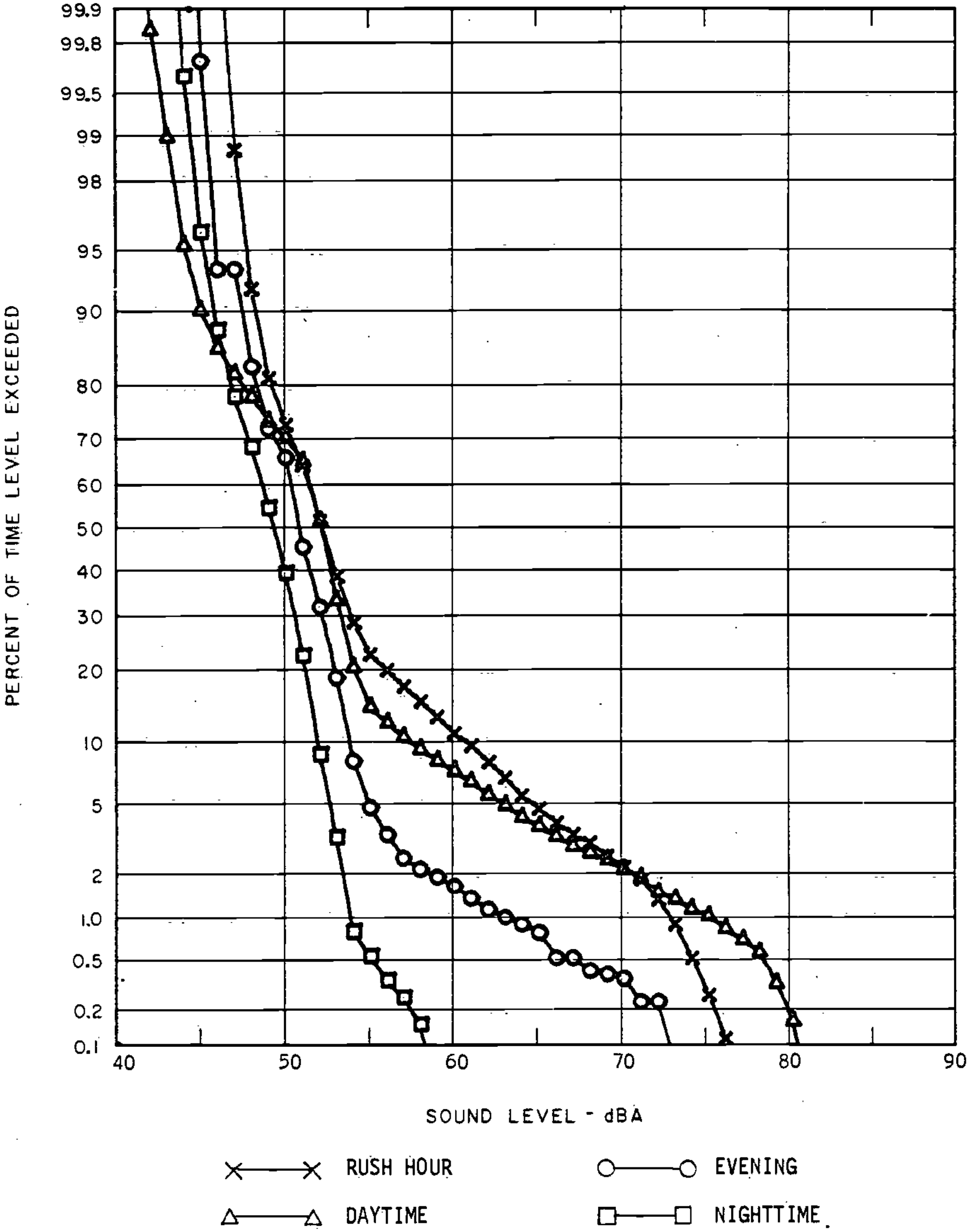


FIGURE A-70 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 125

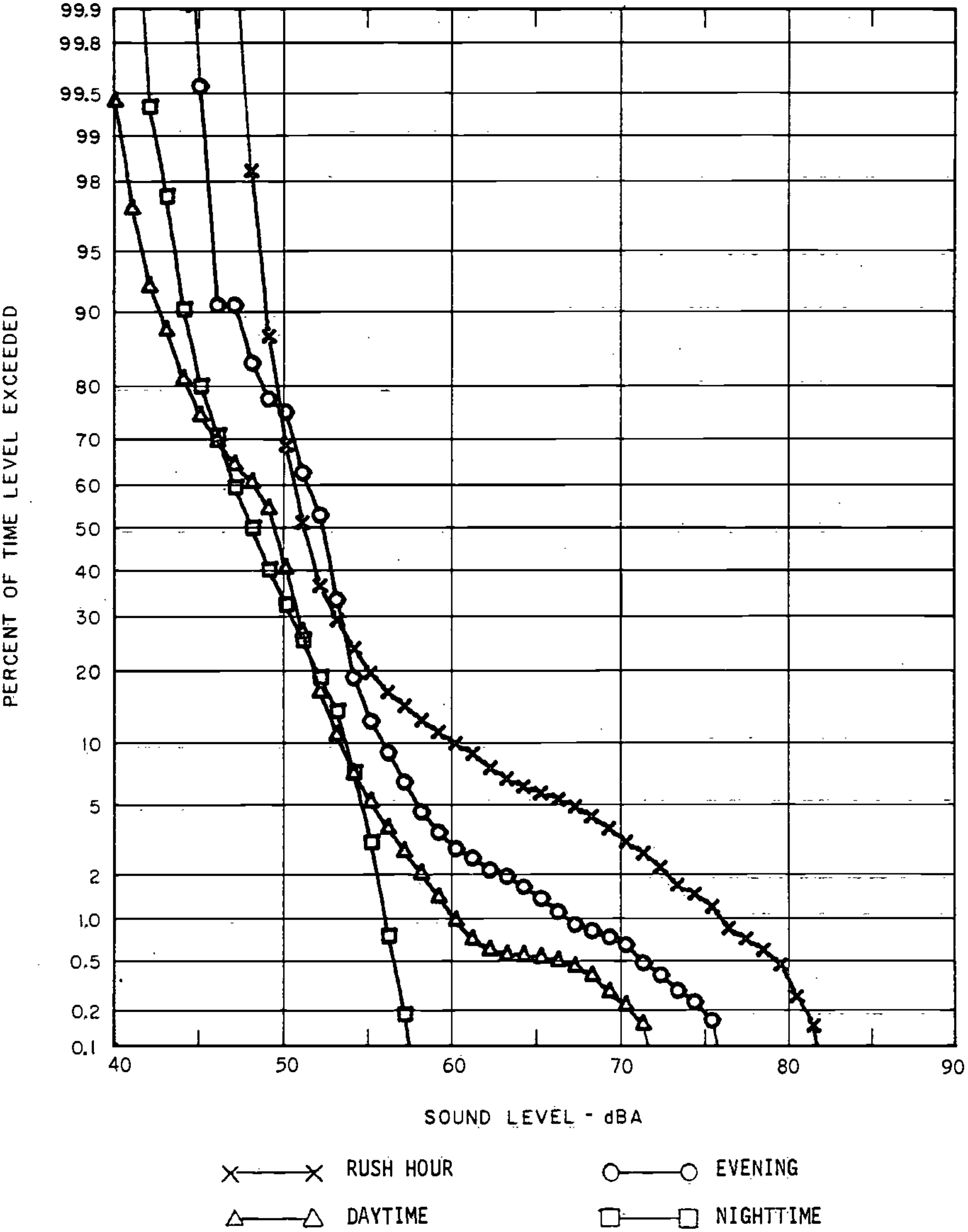


FIGURE A-71 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 126

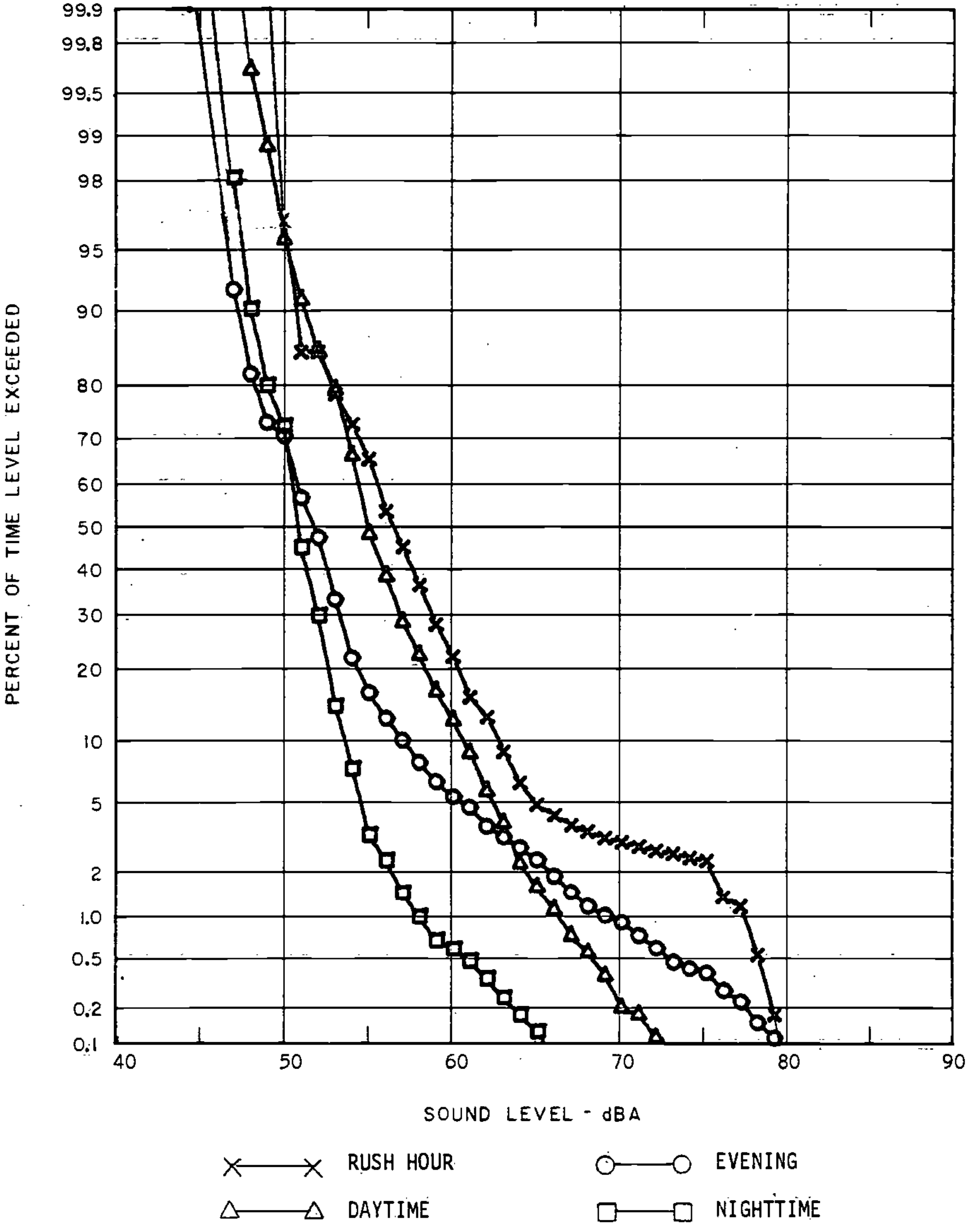


FIGURE A-72 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 127

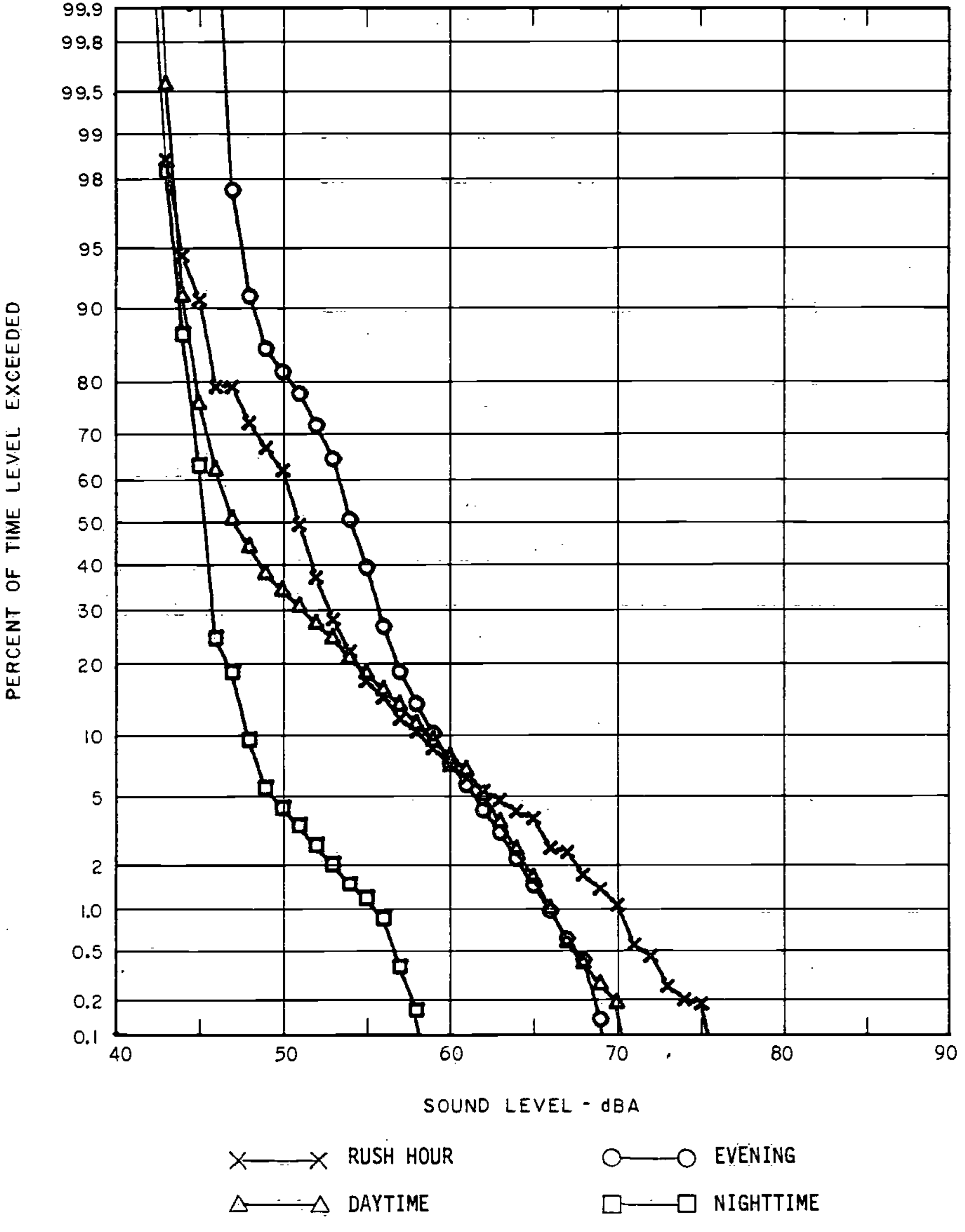


FIGURE A-73 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 128

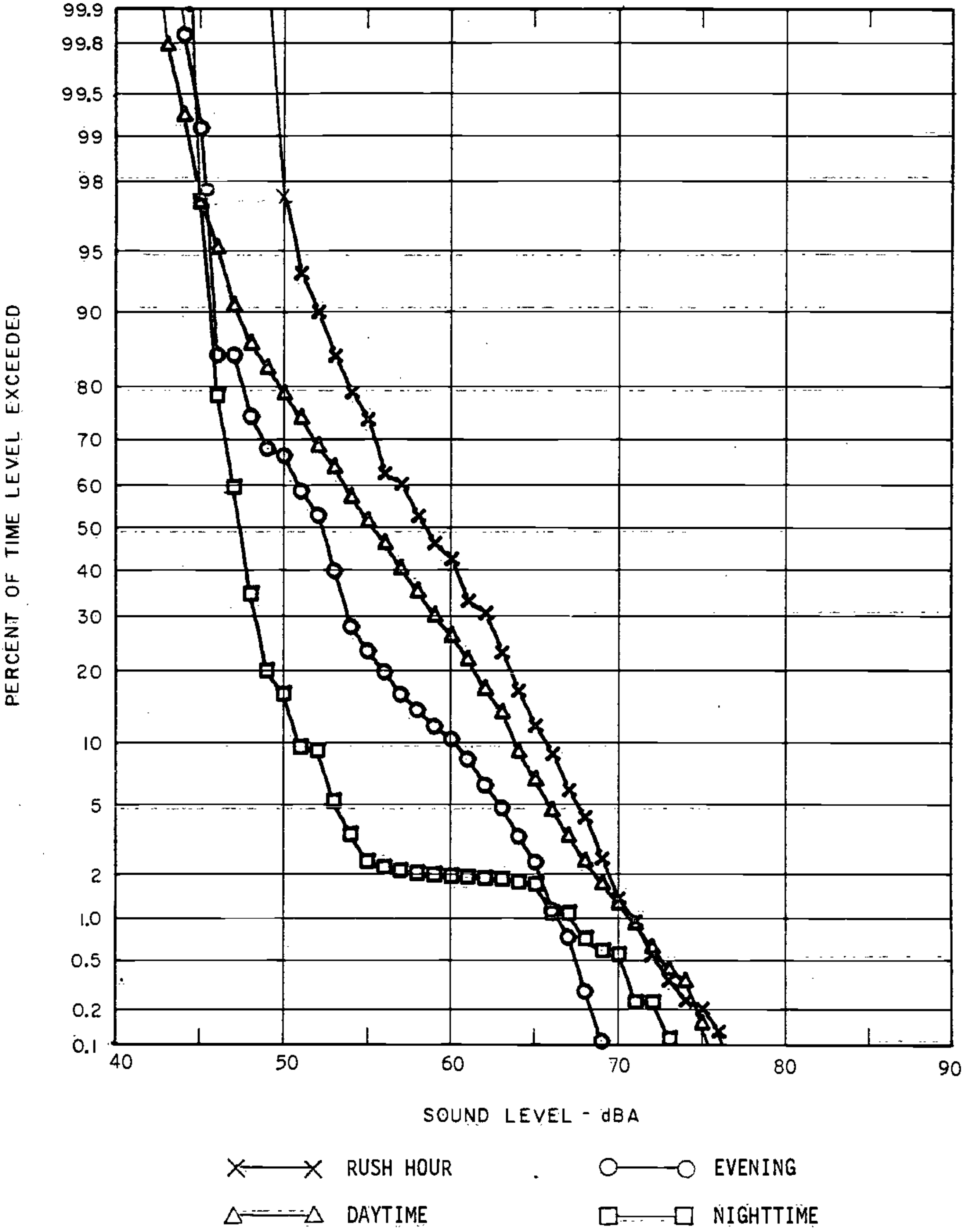


FIGURE A-74 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 129

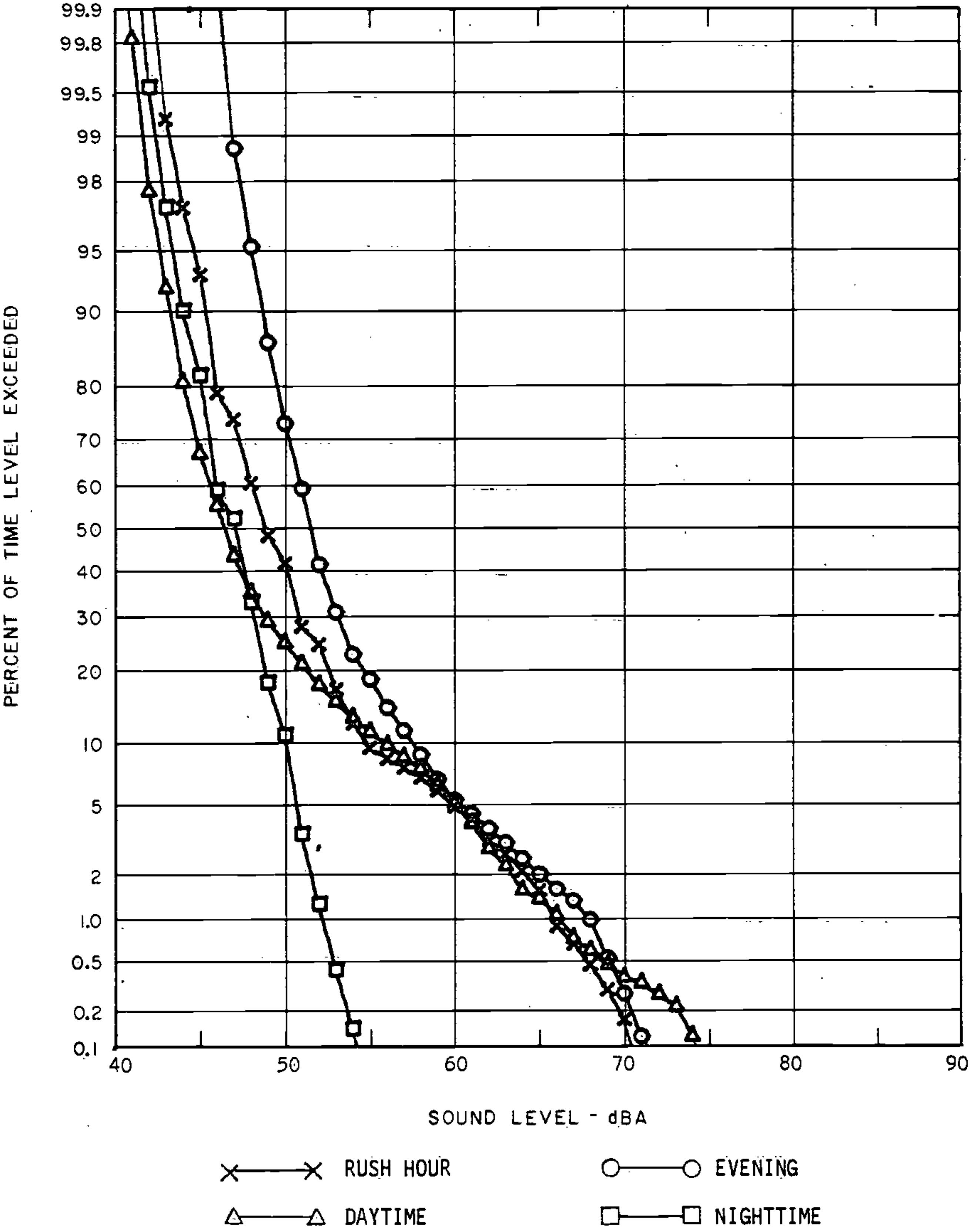


FIGURE A-75 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 130

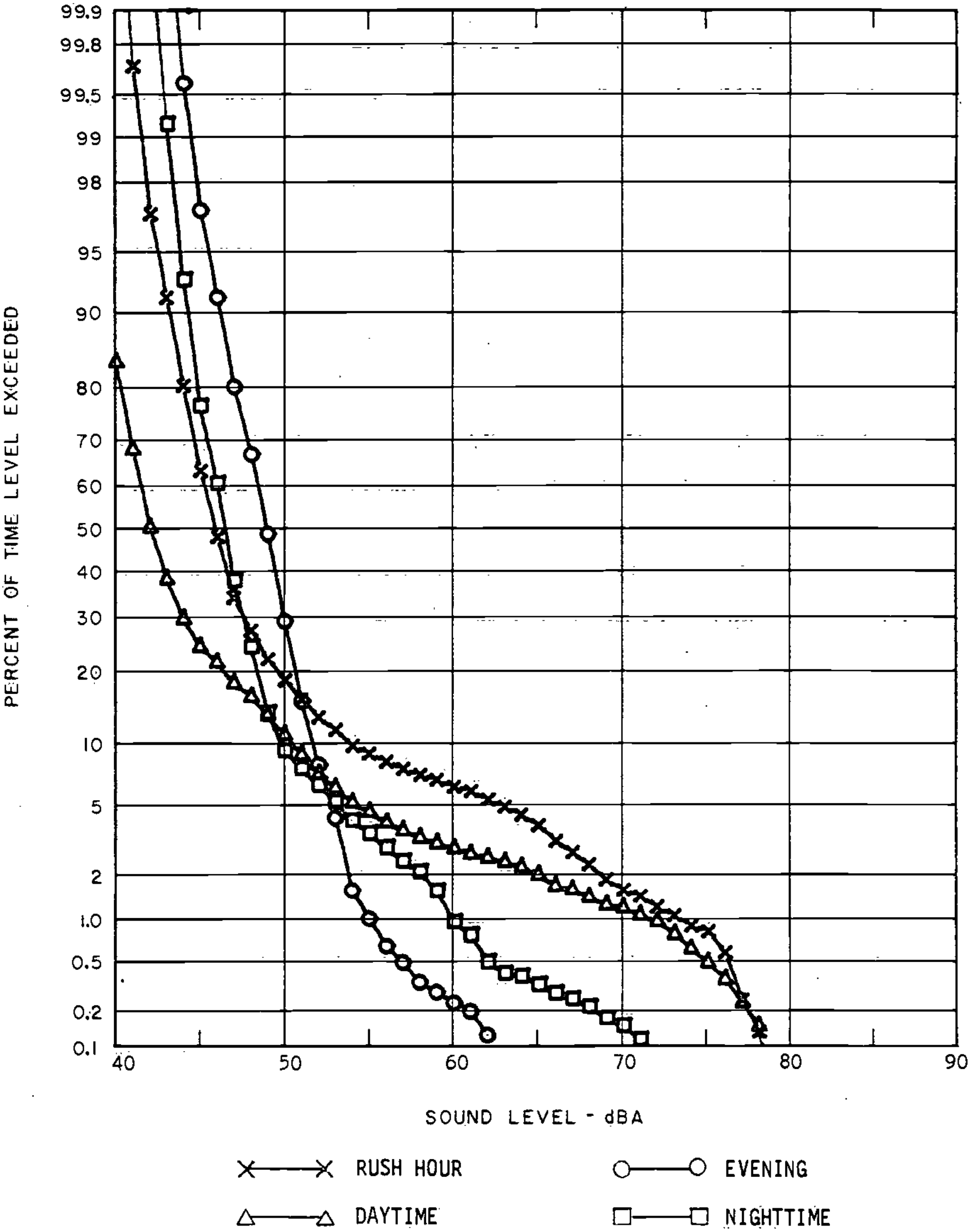


FIGURE A-76 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 131

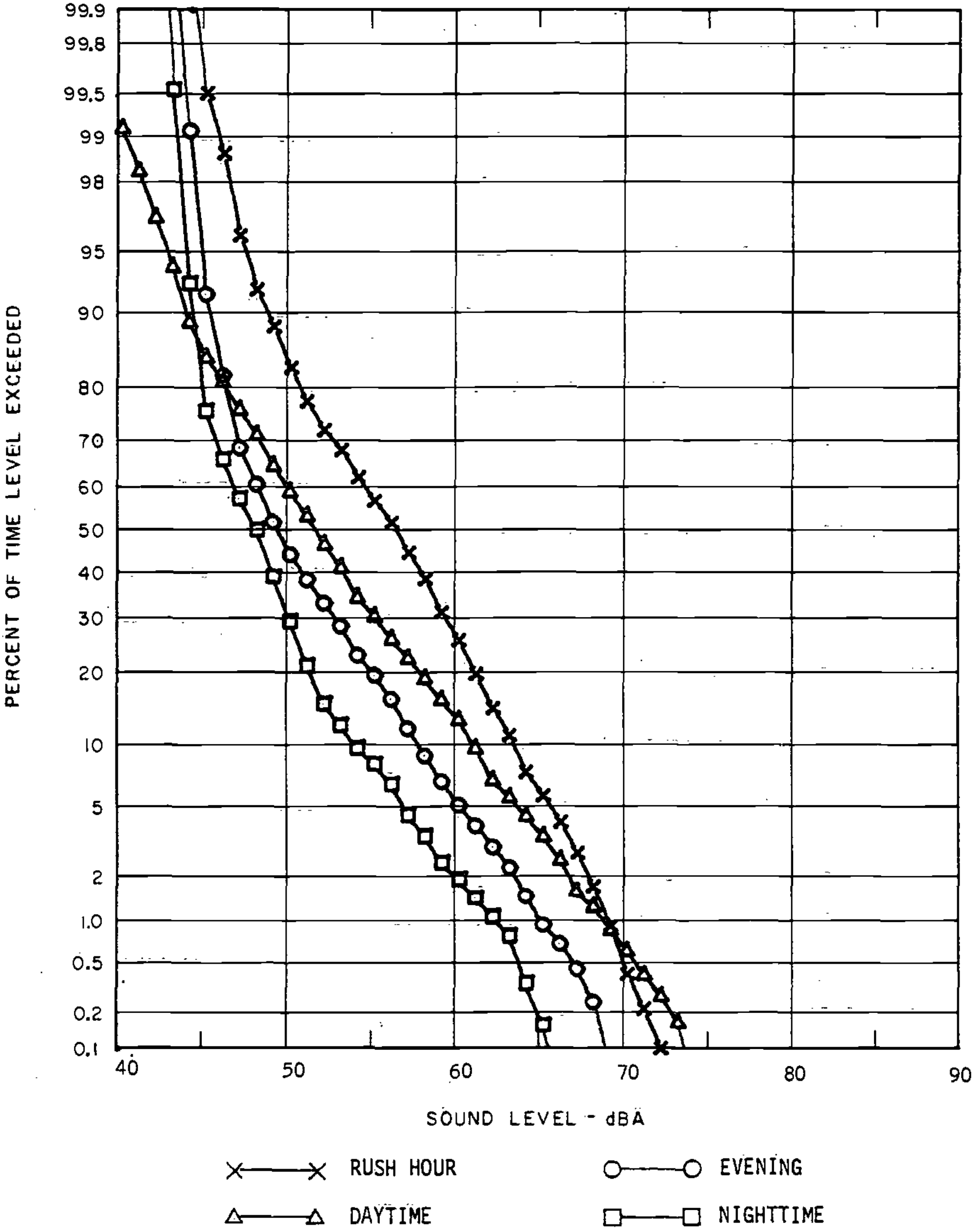


FIGURE A-77 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 132

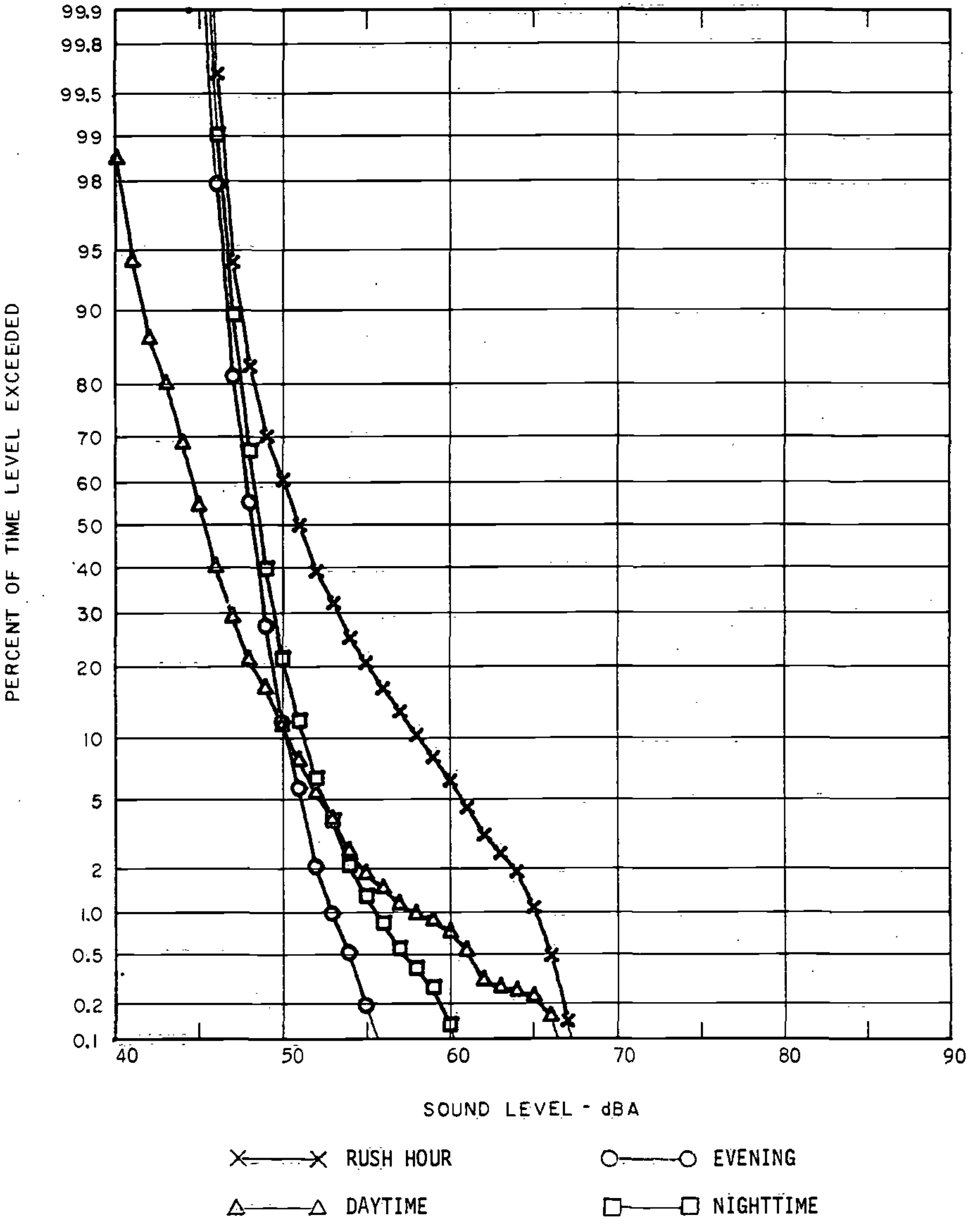


FIGURE A-78 STATISTICAL DISTRIBUTION OF THE NOISE AT LOCATION 133

APPENDIX B

STATISTICAL DISTRIBUTION OF THE VIBRATION AT THE MEASUREMENT LOCATIONS

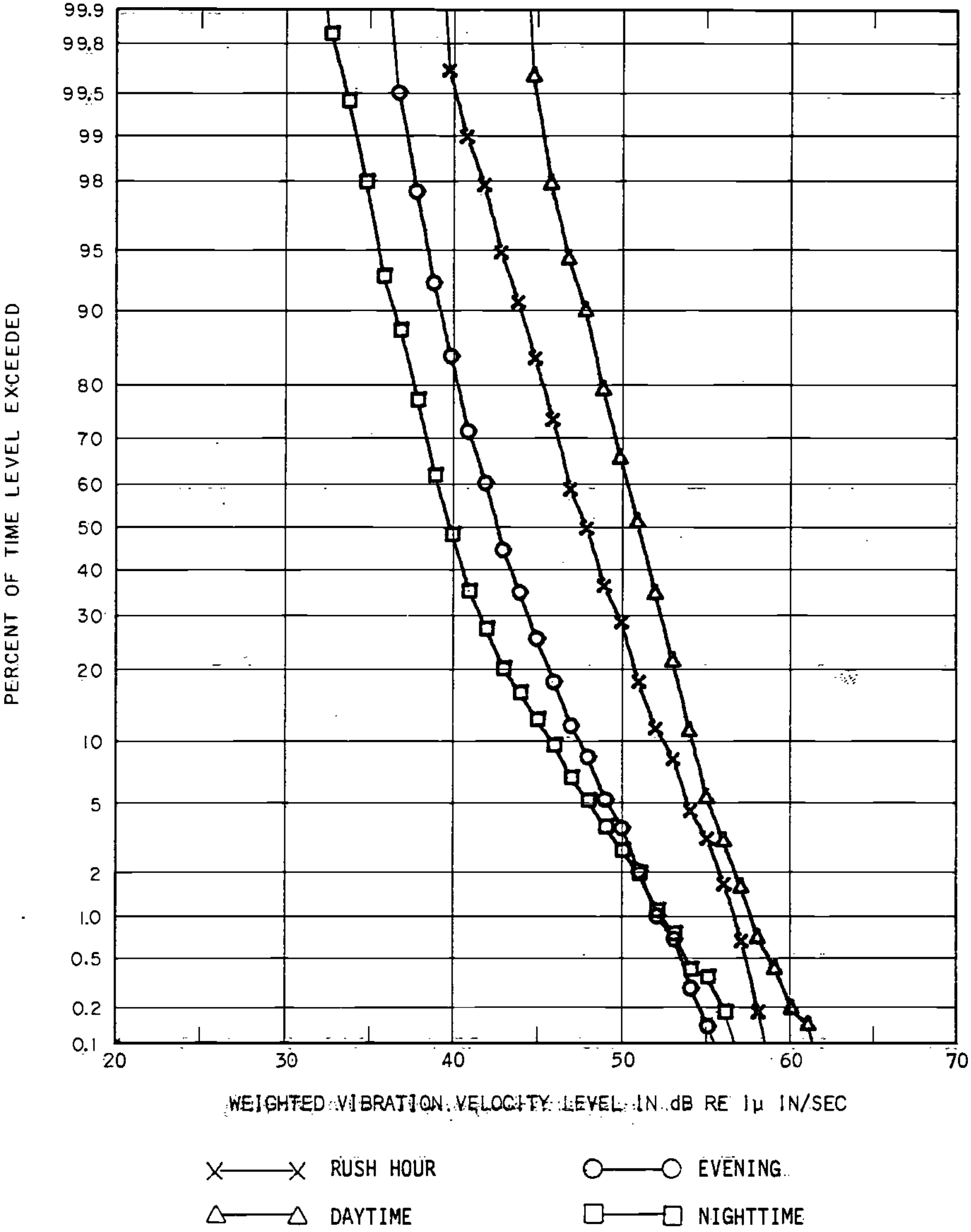


FIGURE B-1 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 1

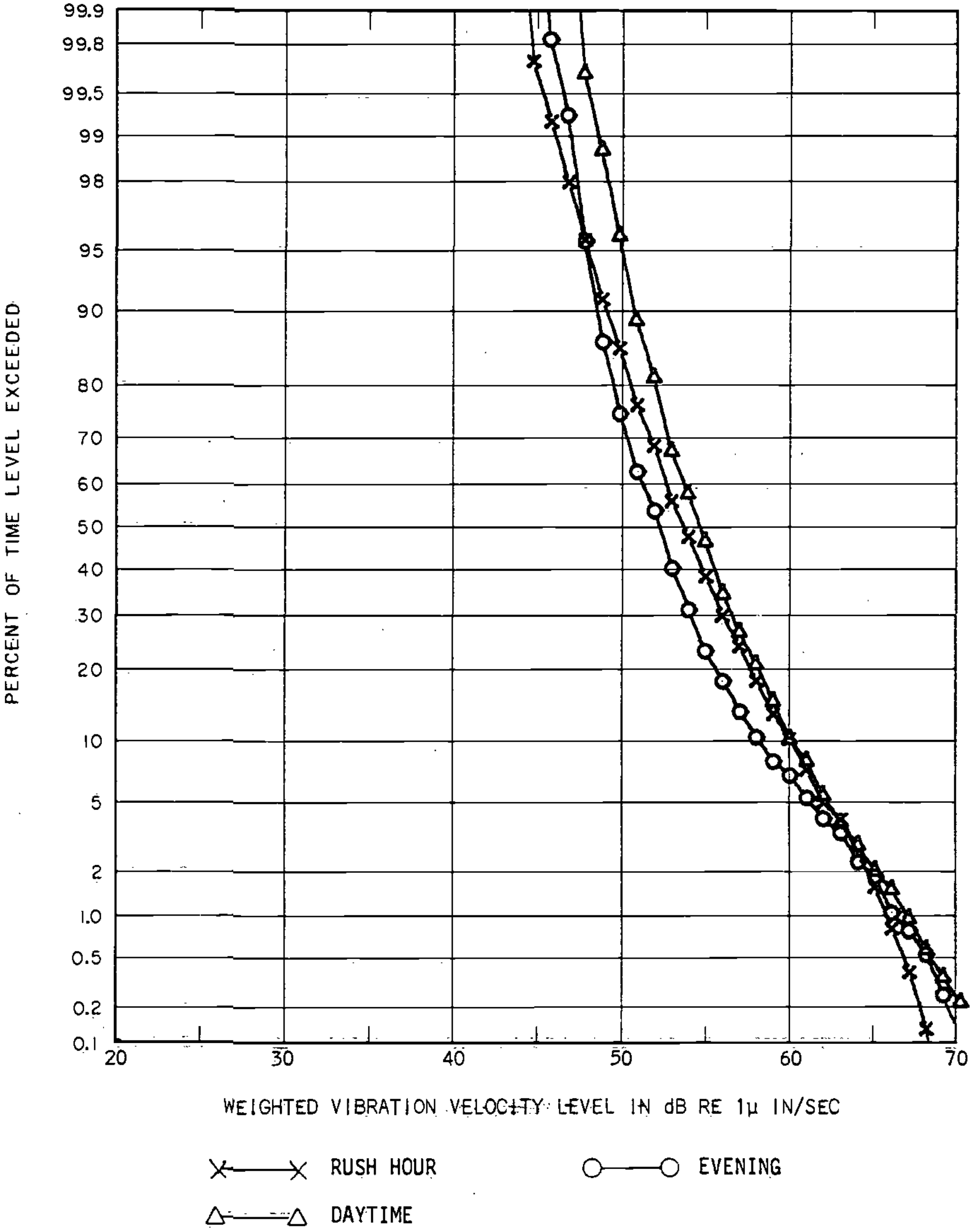


FIGURE B-2 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 2

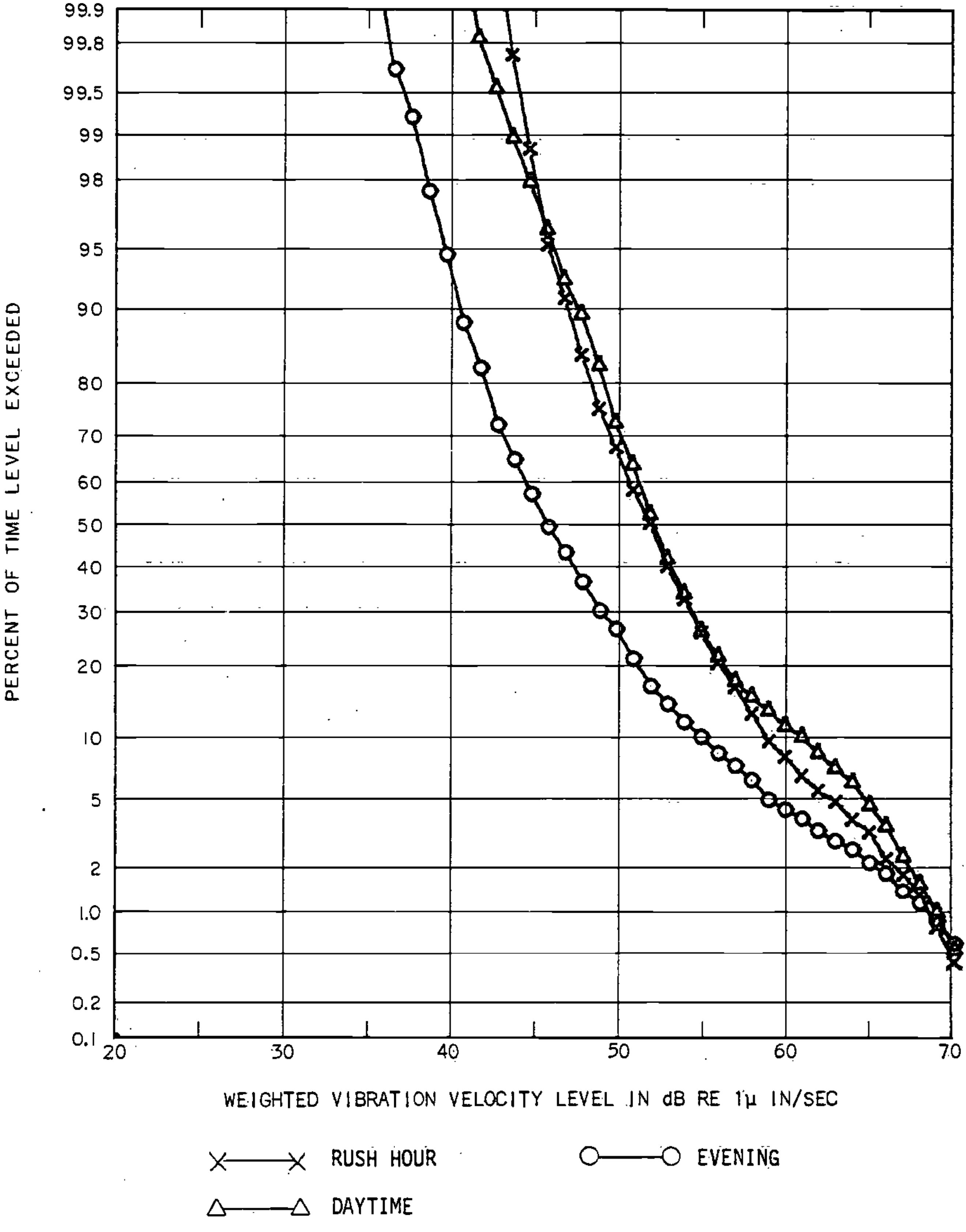


FIGURE B-3 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 3

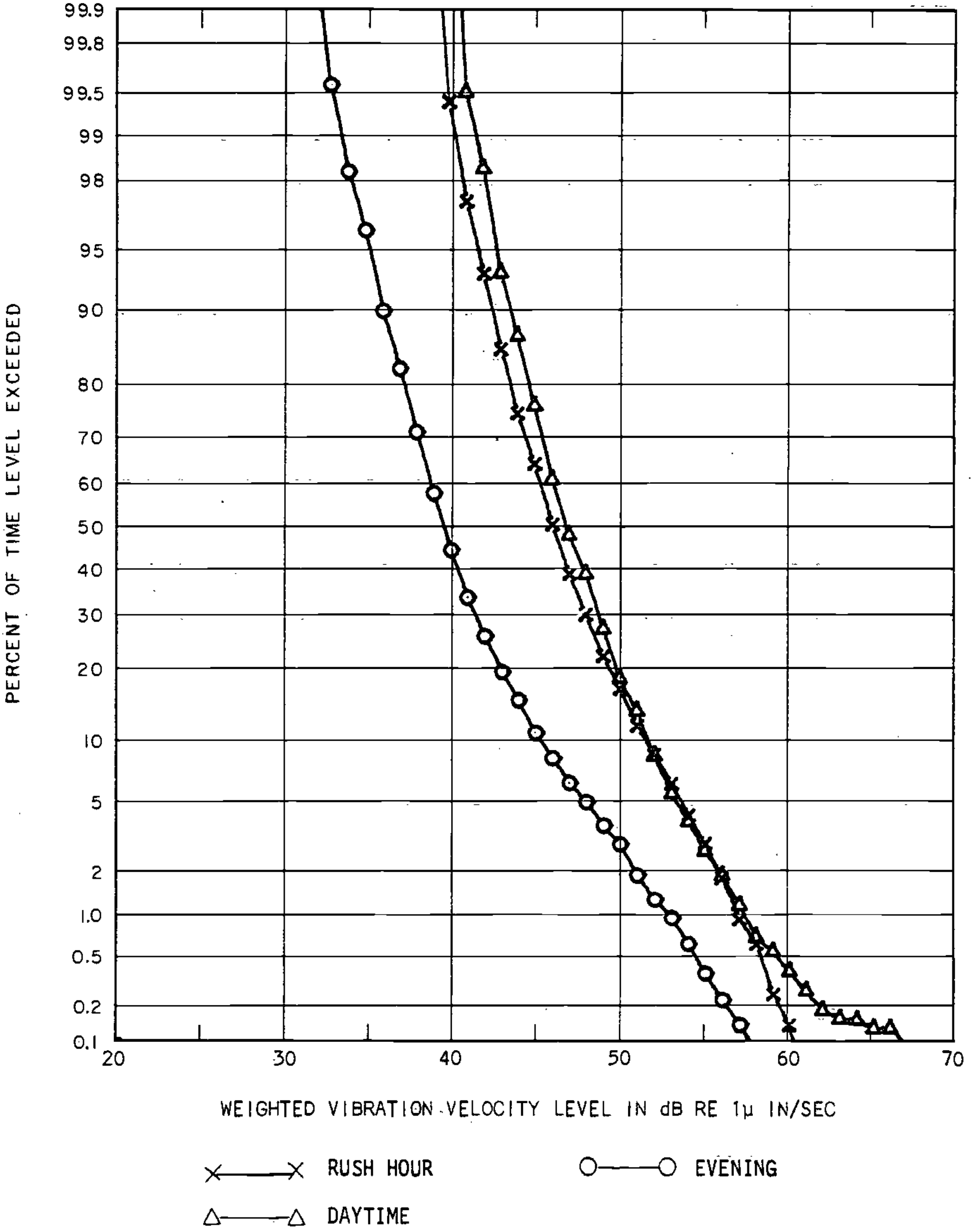


FIGURE B-4 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 4

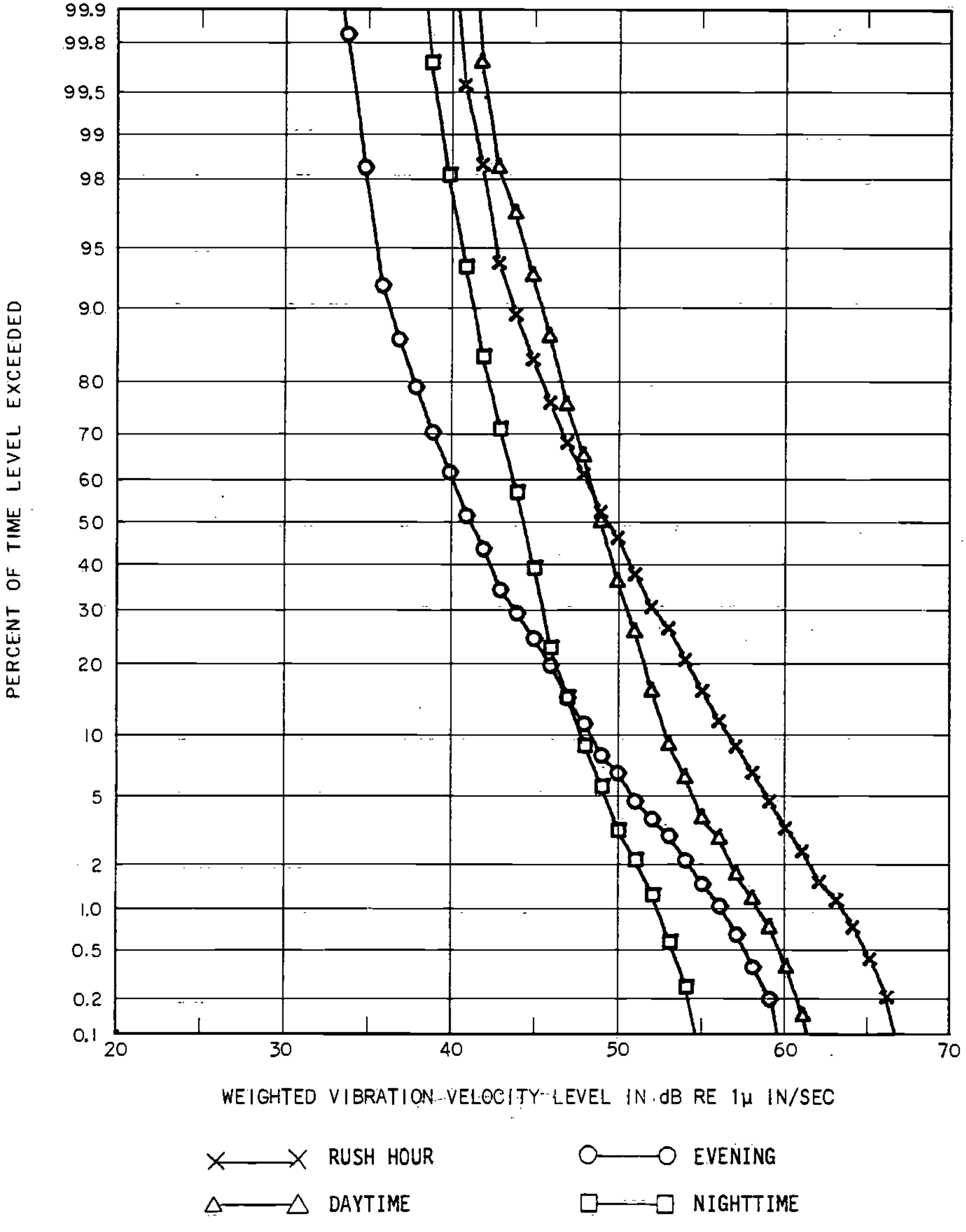


FIGURE B-5 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 5

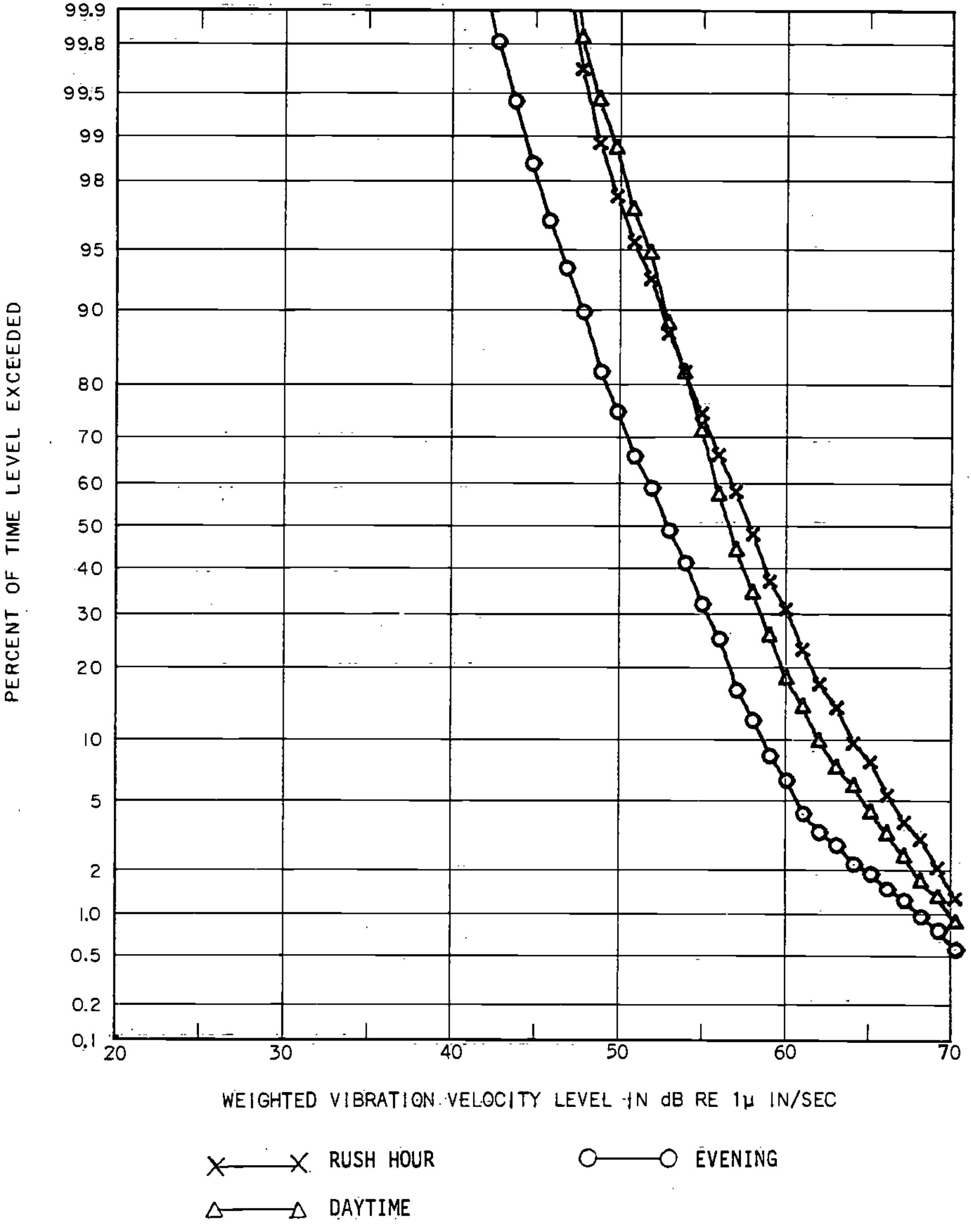


FIGURE B-6 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 6

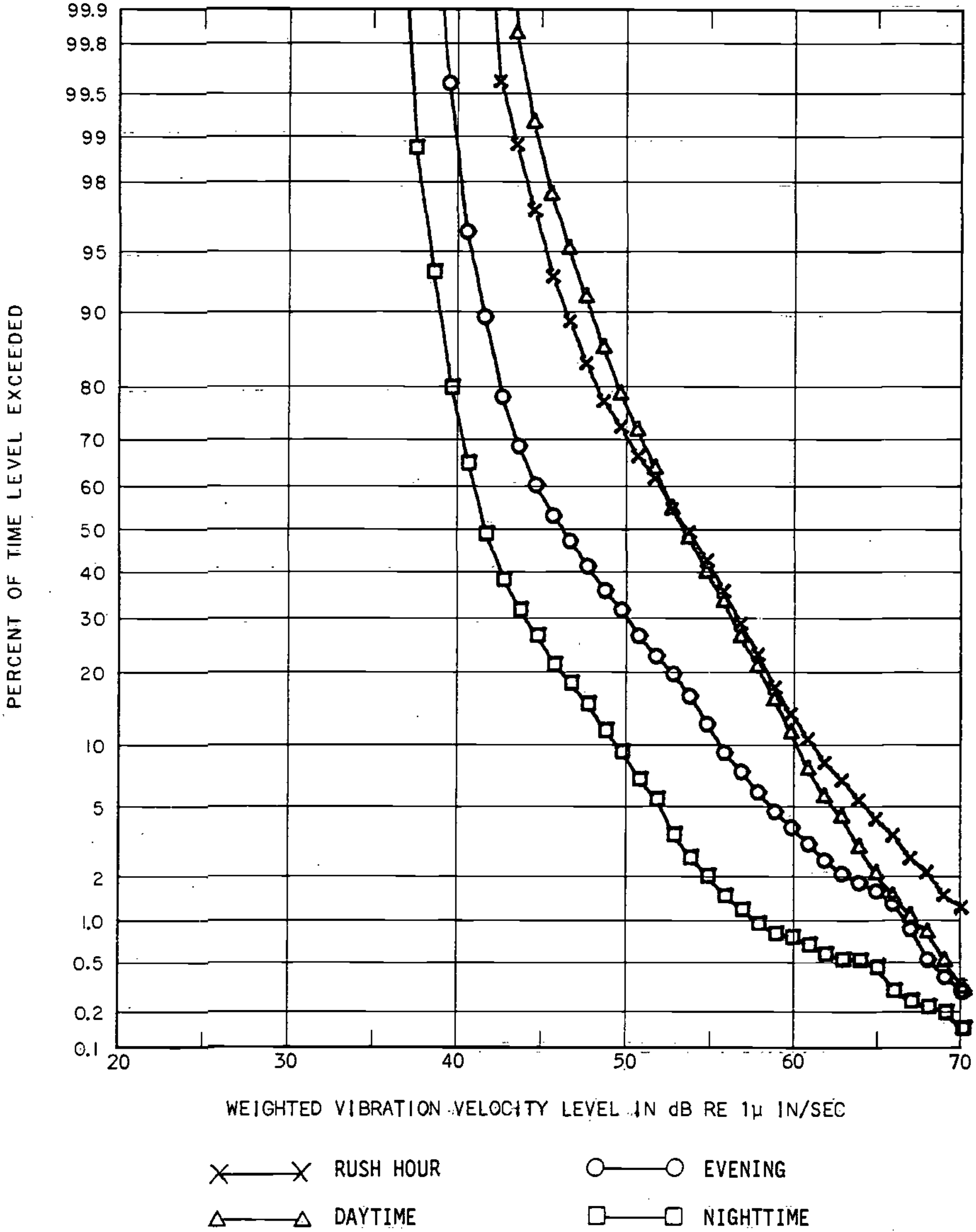


FIGURE B-7 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 7

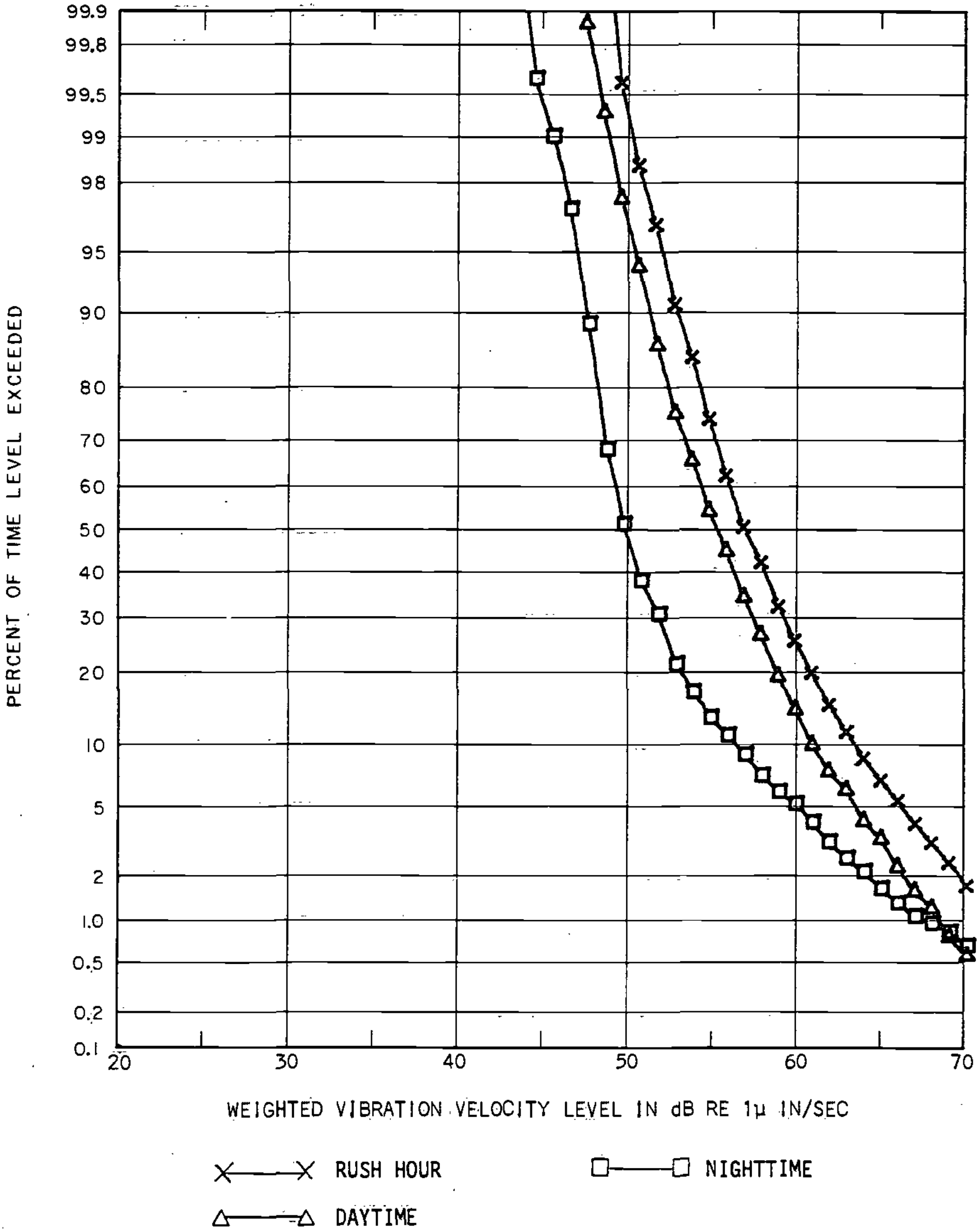


FIGURE B-8 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 8

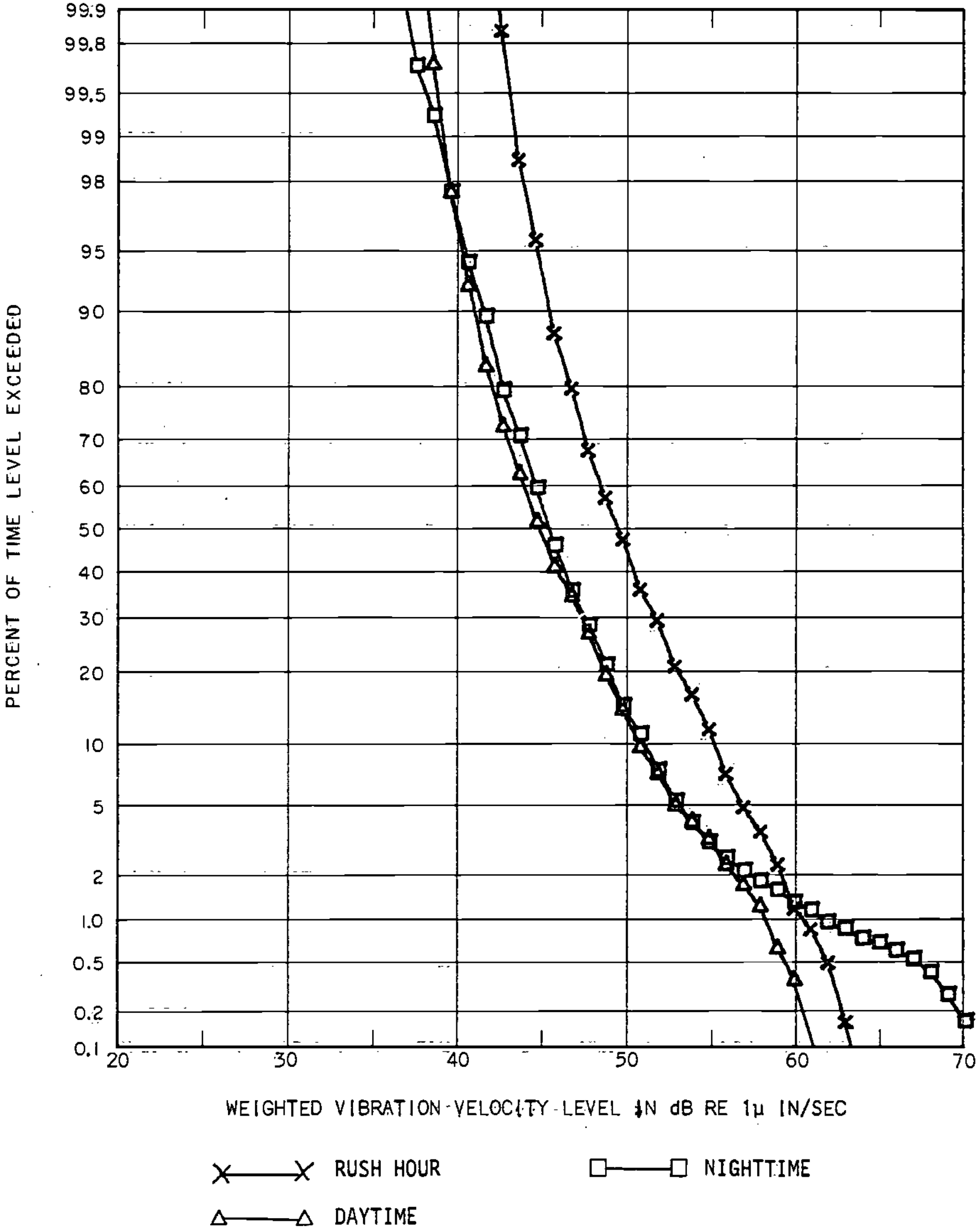


FIGURE B-9 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 9

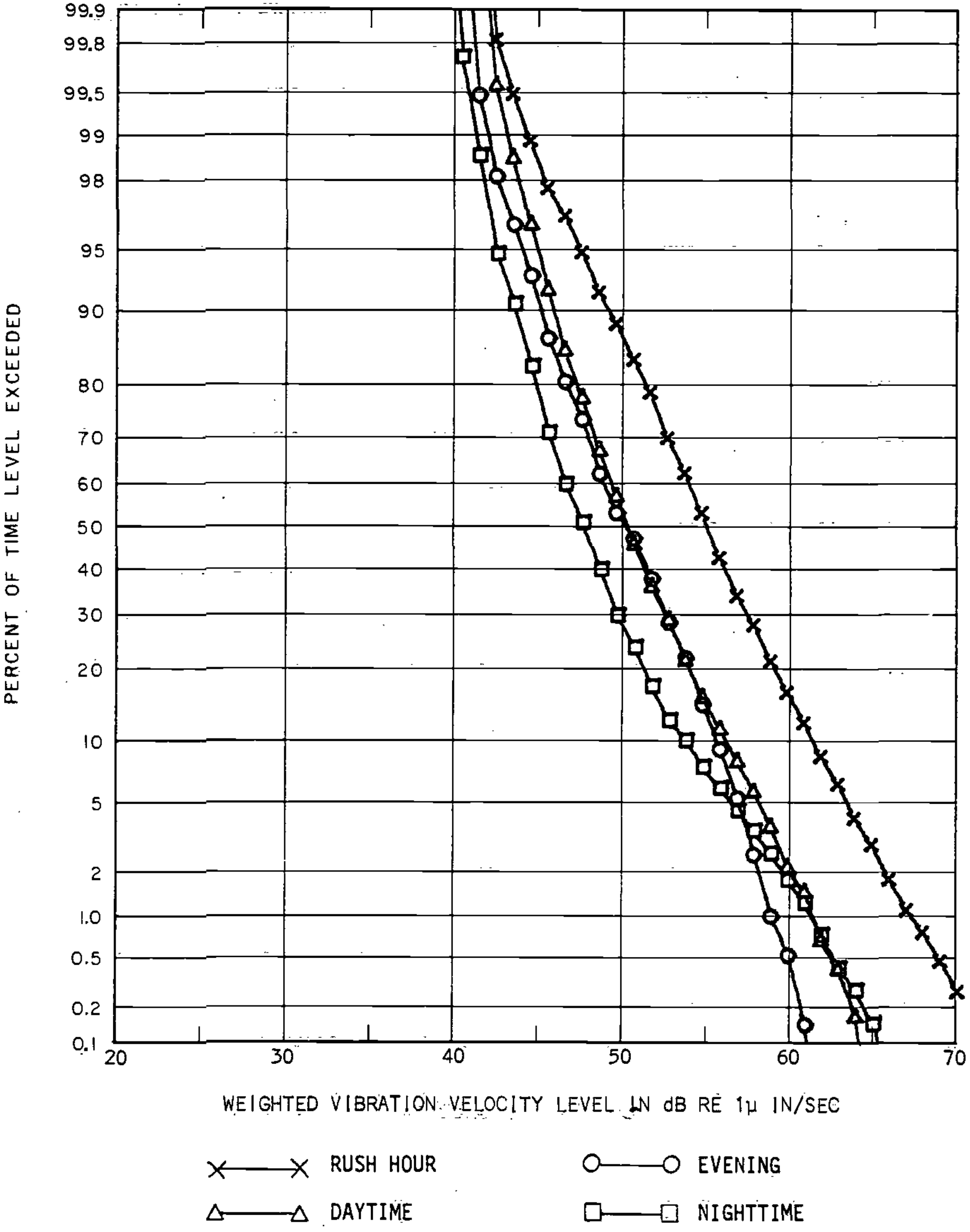


FIGURE B-10 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 10

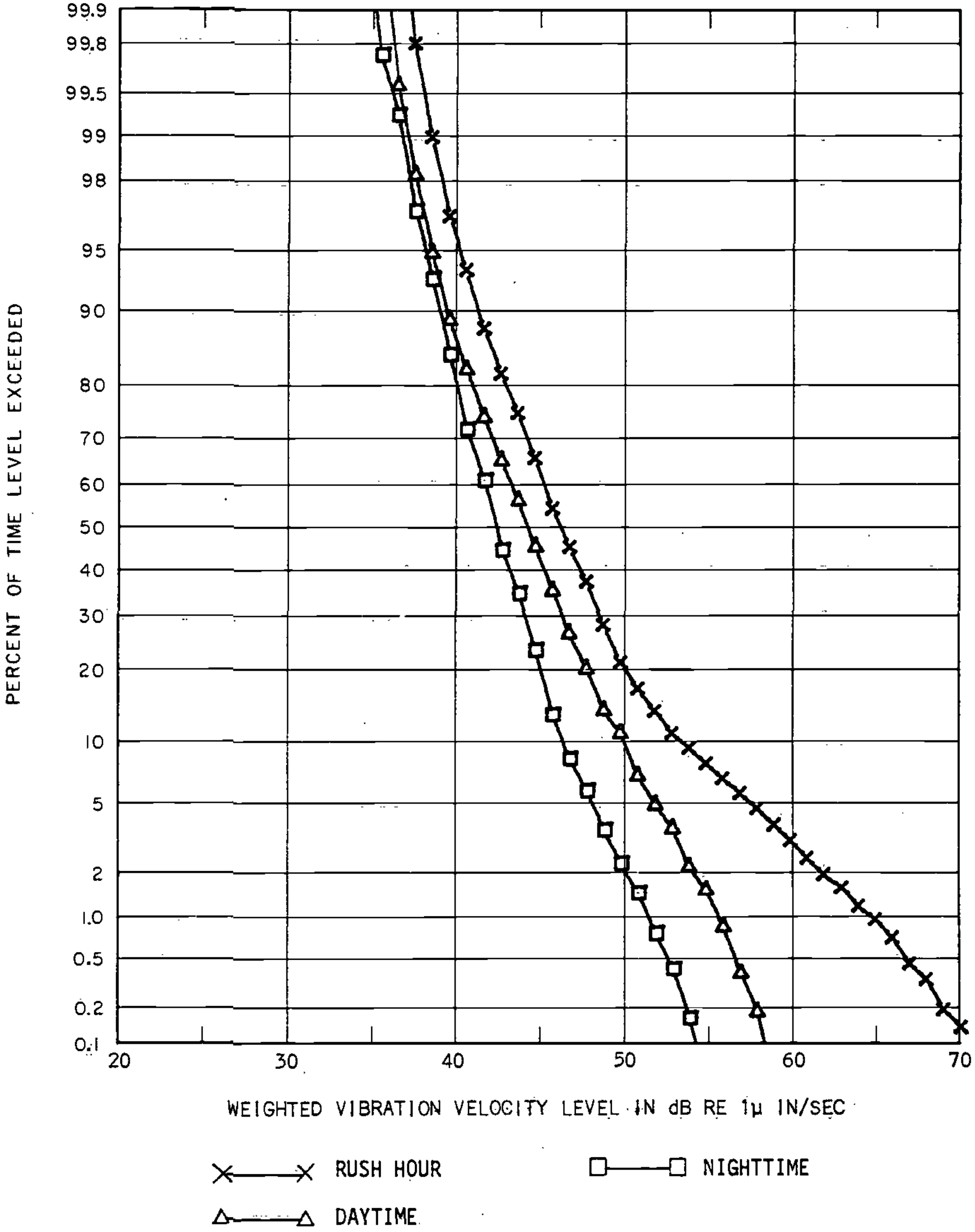


FIGURE B-11 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 11

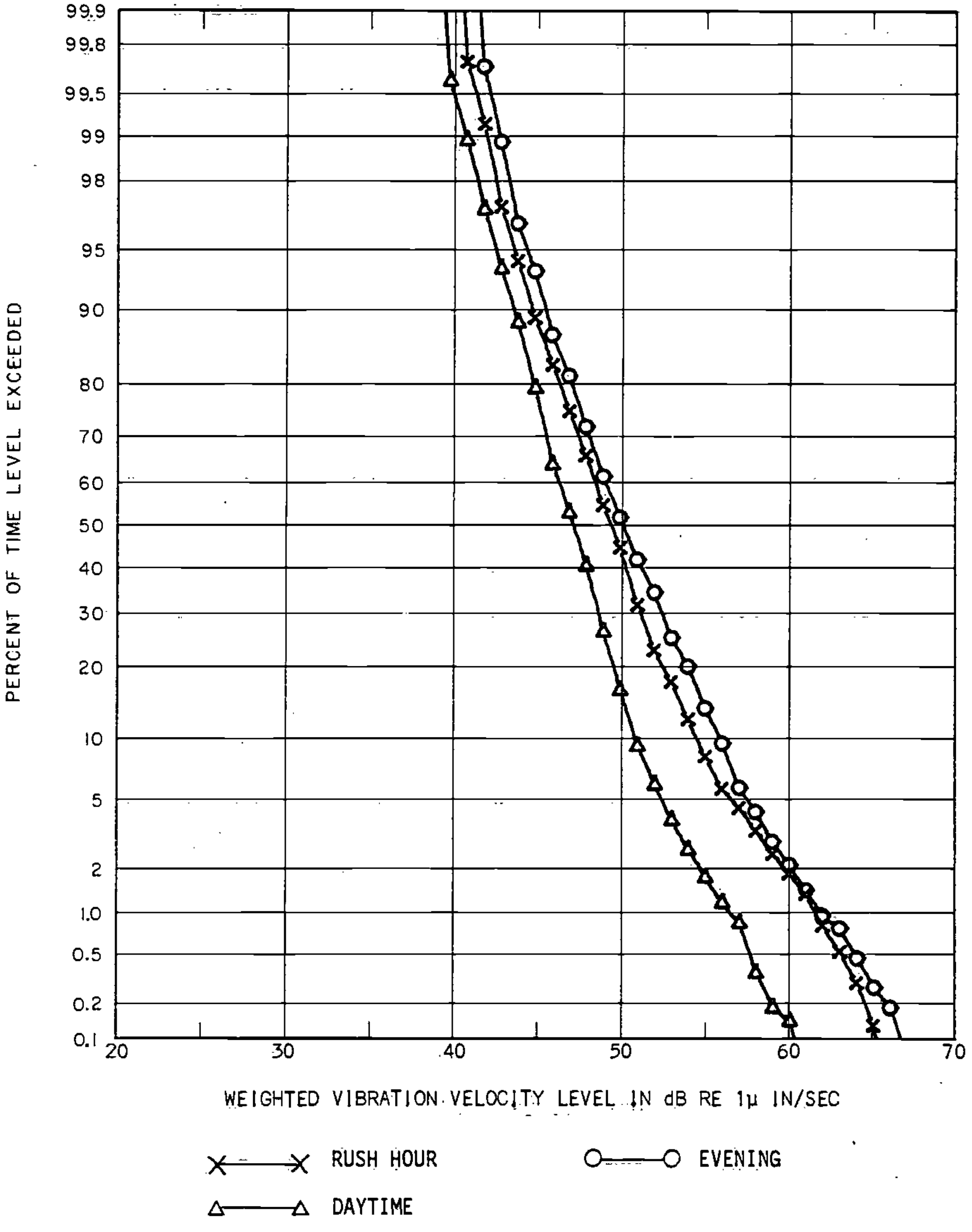


FIGURE B-12 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 12

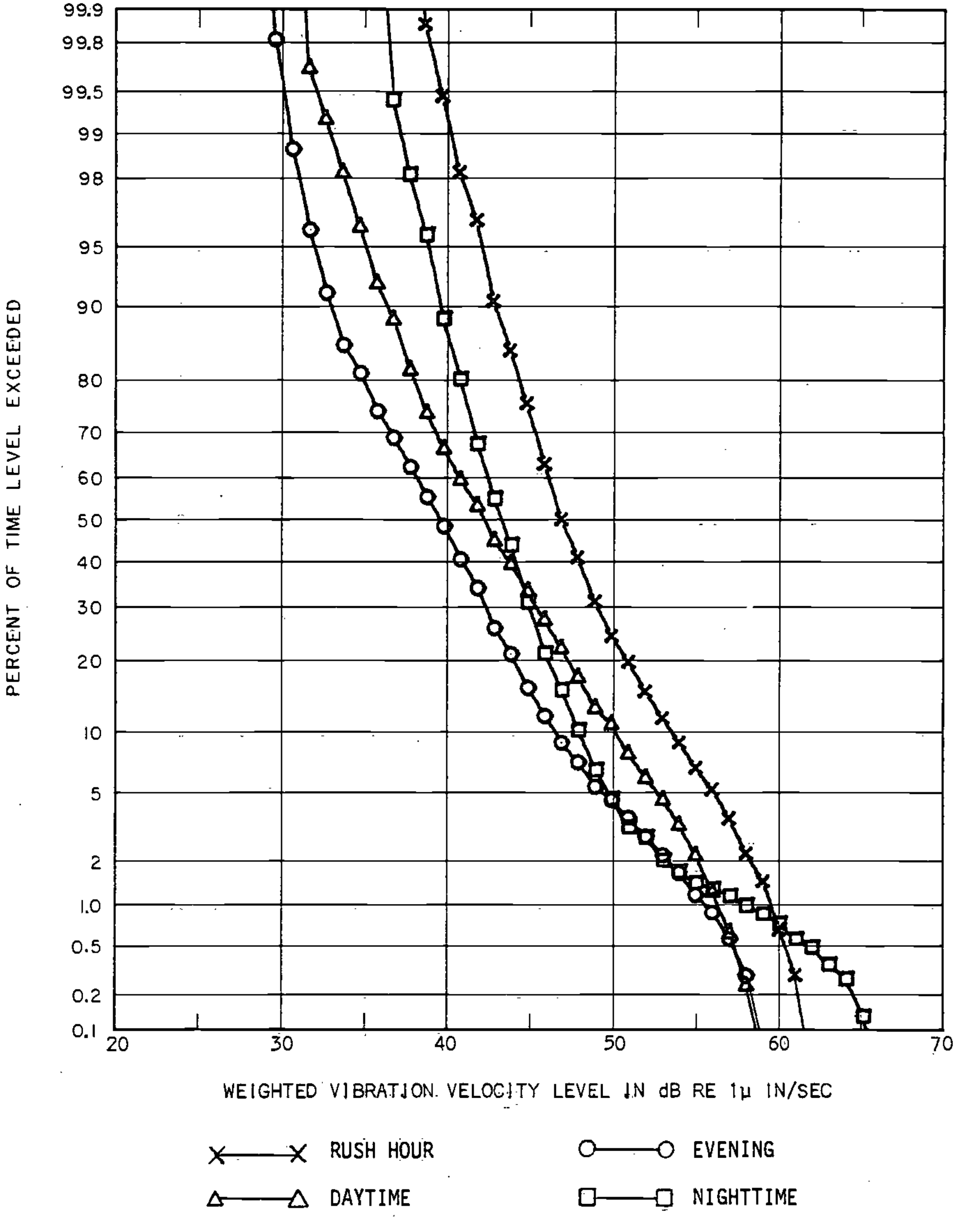


FIGURE B-13 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 13

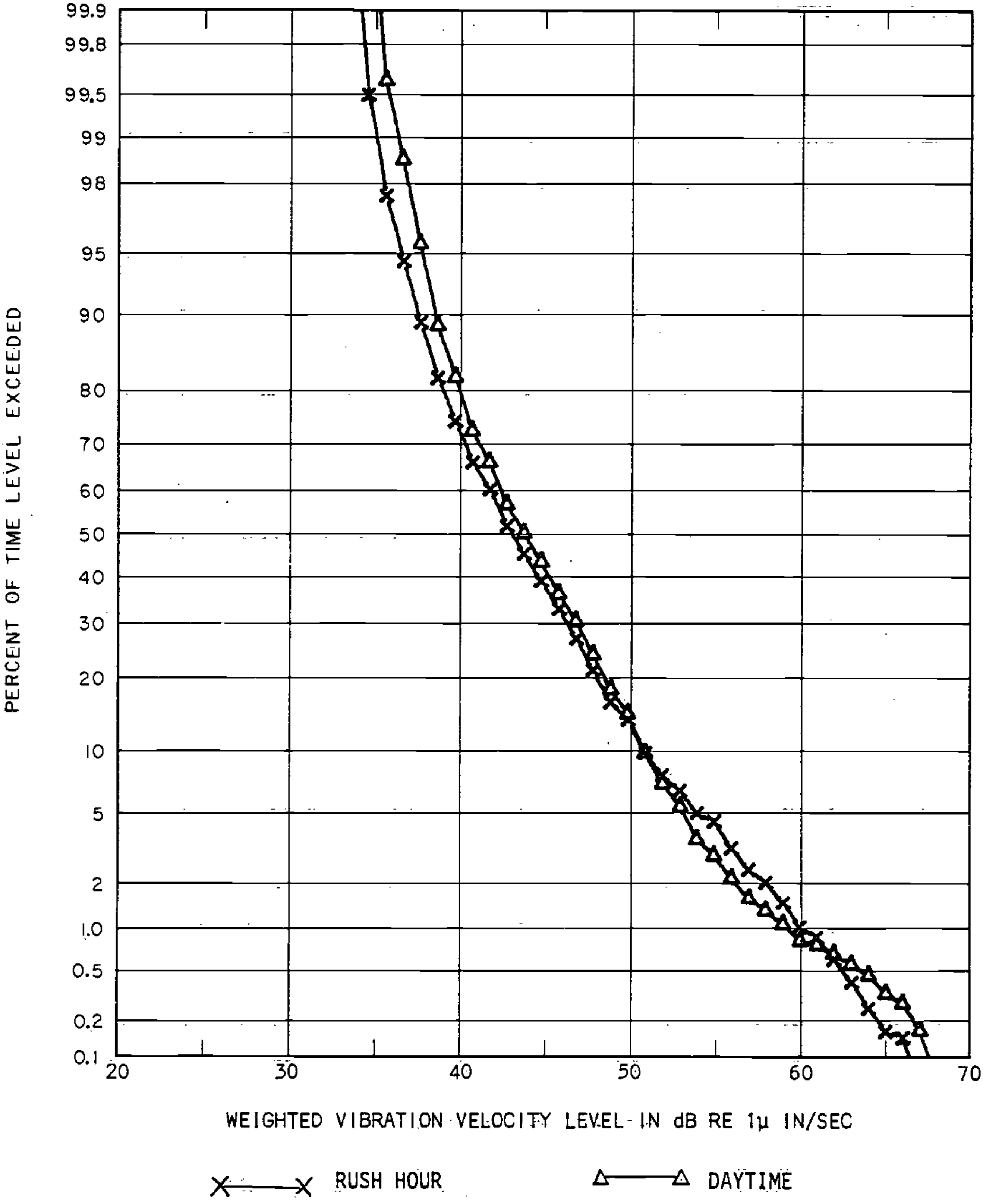


FIGURE B-14 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 14

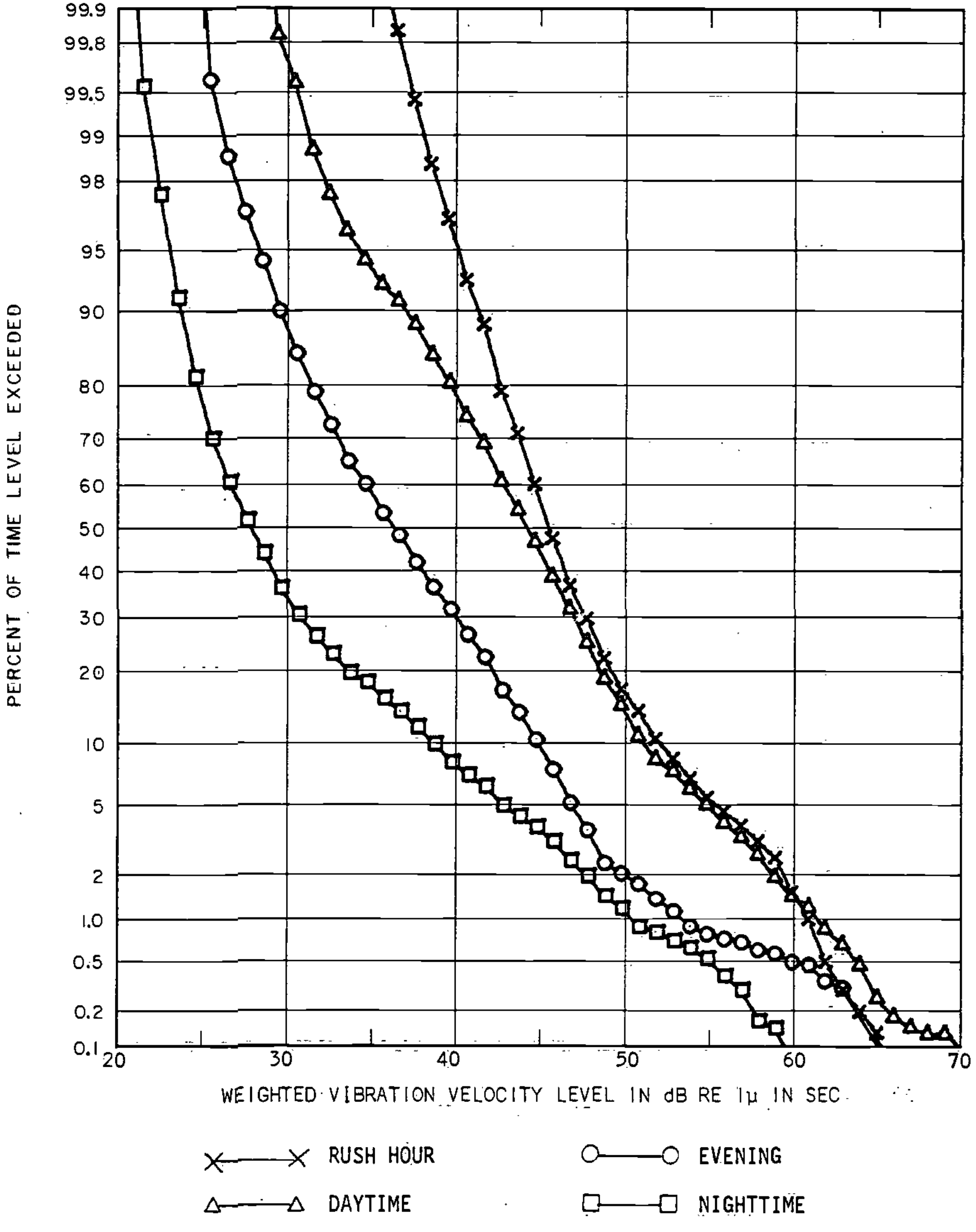


FIGURE B-15 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 15

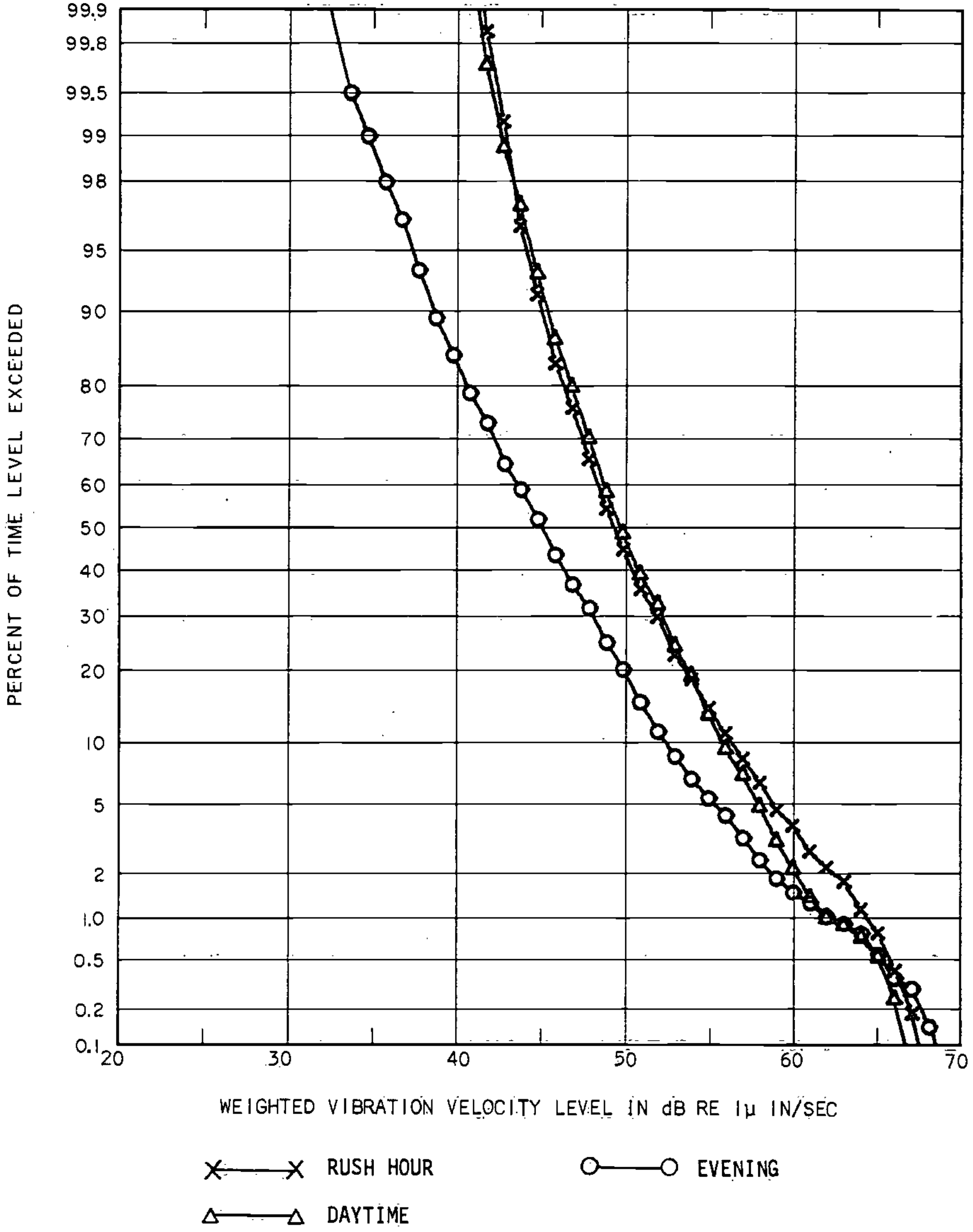


FIGURE B-16 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 16

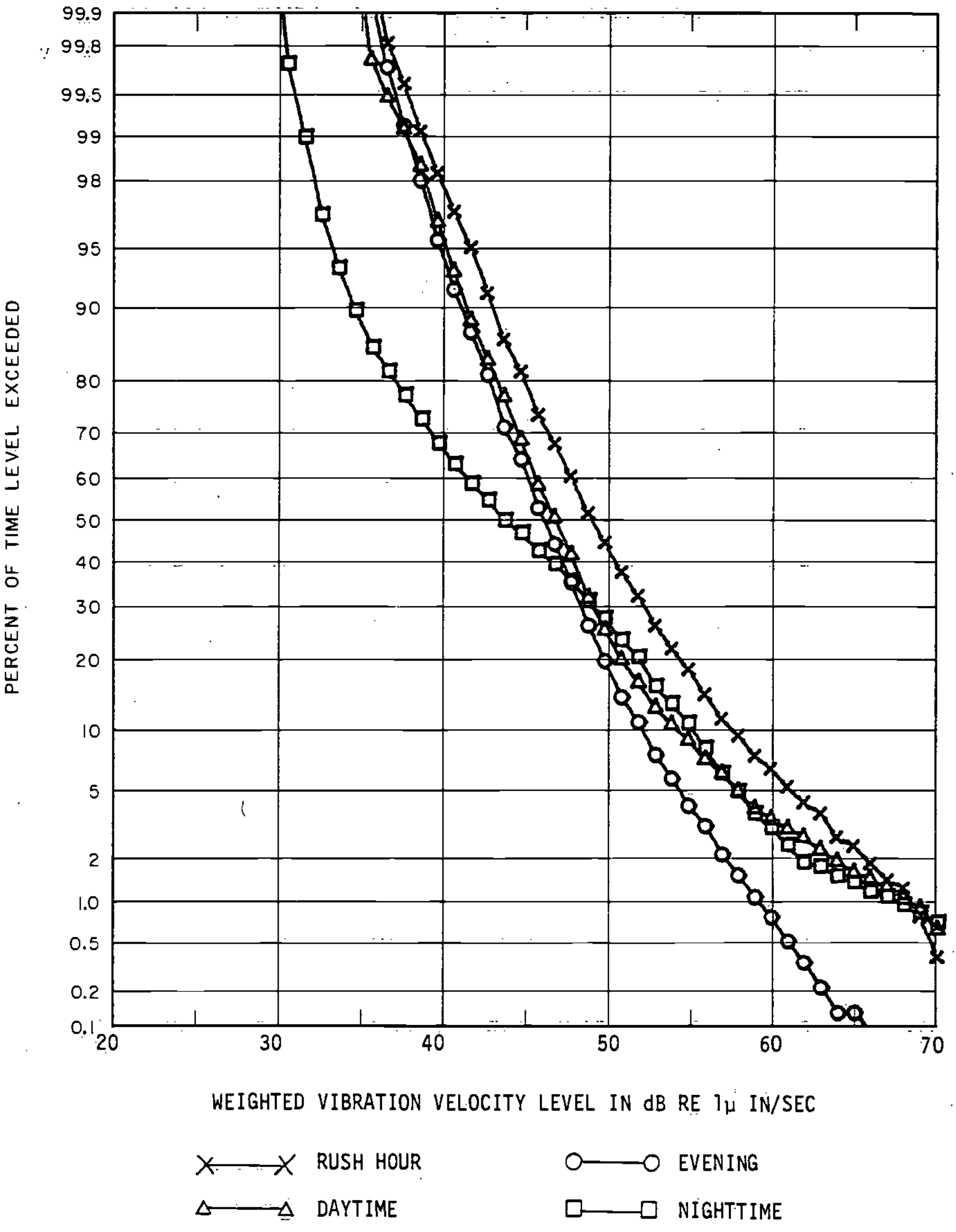


FIGURE B-17 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 17

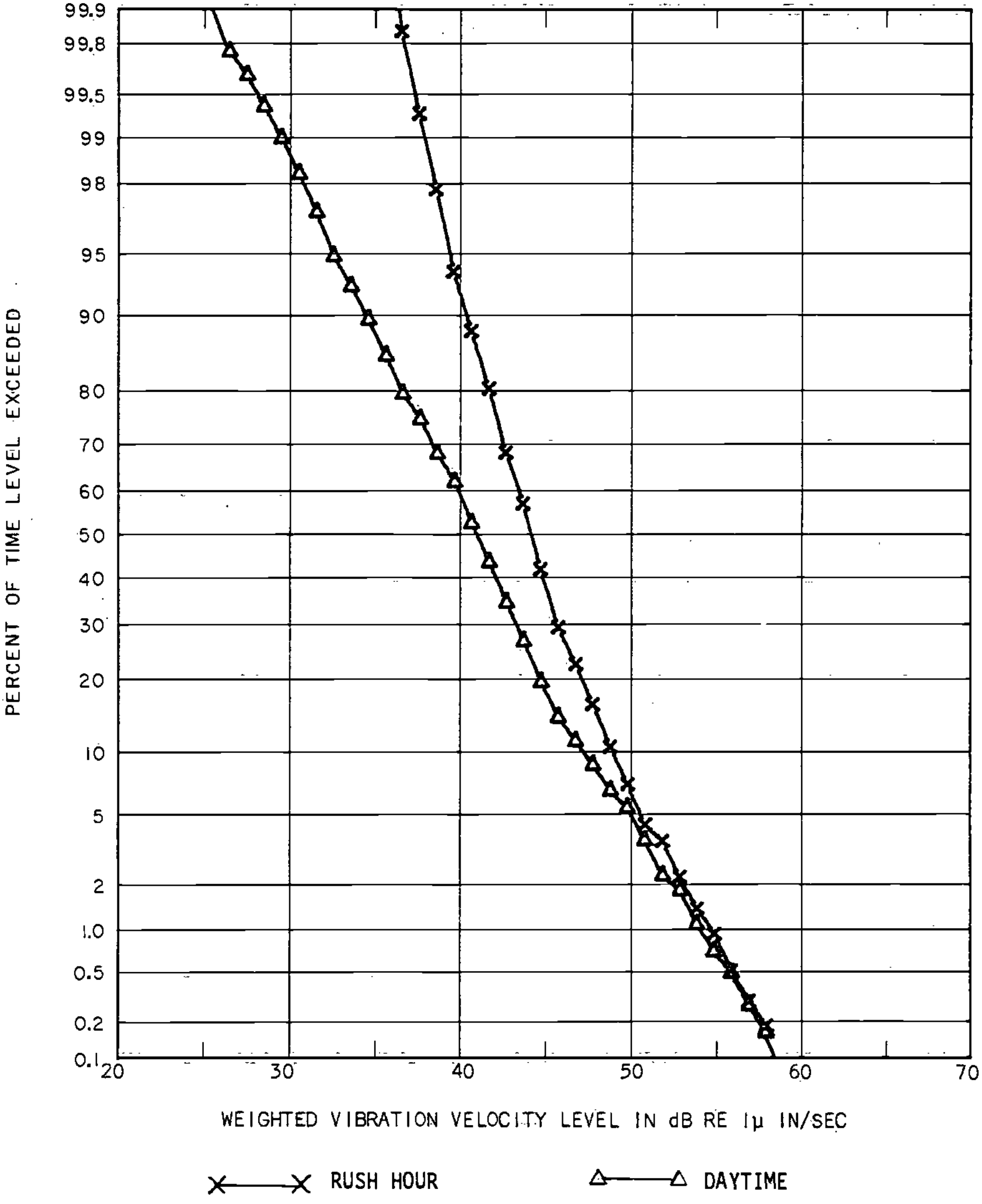


FIGURE B-18 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 18

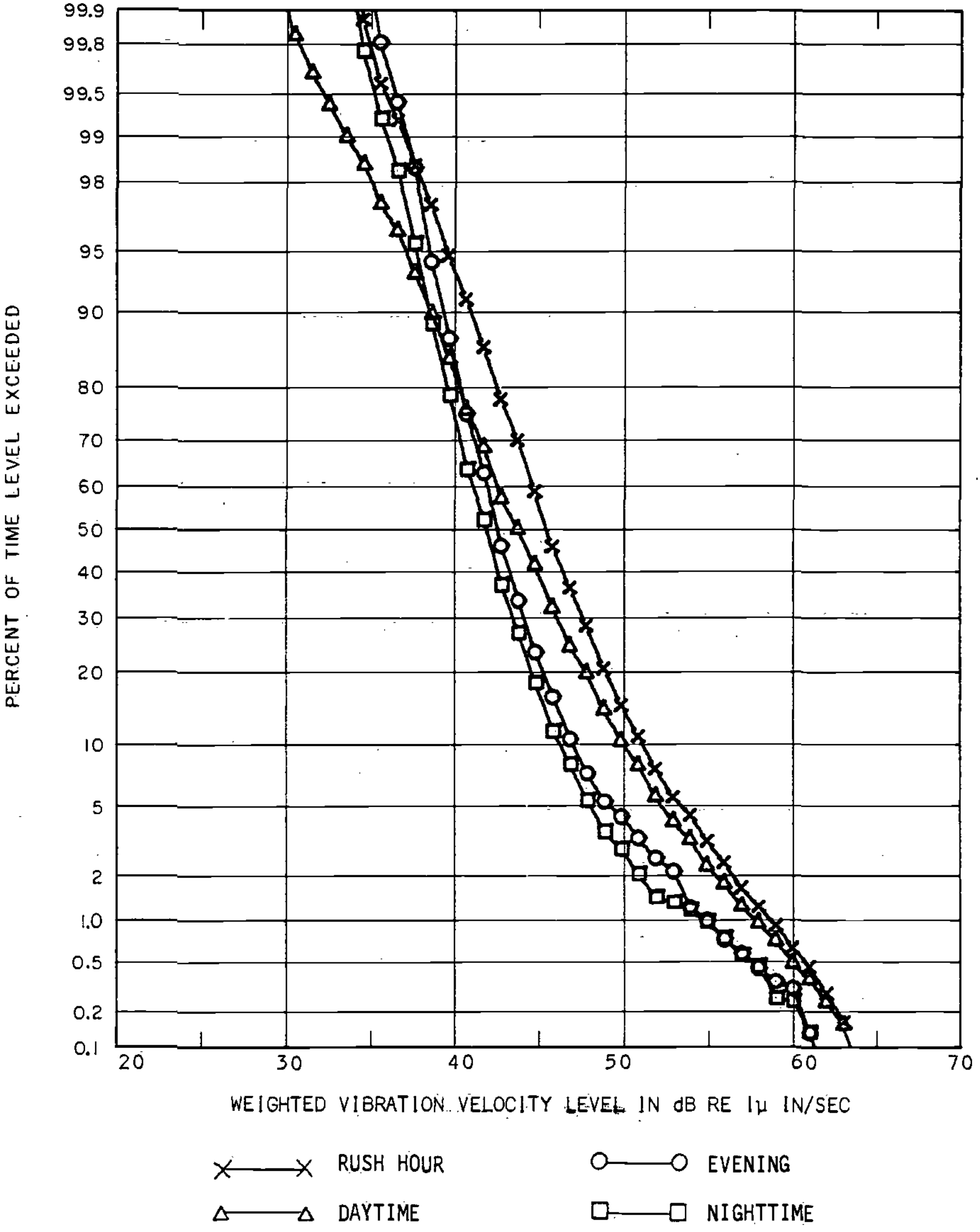


FIGURE B-19 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 19

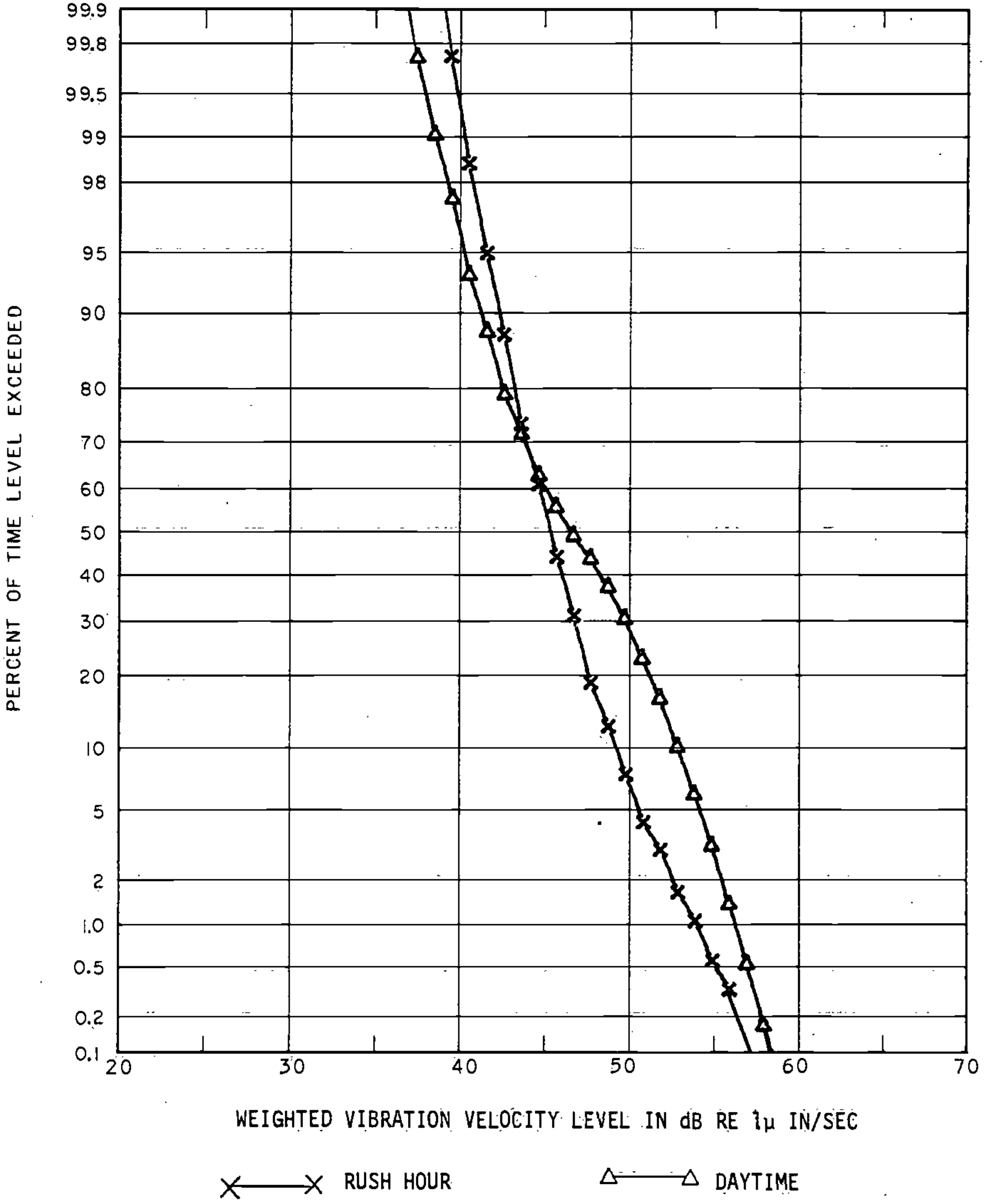


FIGURE B-20 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 20

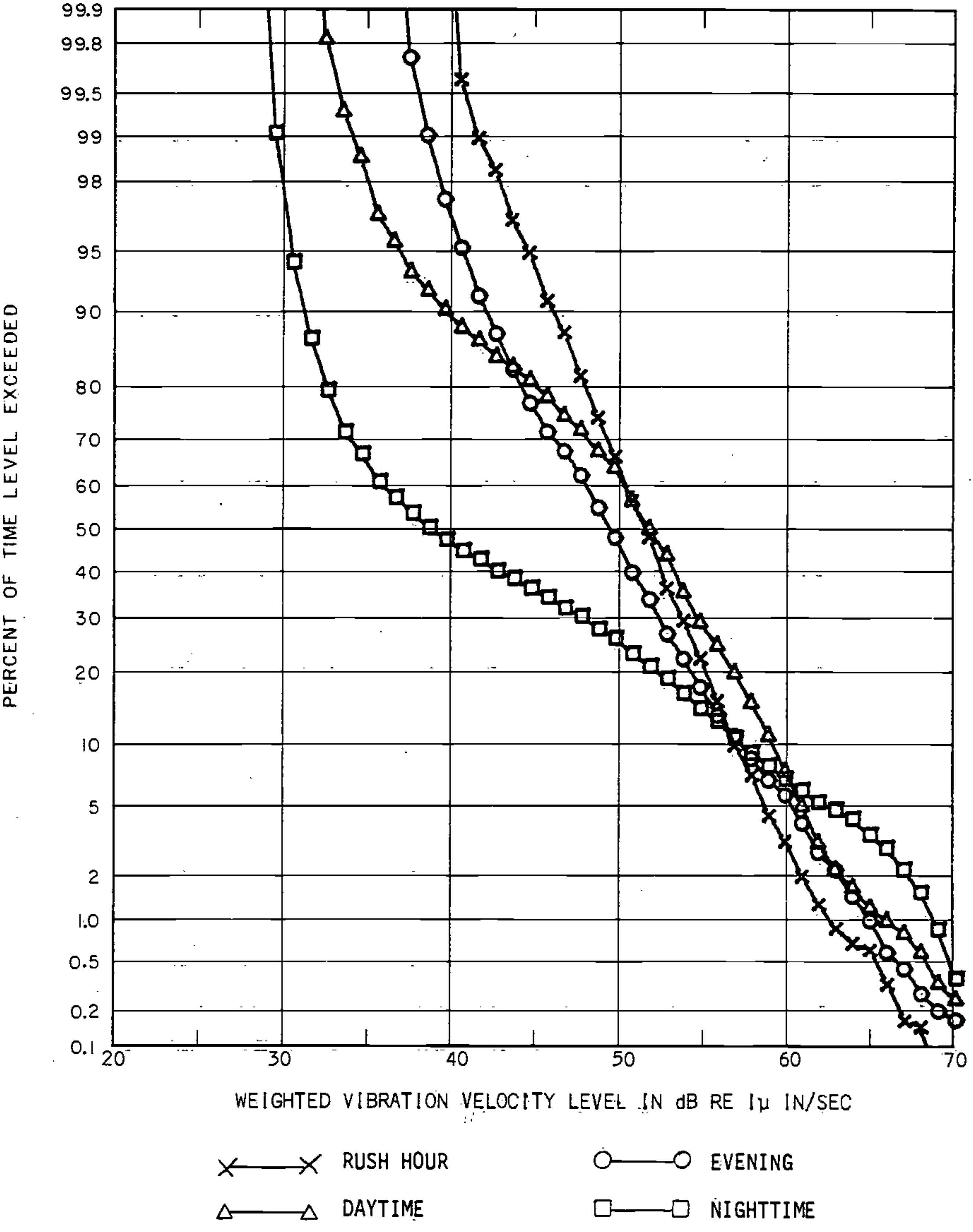


FIGURE B-21 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 21

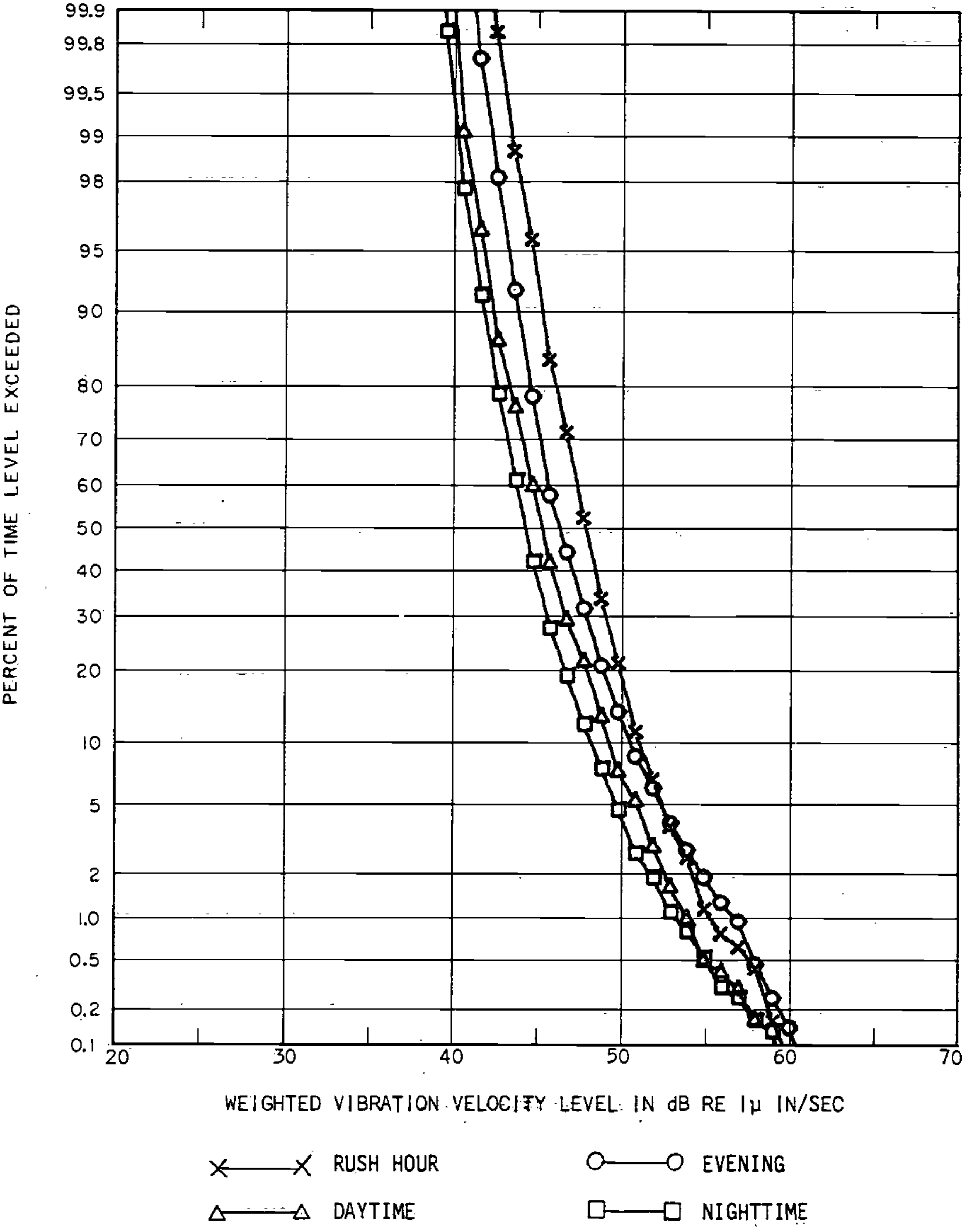


FIGURE B-22 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 22

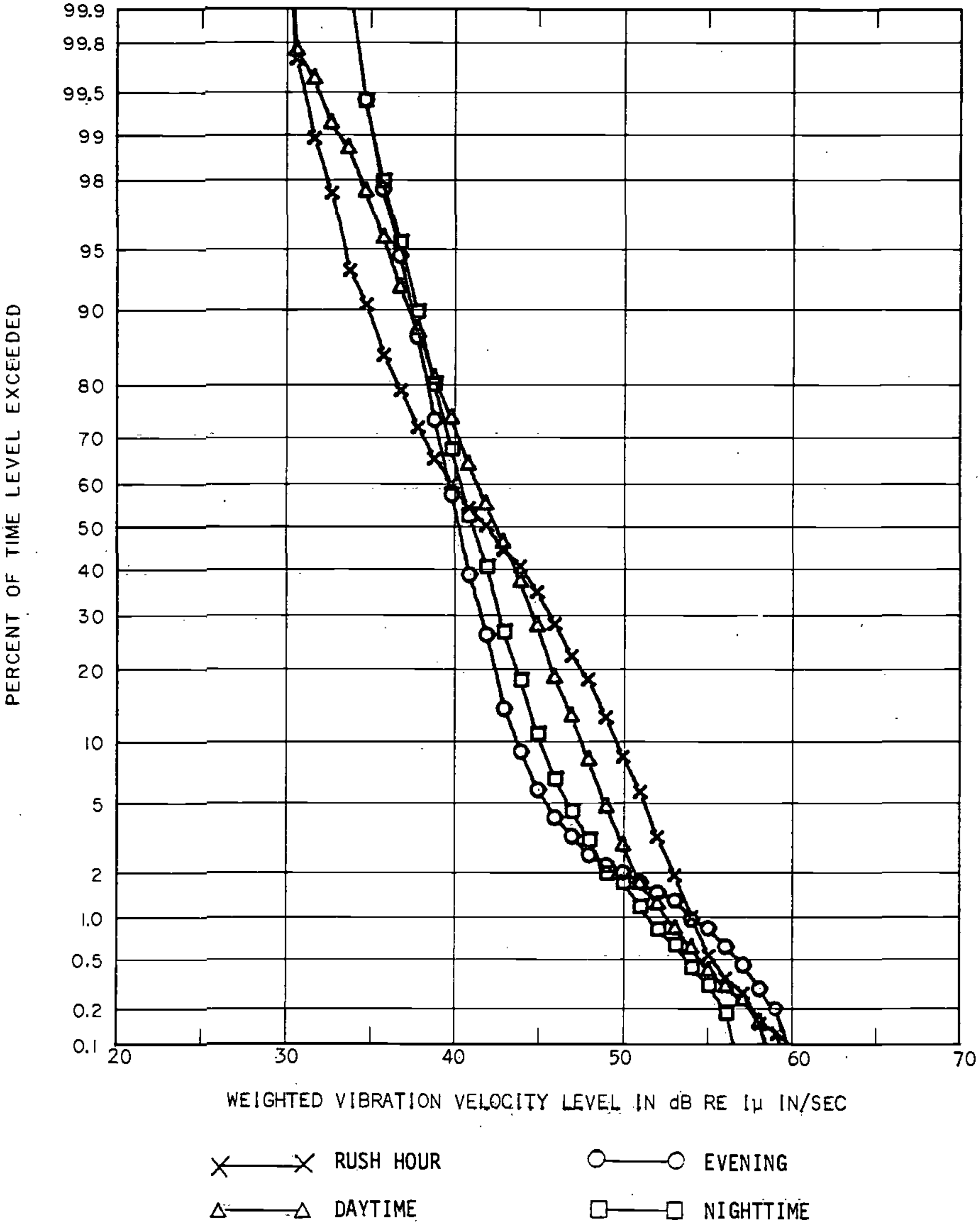


FIGURE B-23 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 23

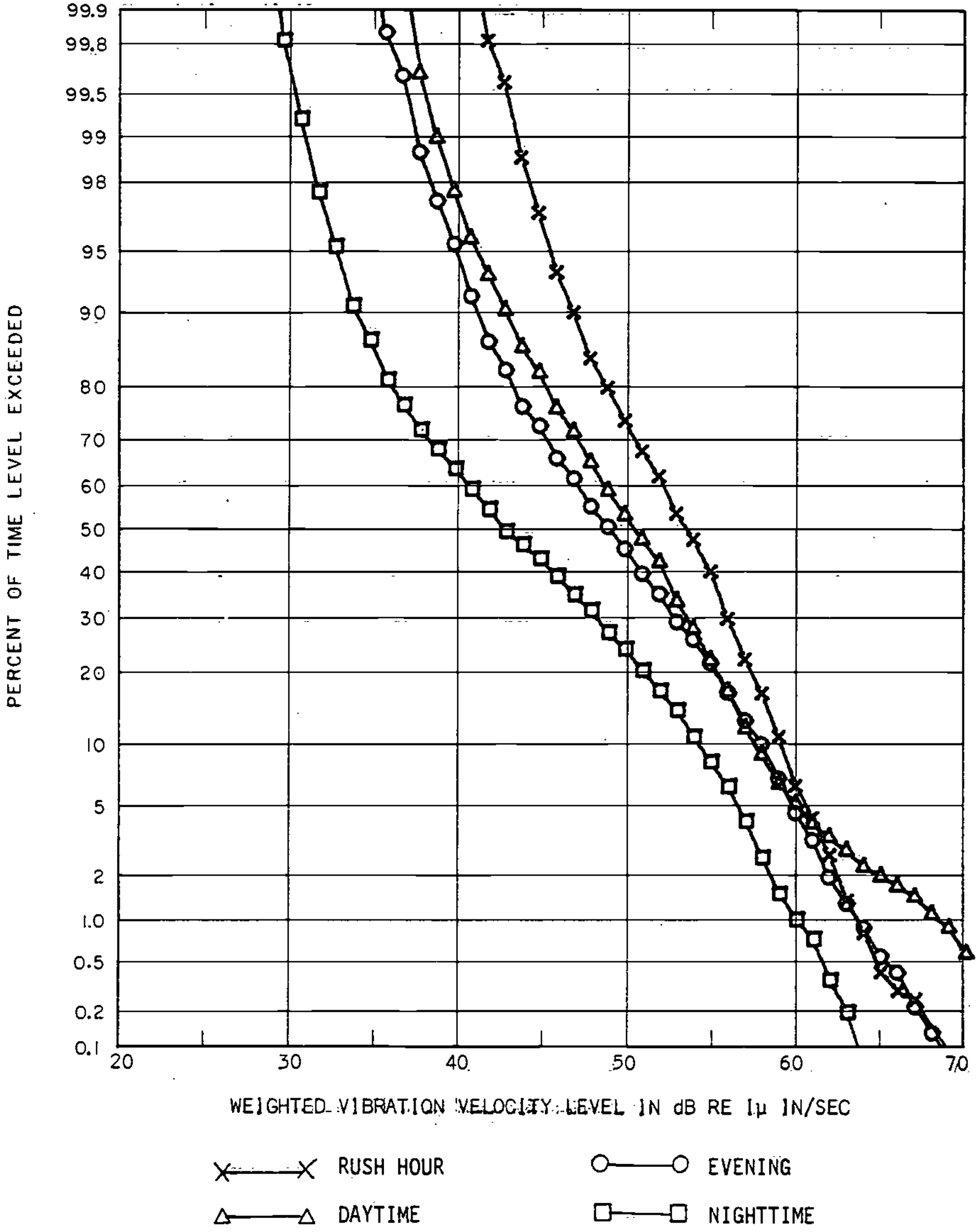


FIGURE B-24 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 24

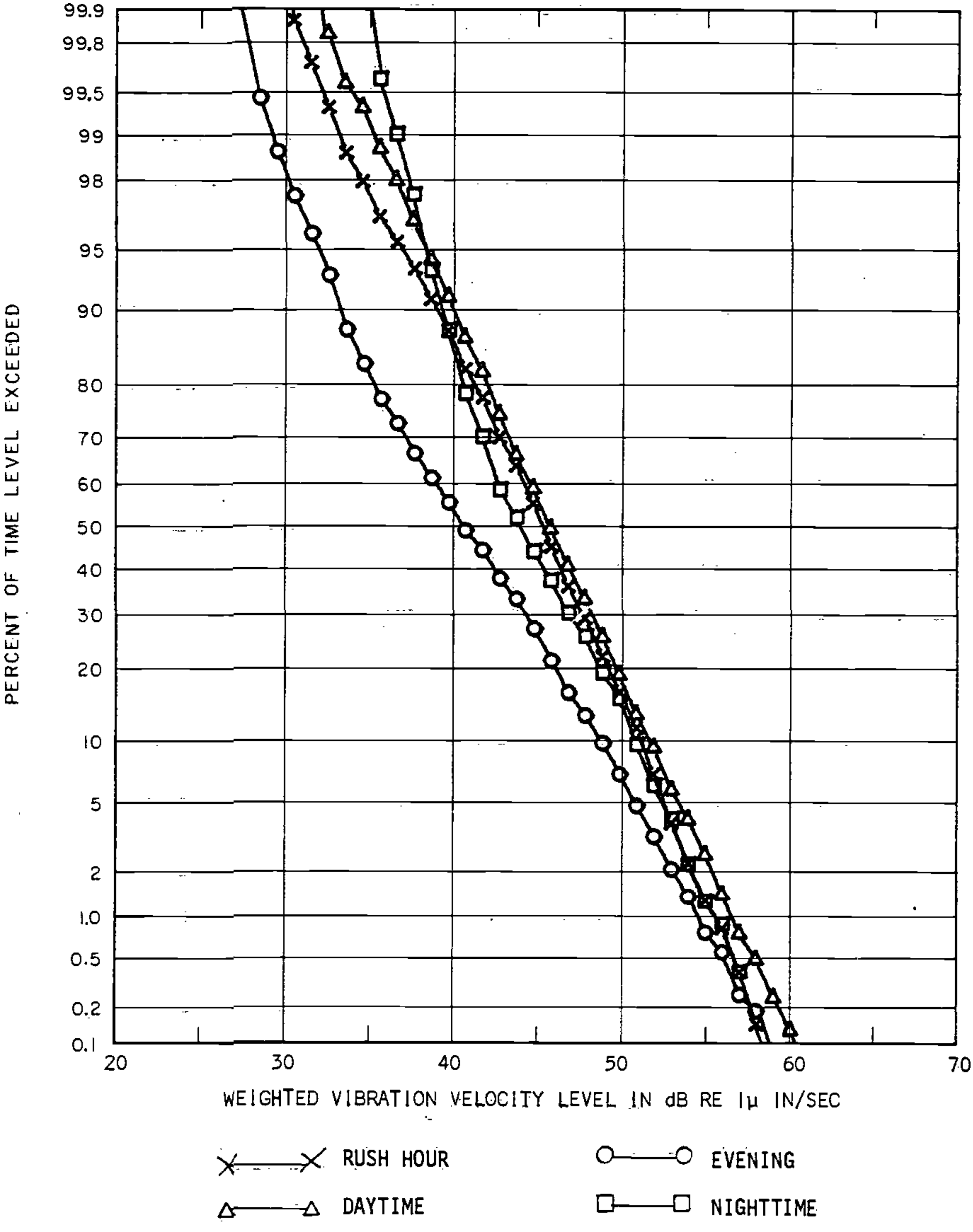


FIGURE B-25 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 25

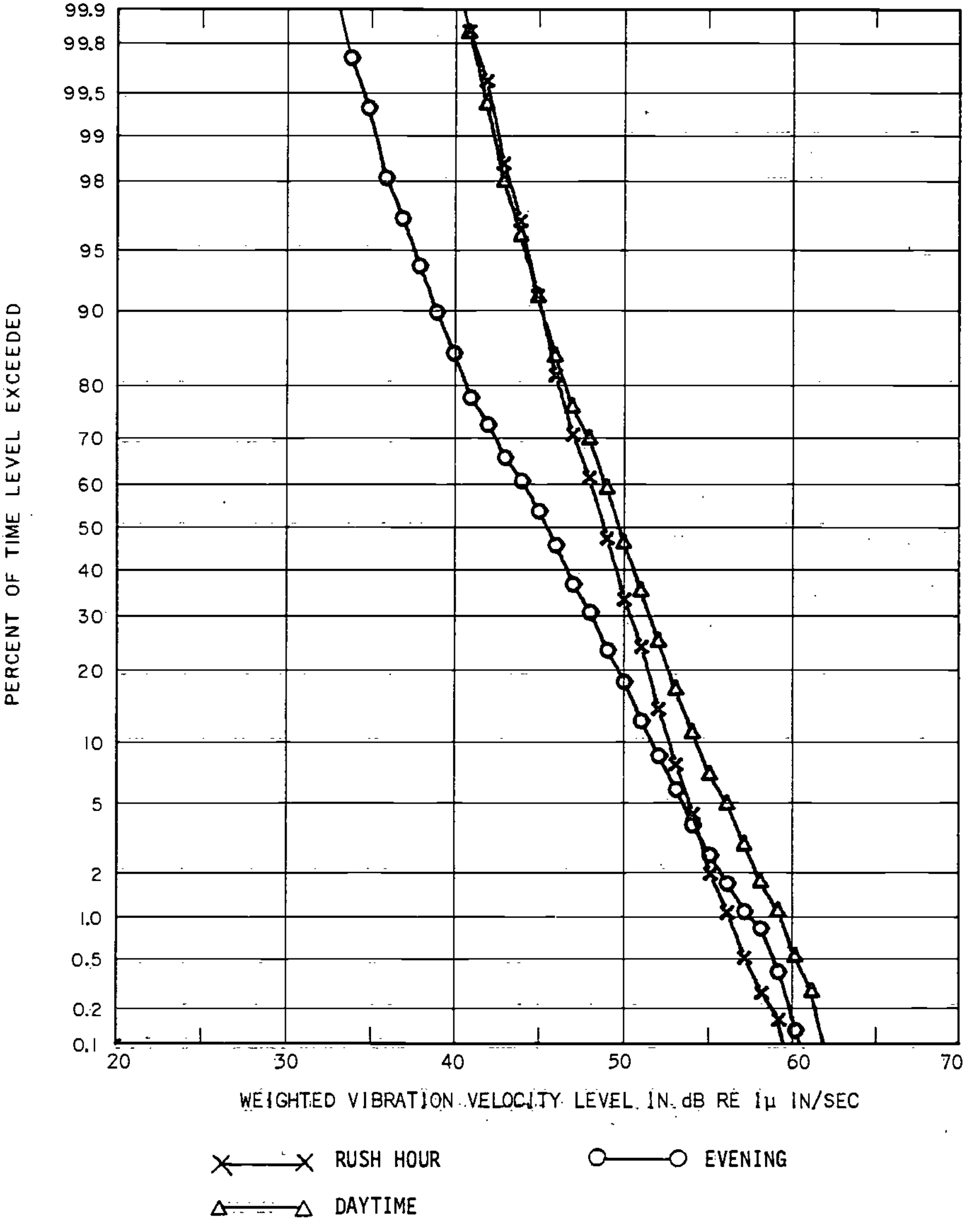


FIGURE B-26 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 26

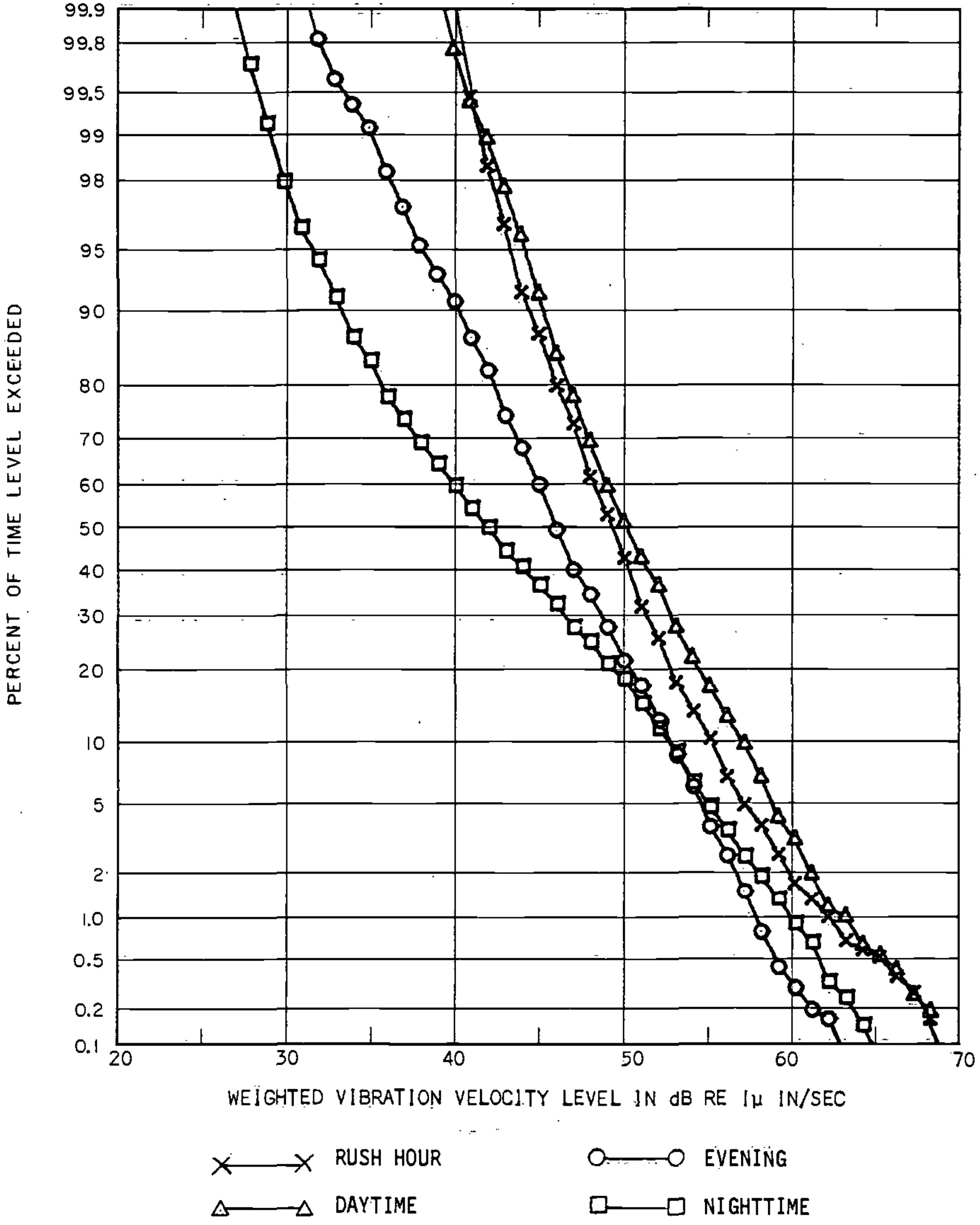


FIGURE B-27 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 27

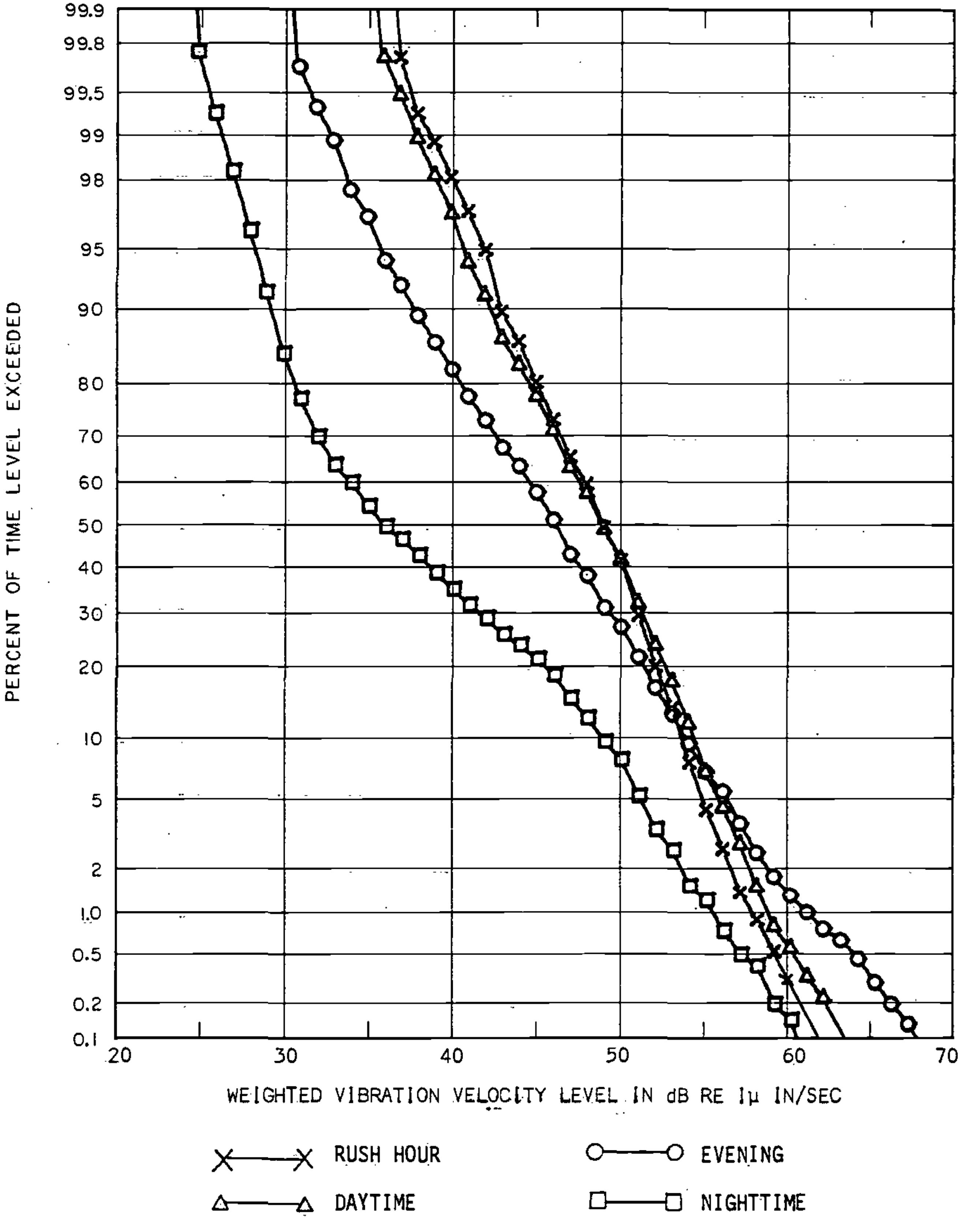


FIGURE B-28 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 28

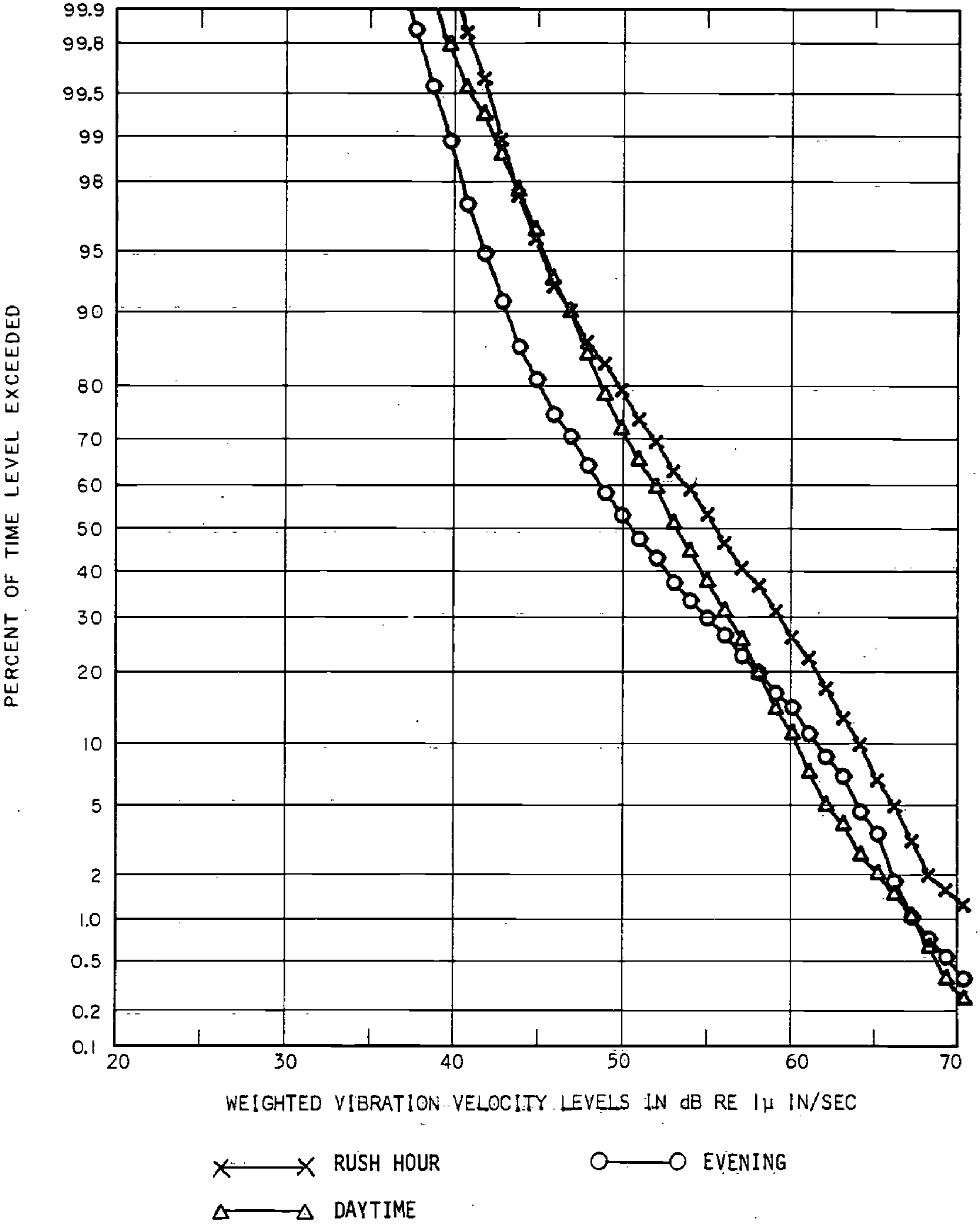


FIGURE B-29 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 29

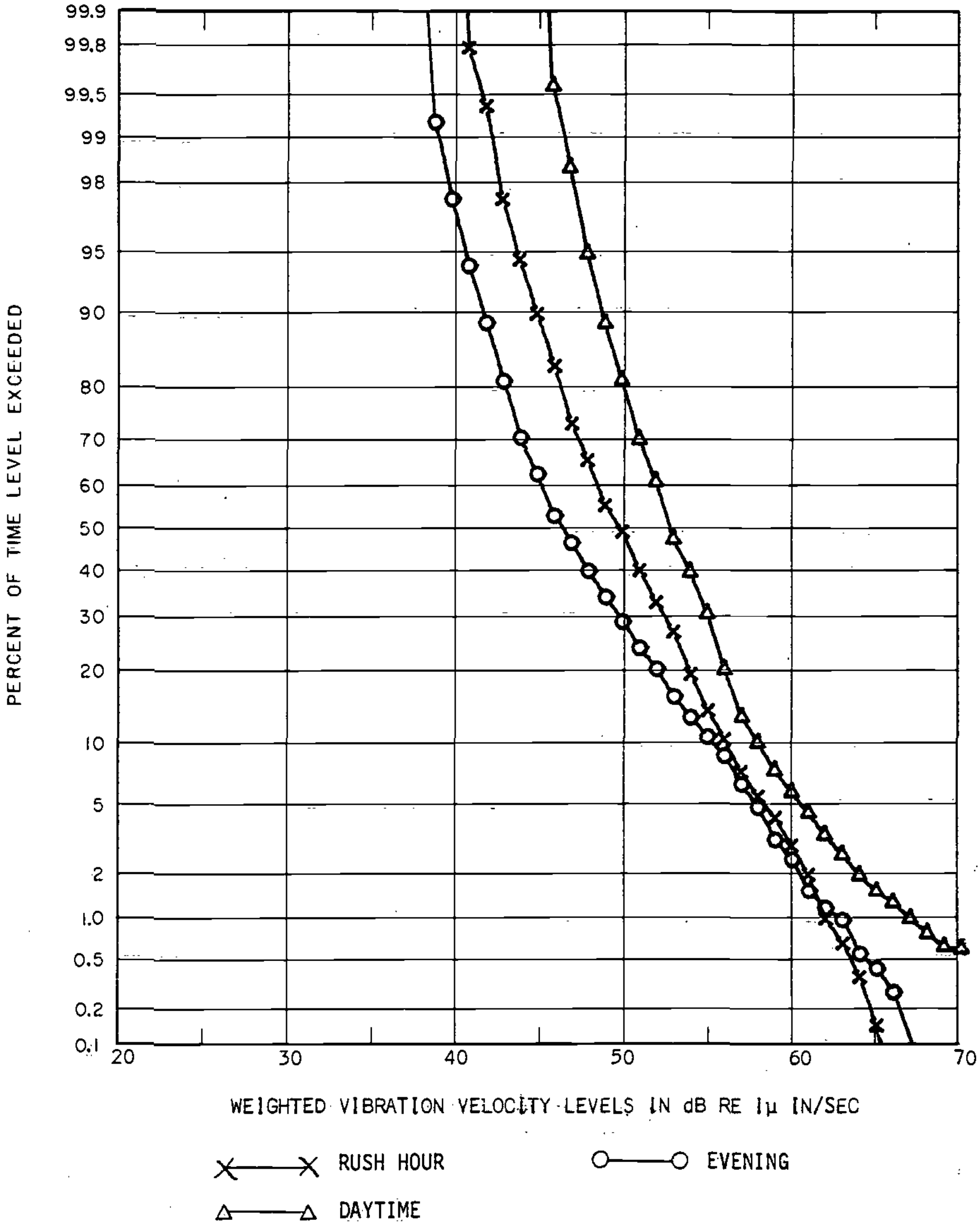


FIGURE B-30 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 30

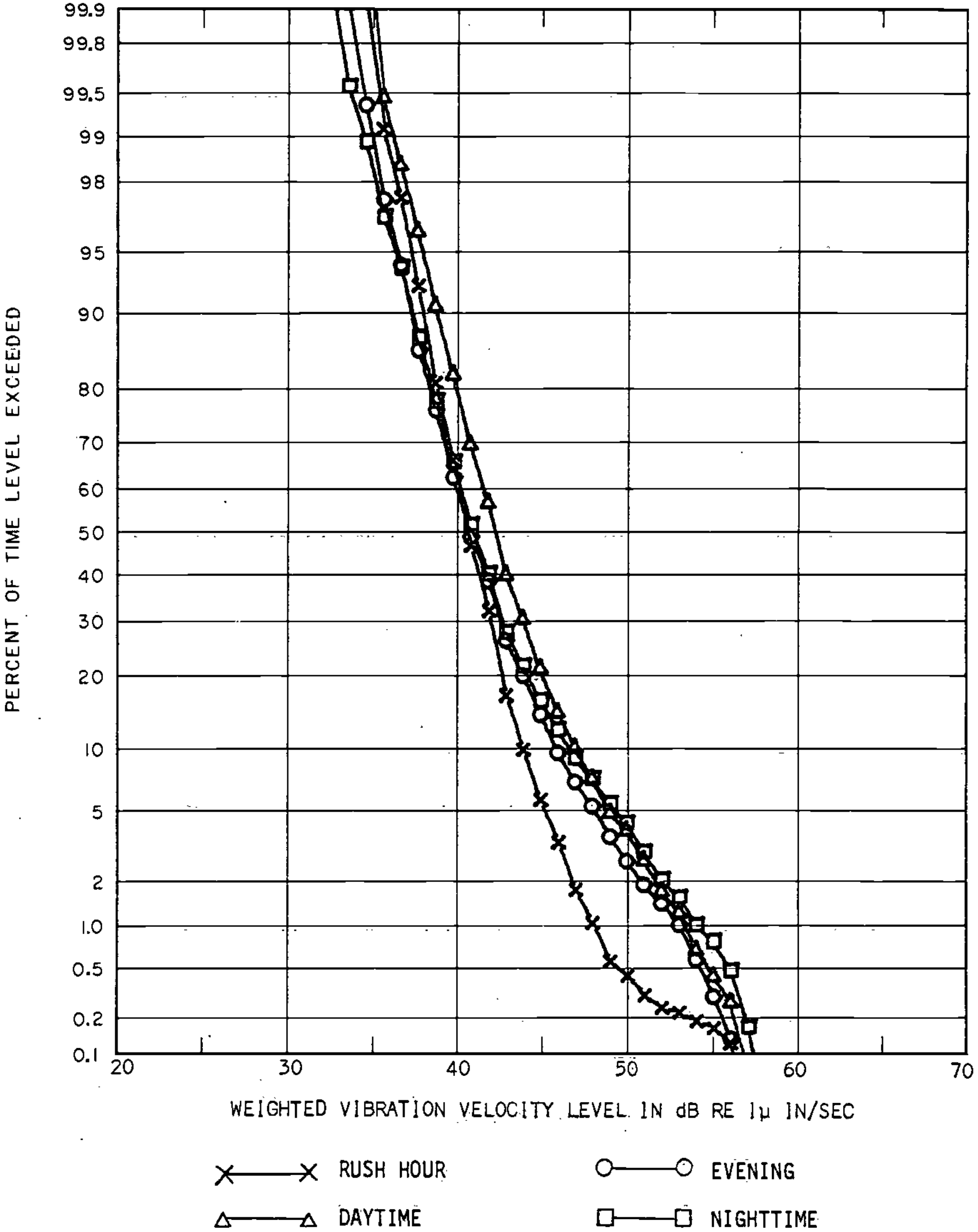


FIGURE B-31 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 31

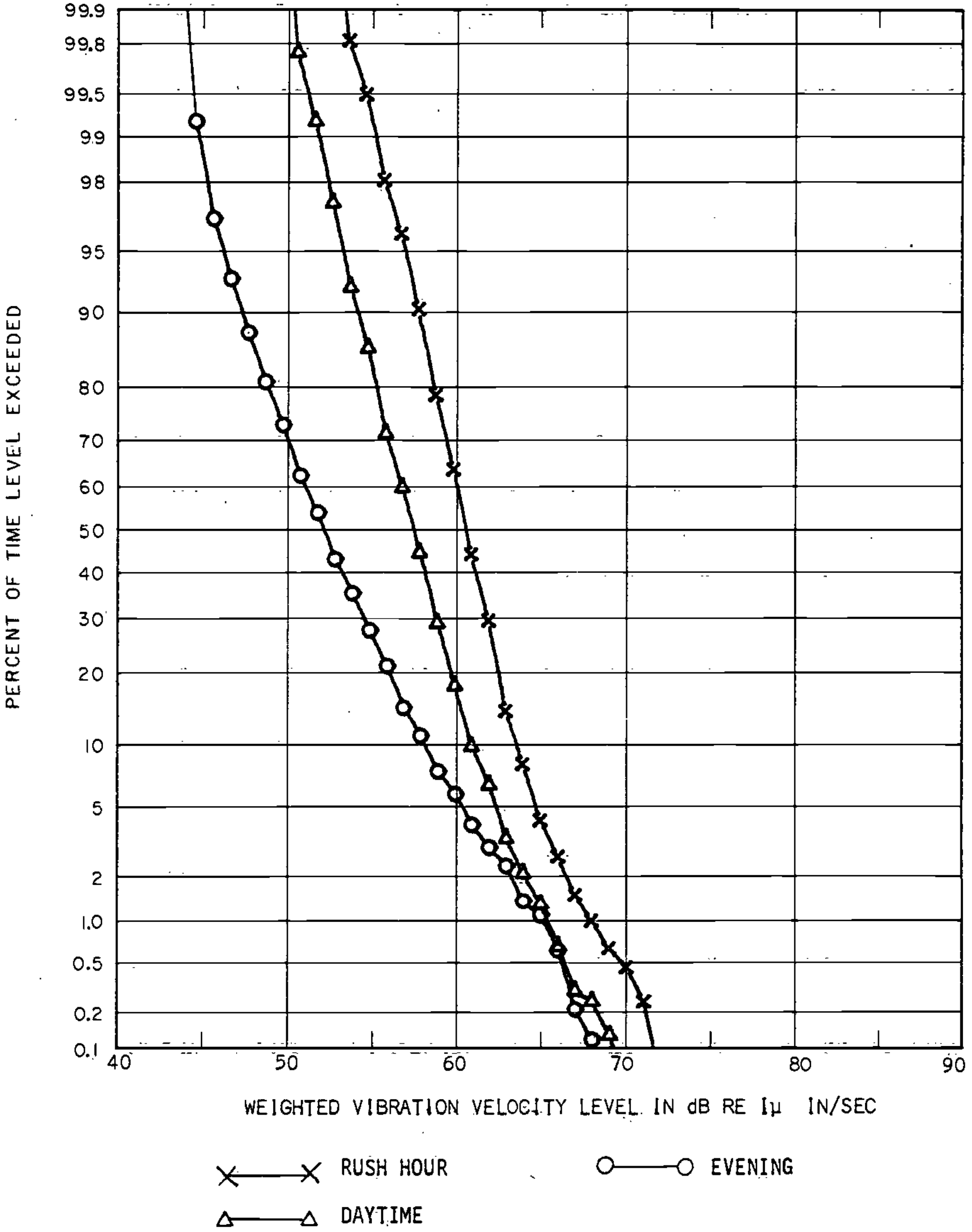


FIGURE B-32 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 32

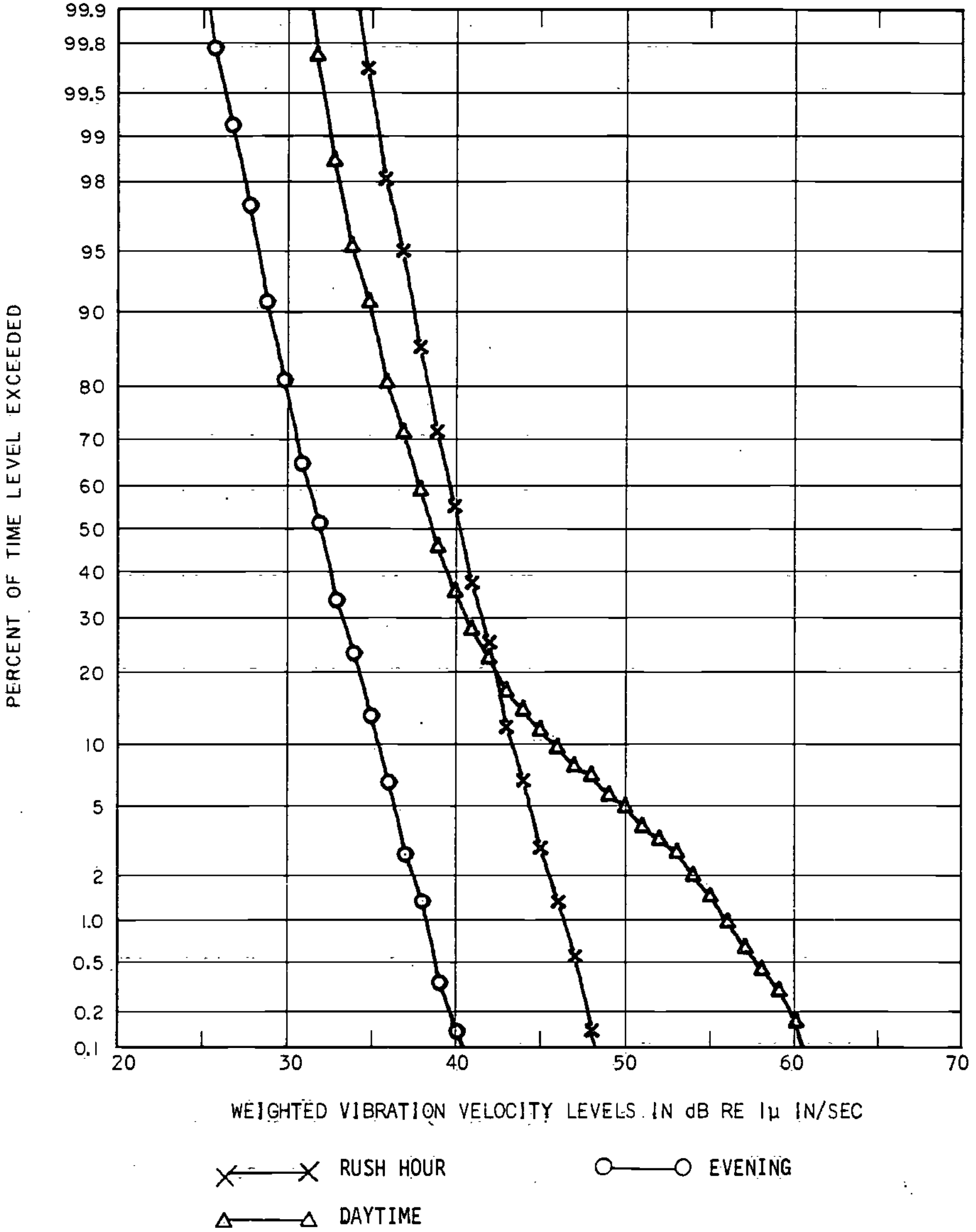


FIGURE B-33 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 33

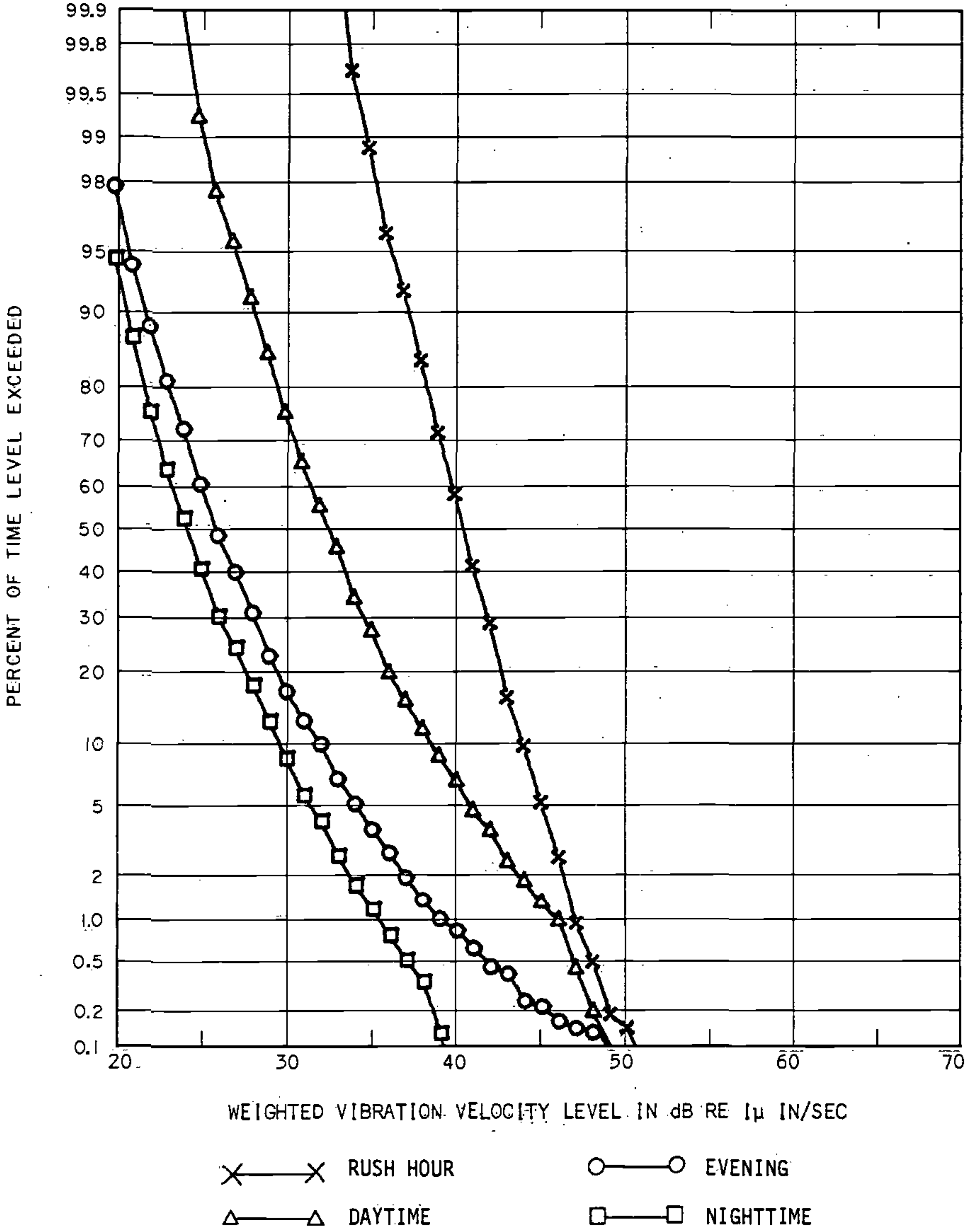


FIGURE B-34 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 34

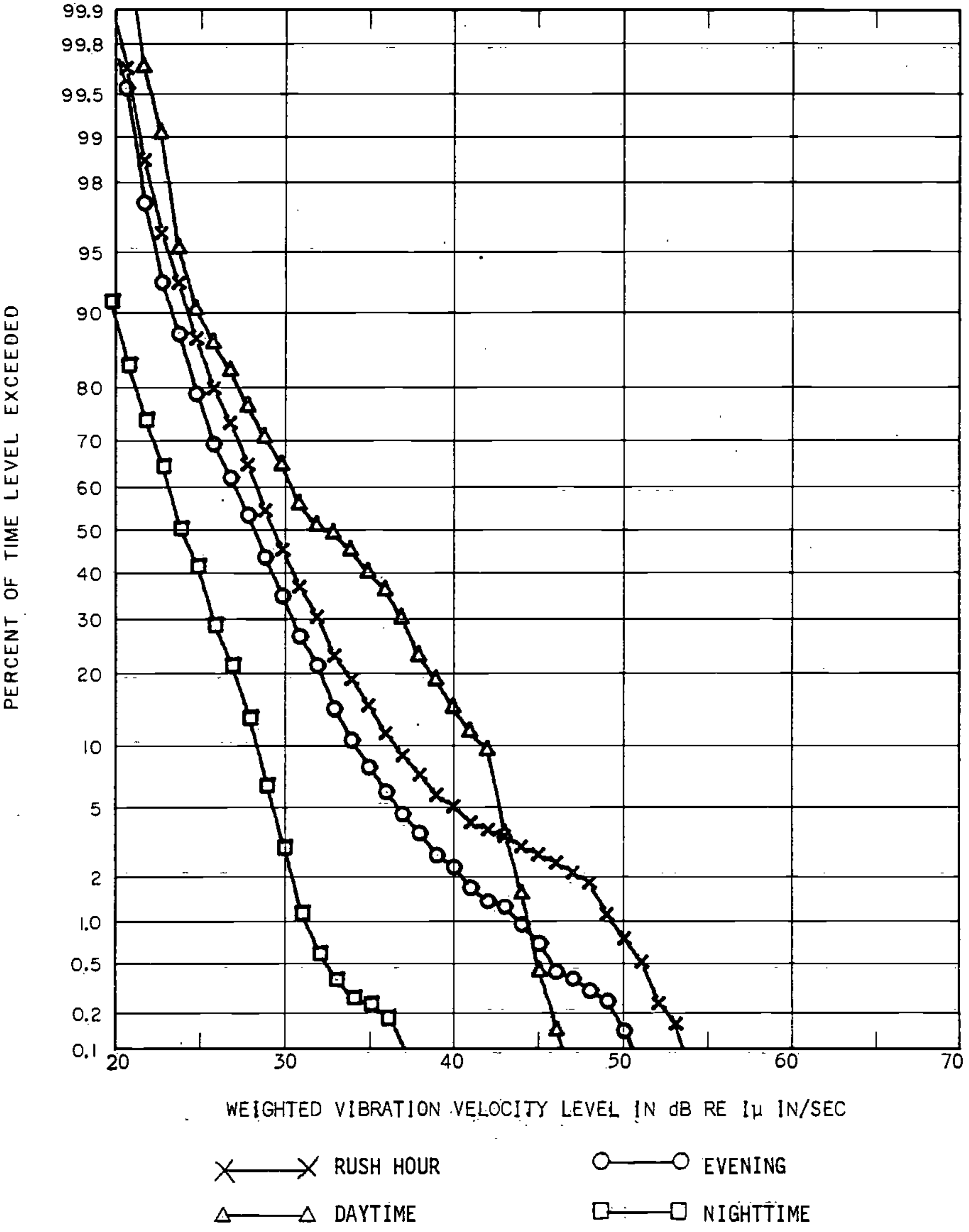


FIGURE B-35 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 35

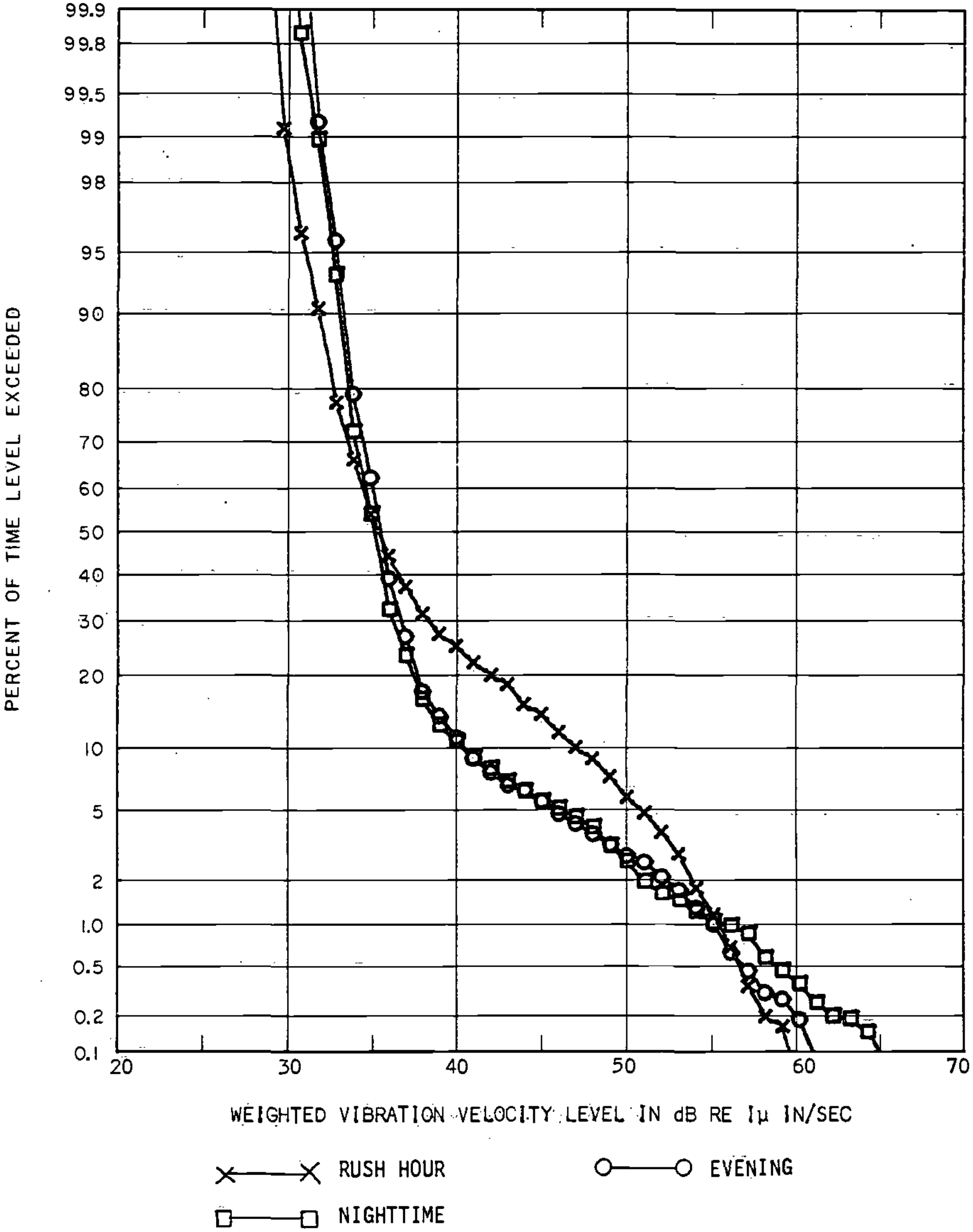


FIGURE B-36 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 36

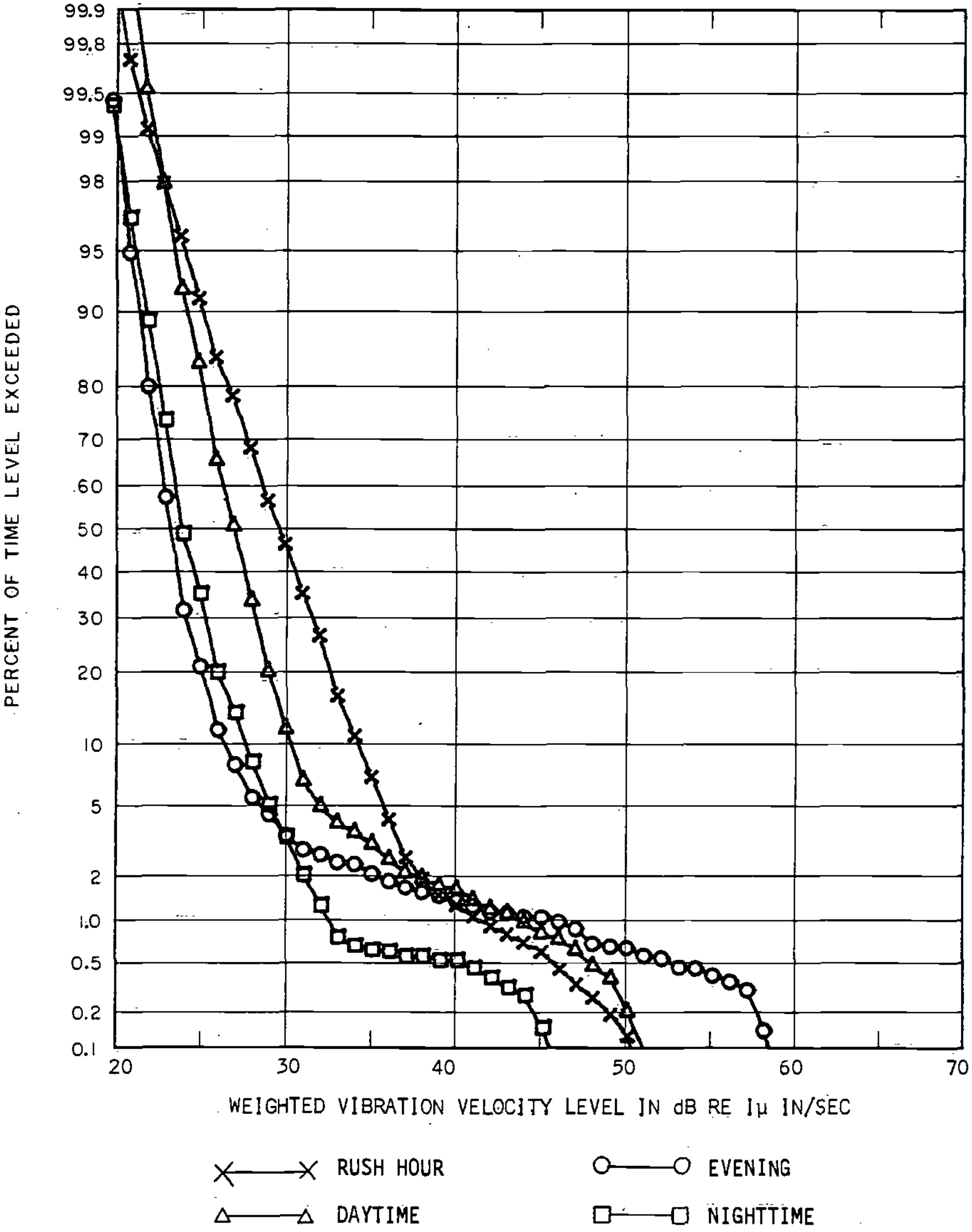


FIGURE B-37 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 37

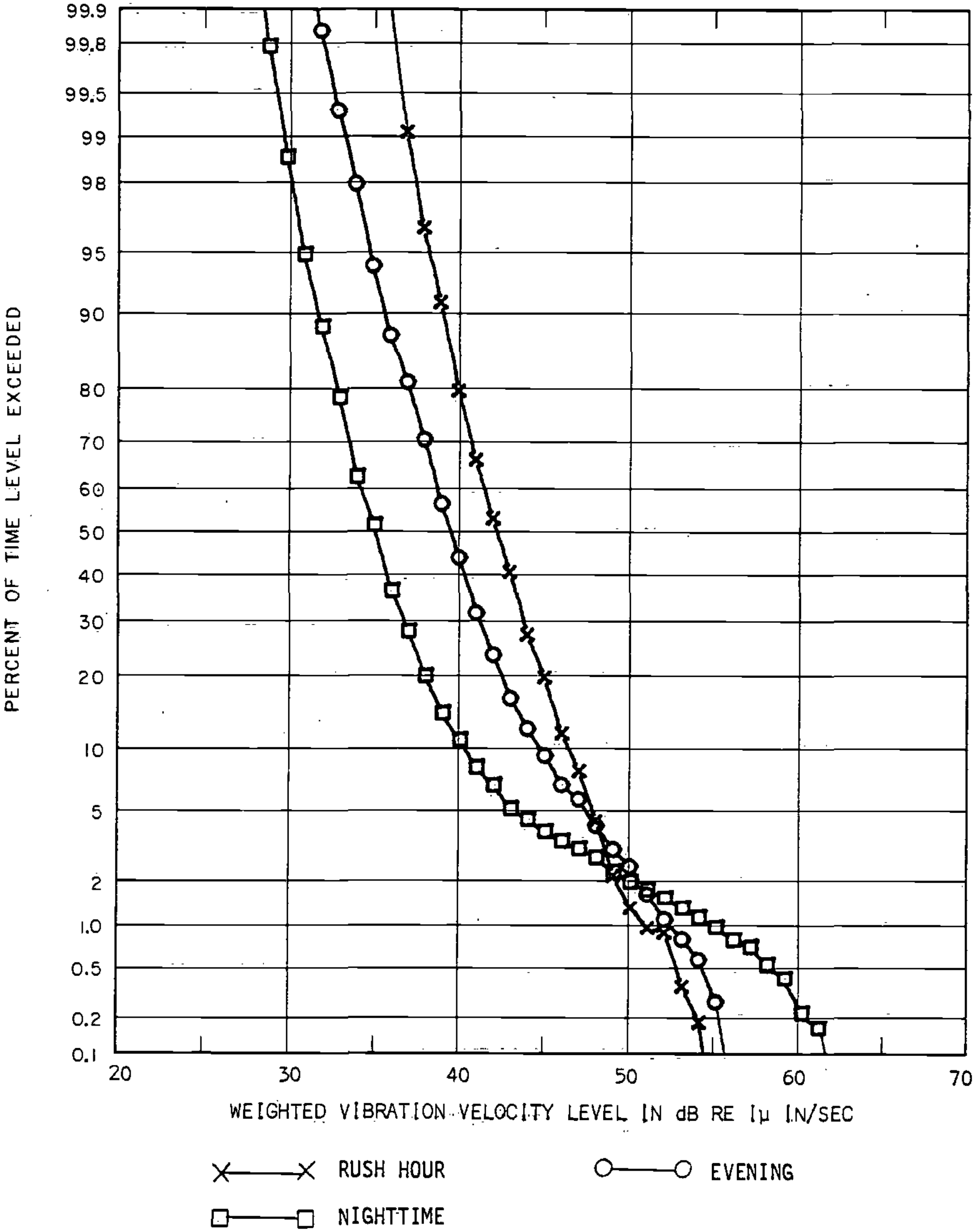


FIGURE B-38 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 38

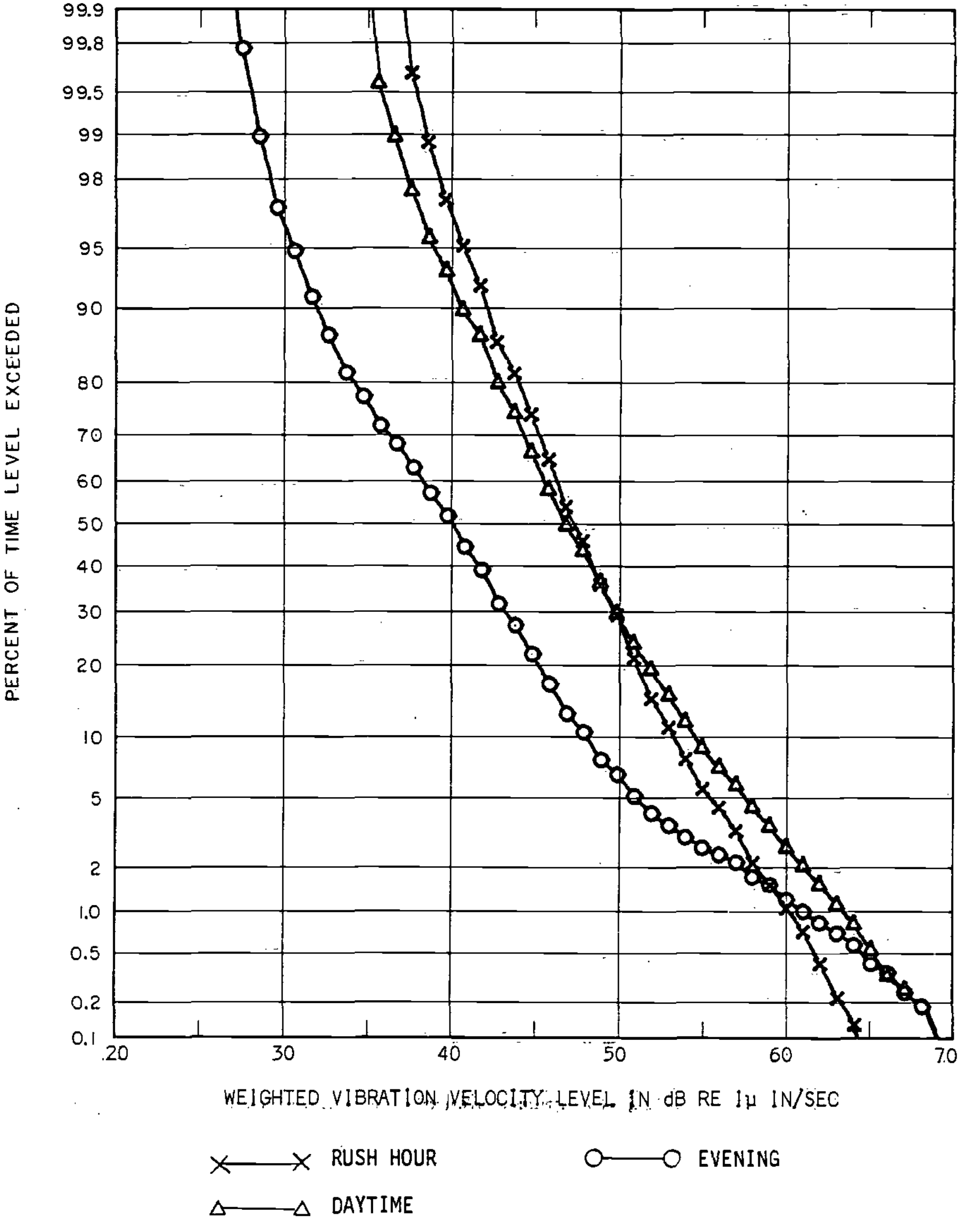


FIGURE B-39 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 39

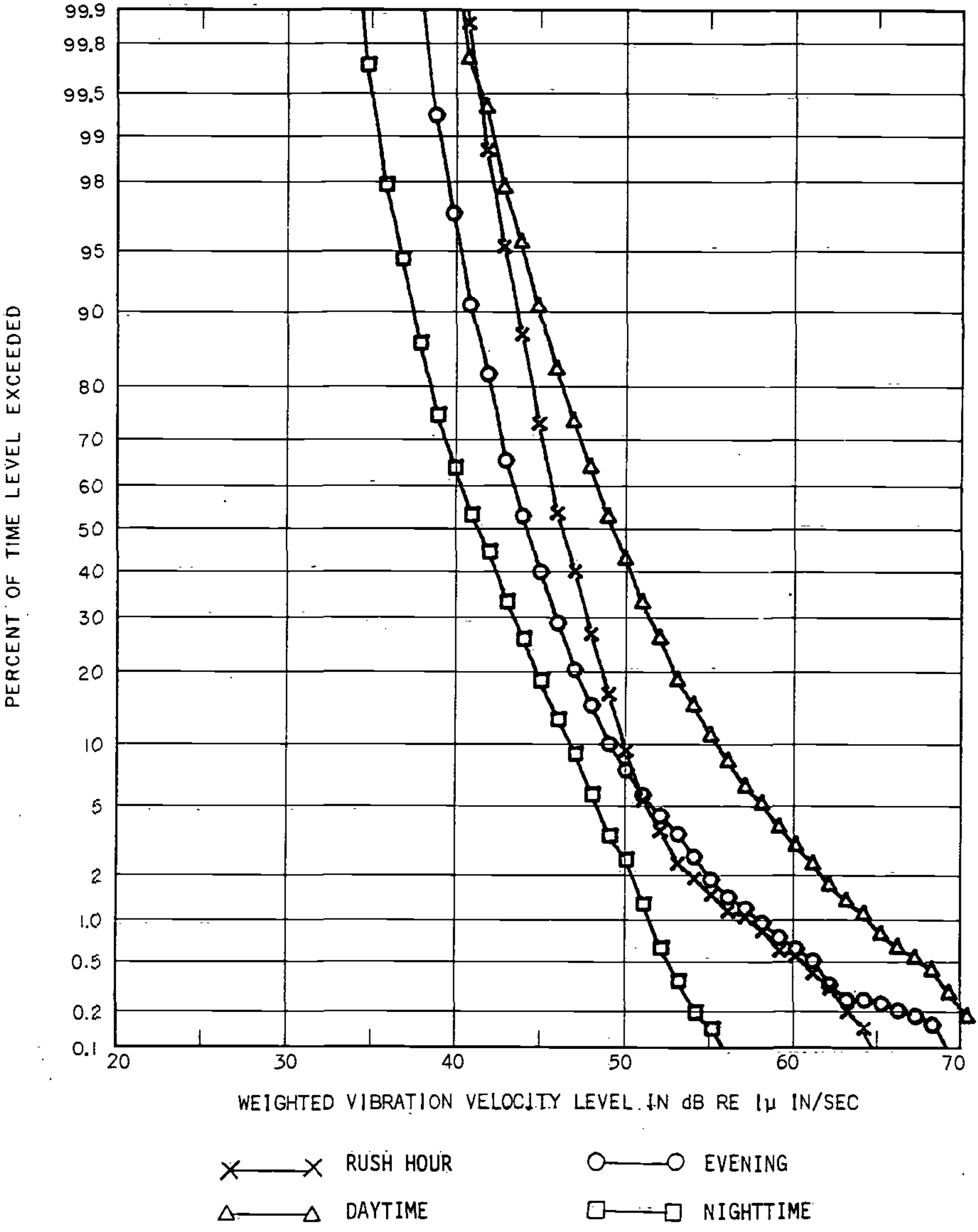


FIGURE B-40 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 40

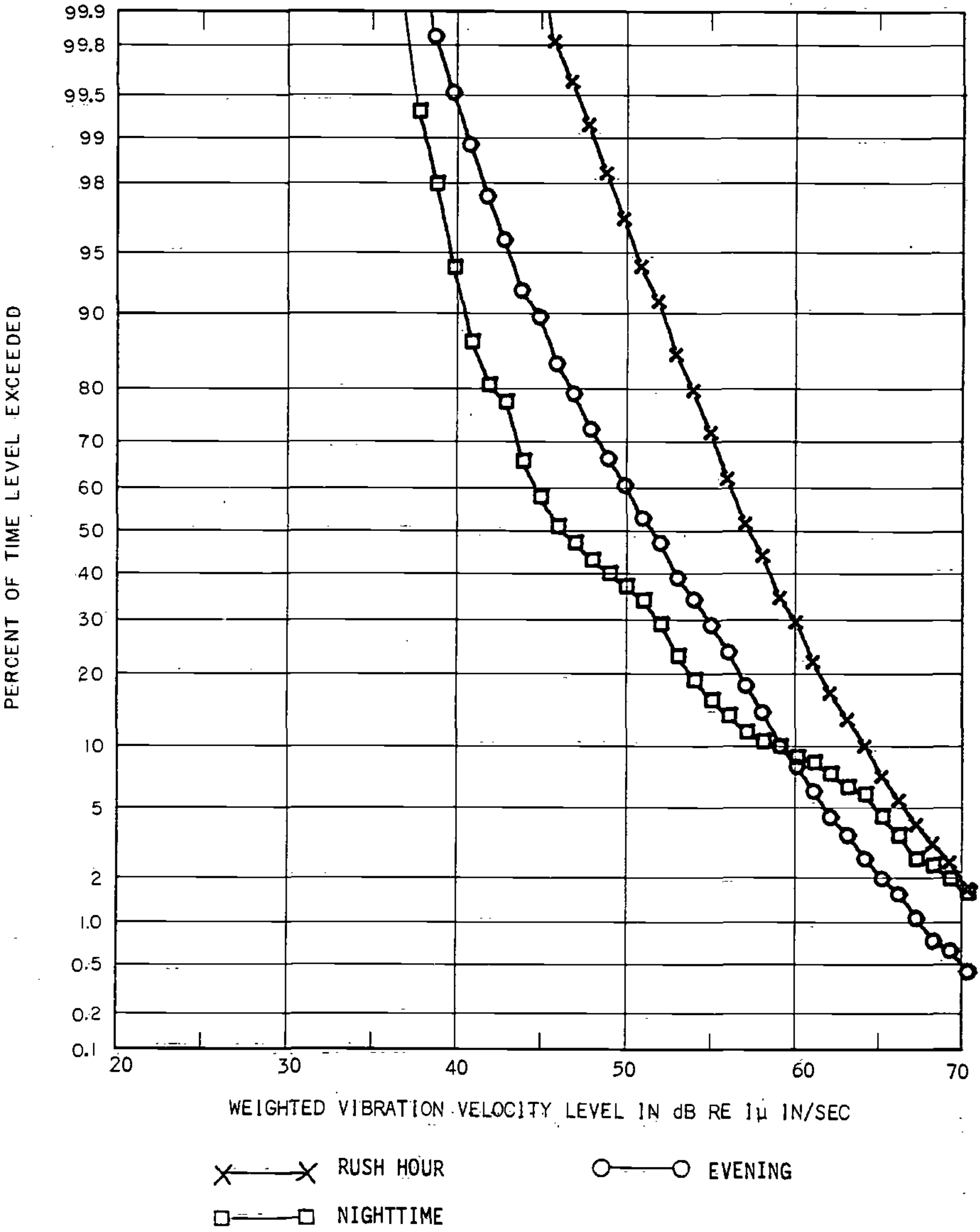


FIGURE B-41 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 41

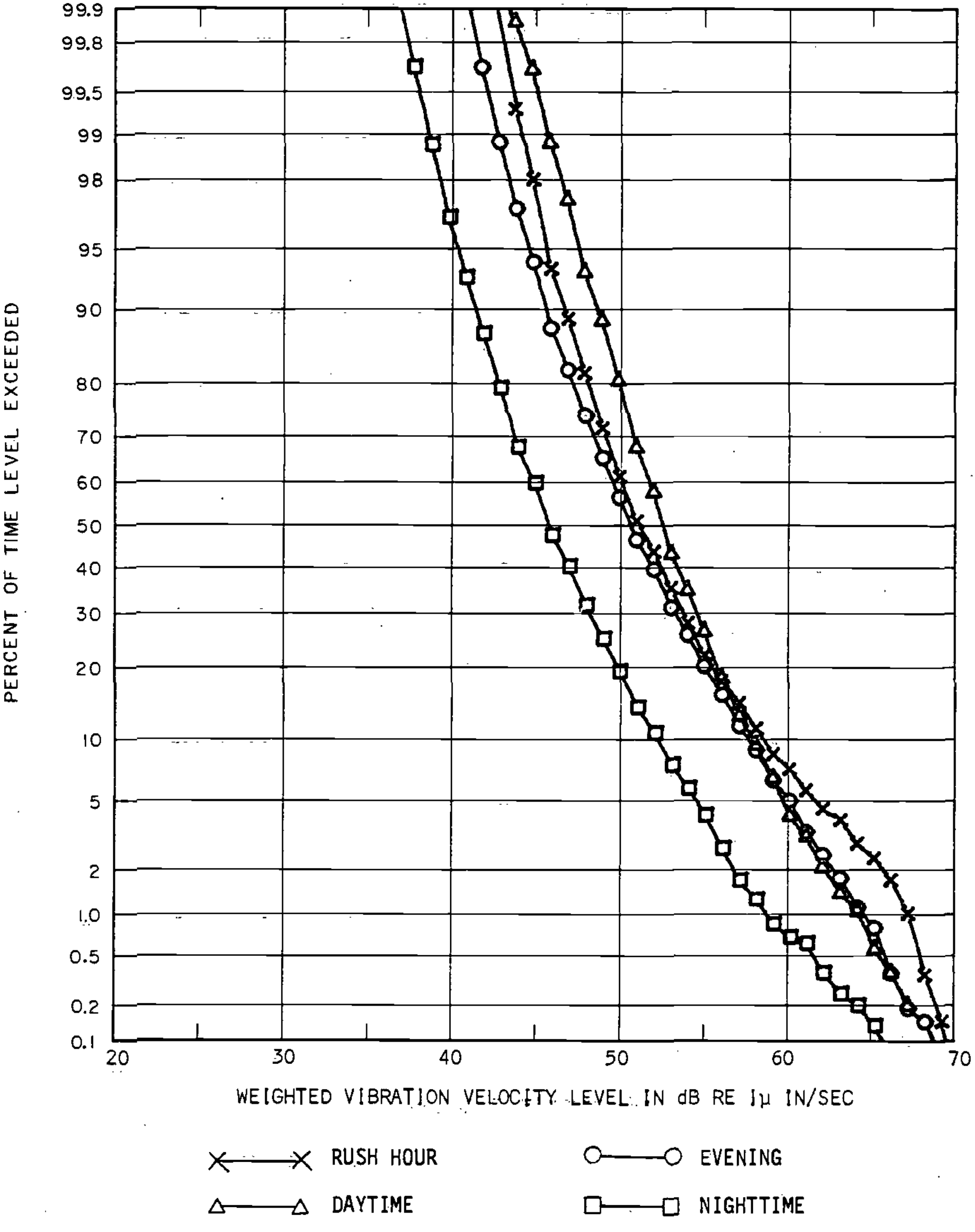


FIGURE B-42 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 42

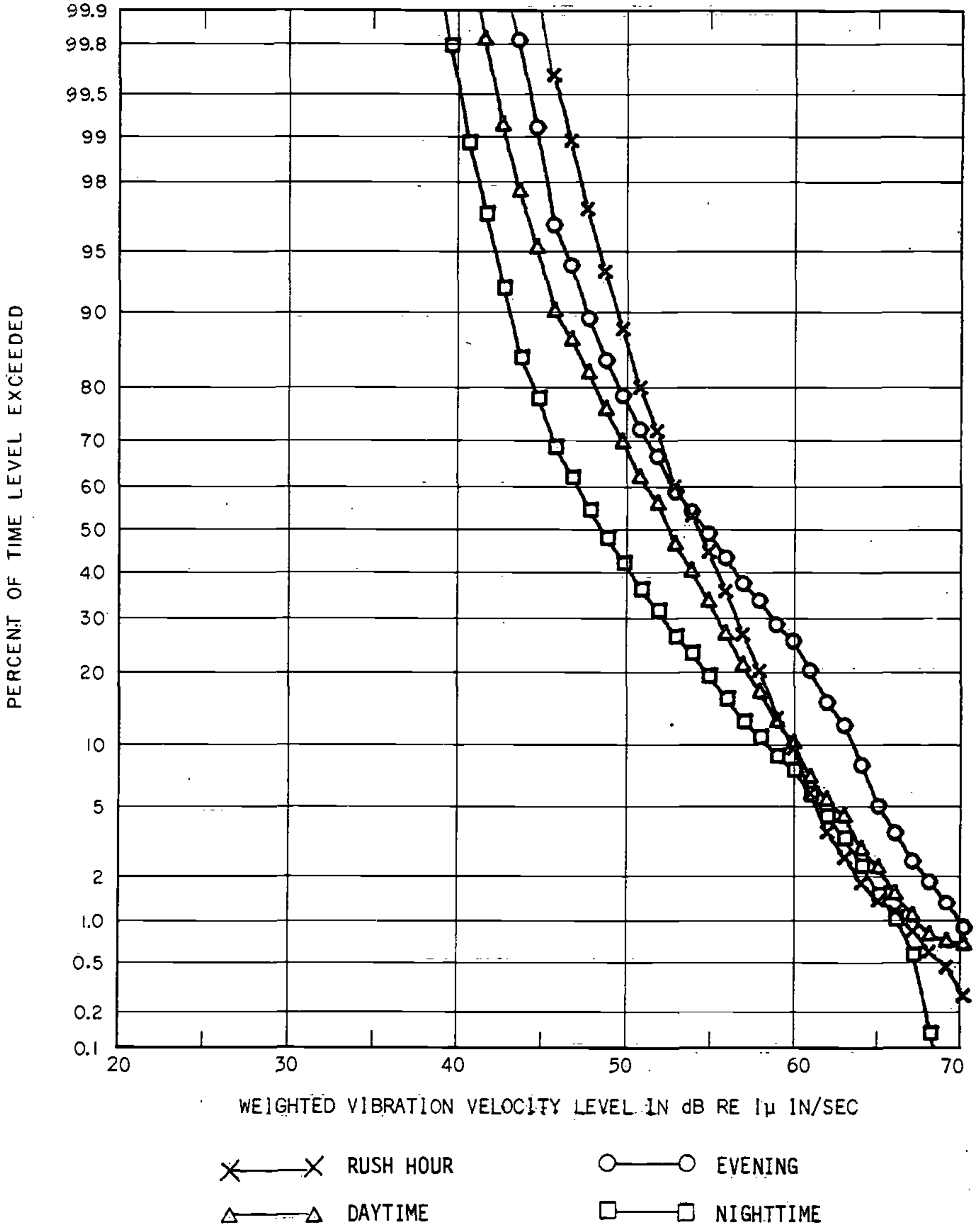


FIGURE B-43 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 43

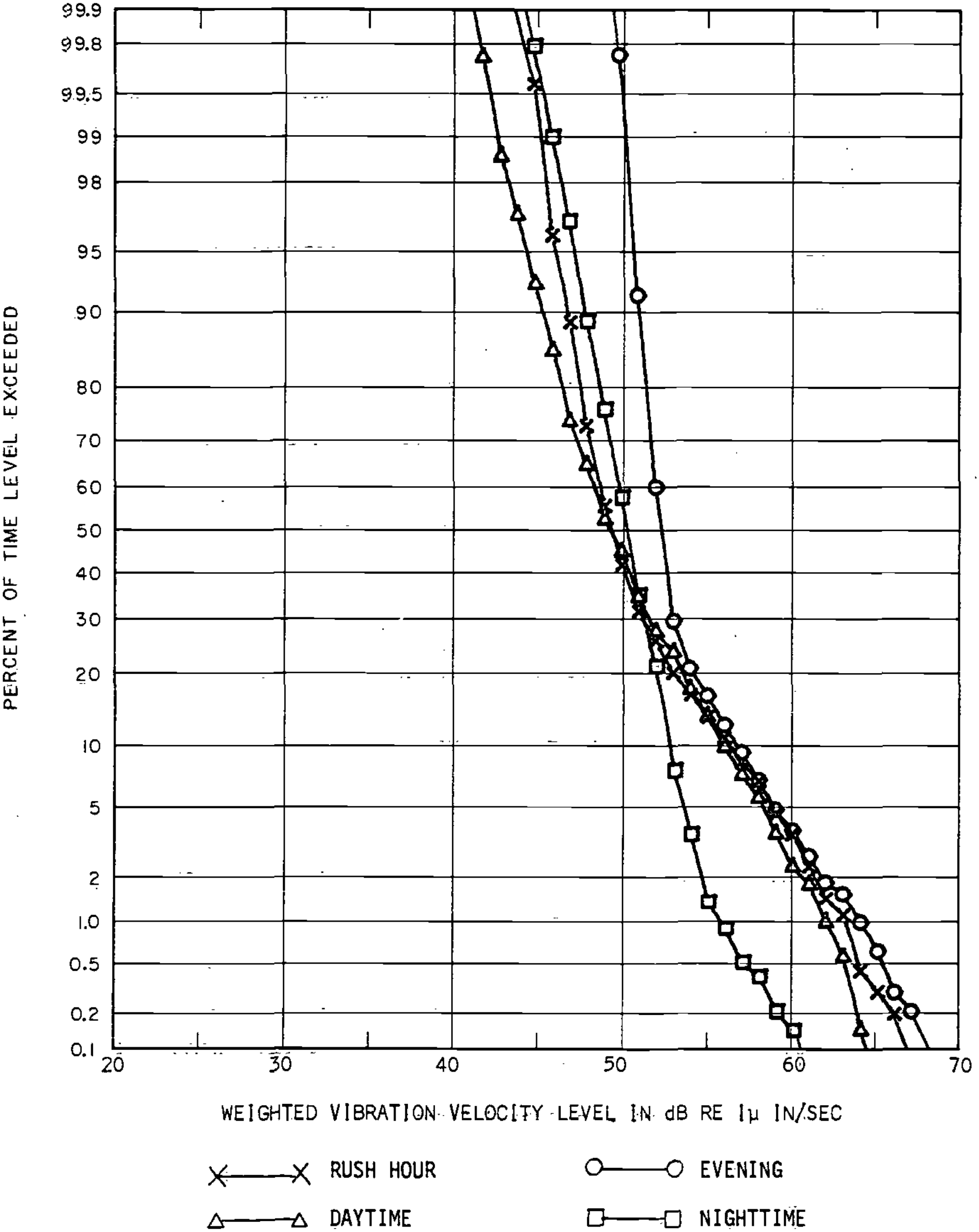
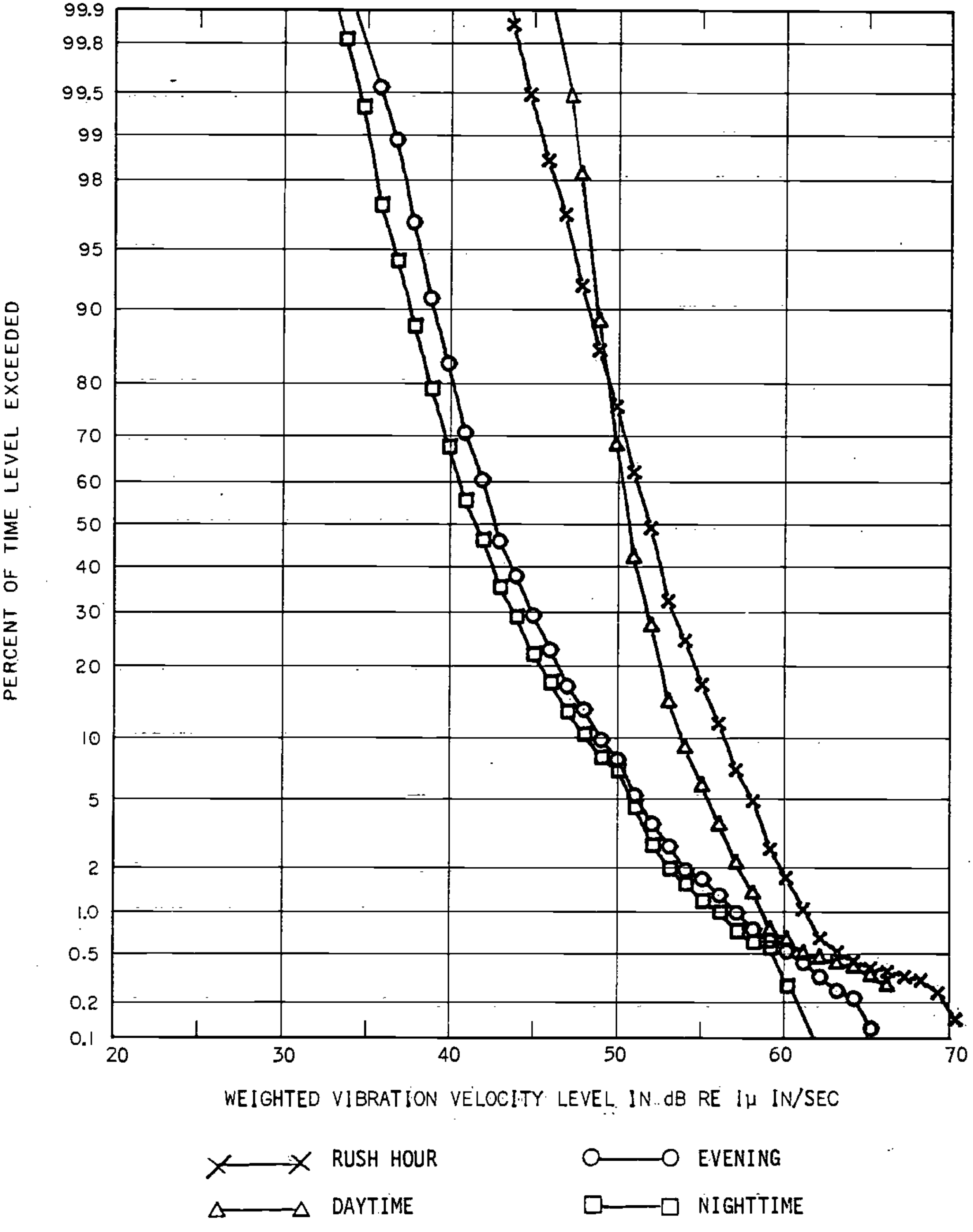


FIGURE B-44 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 44



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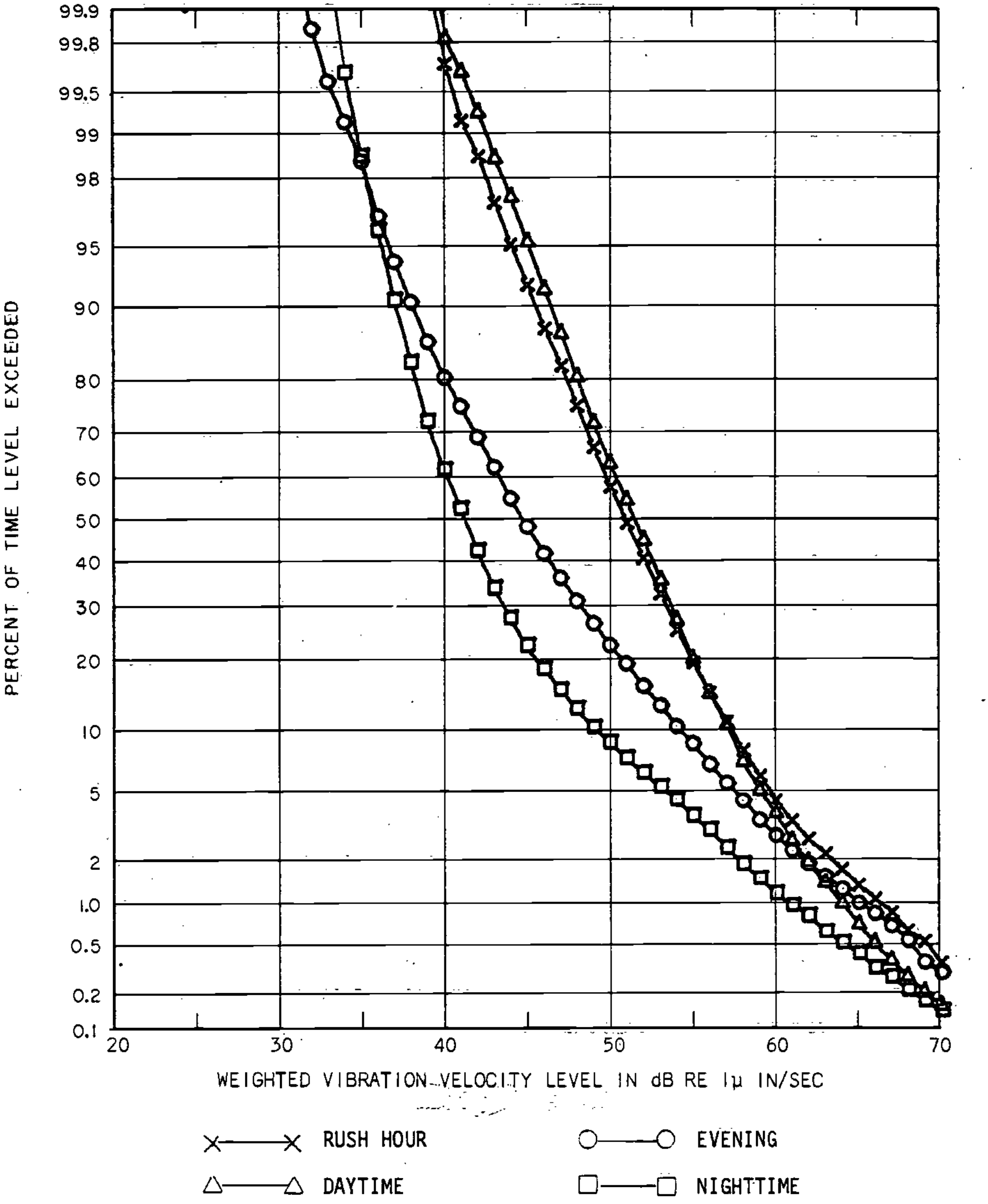

FIGURE B-46 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 101

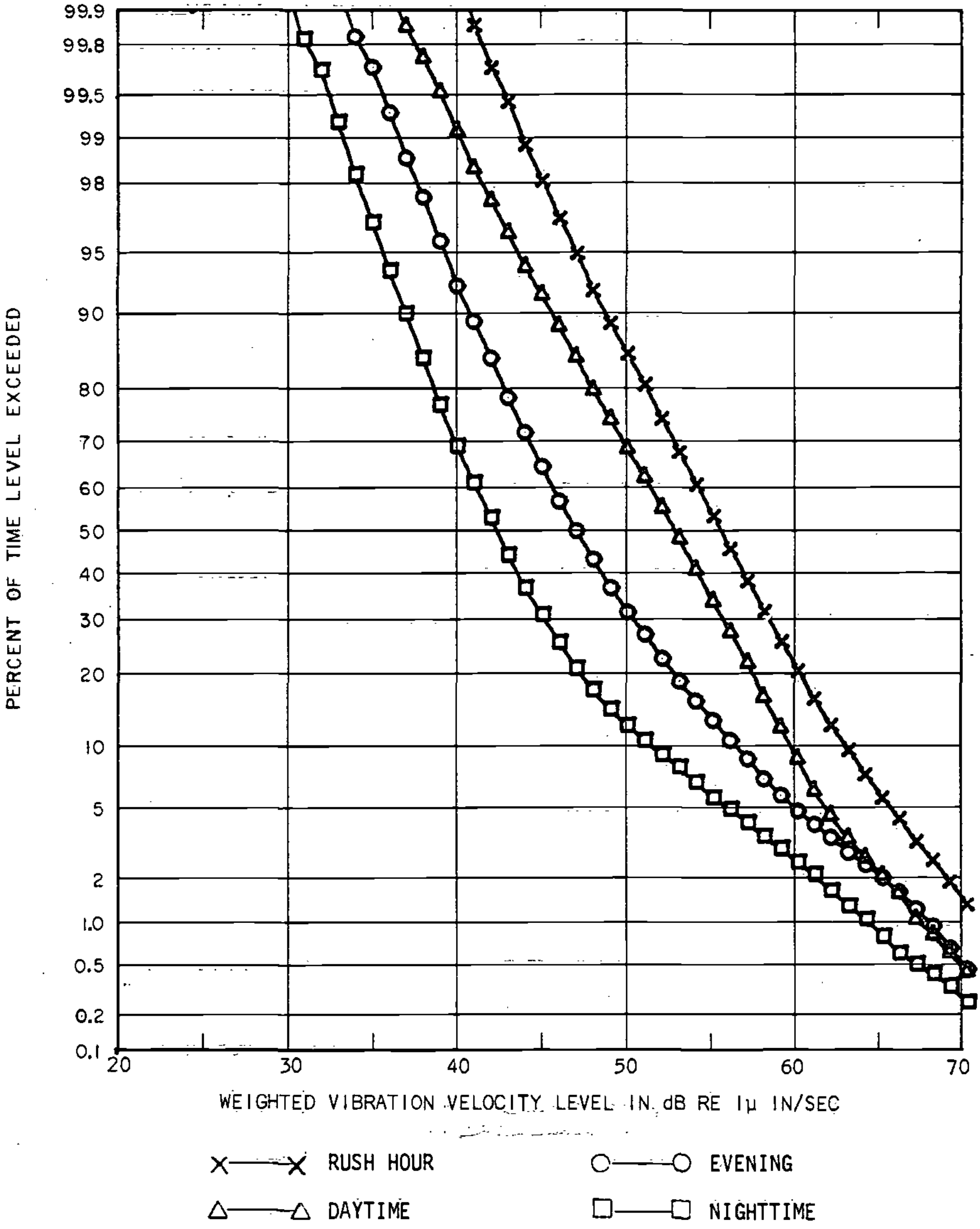

FIGURE B-47 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 102

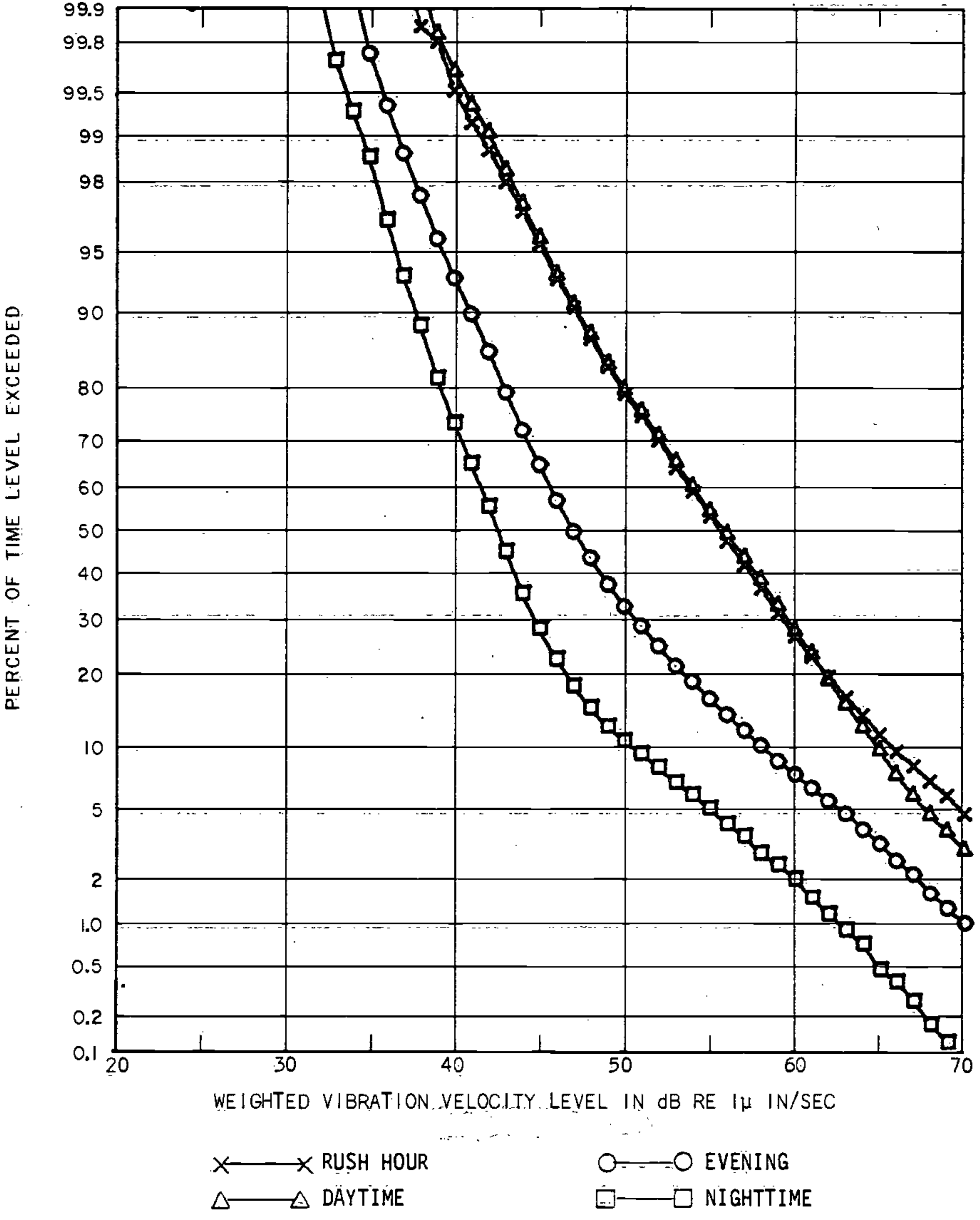

FIGURE B-48 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 103

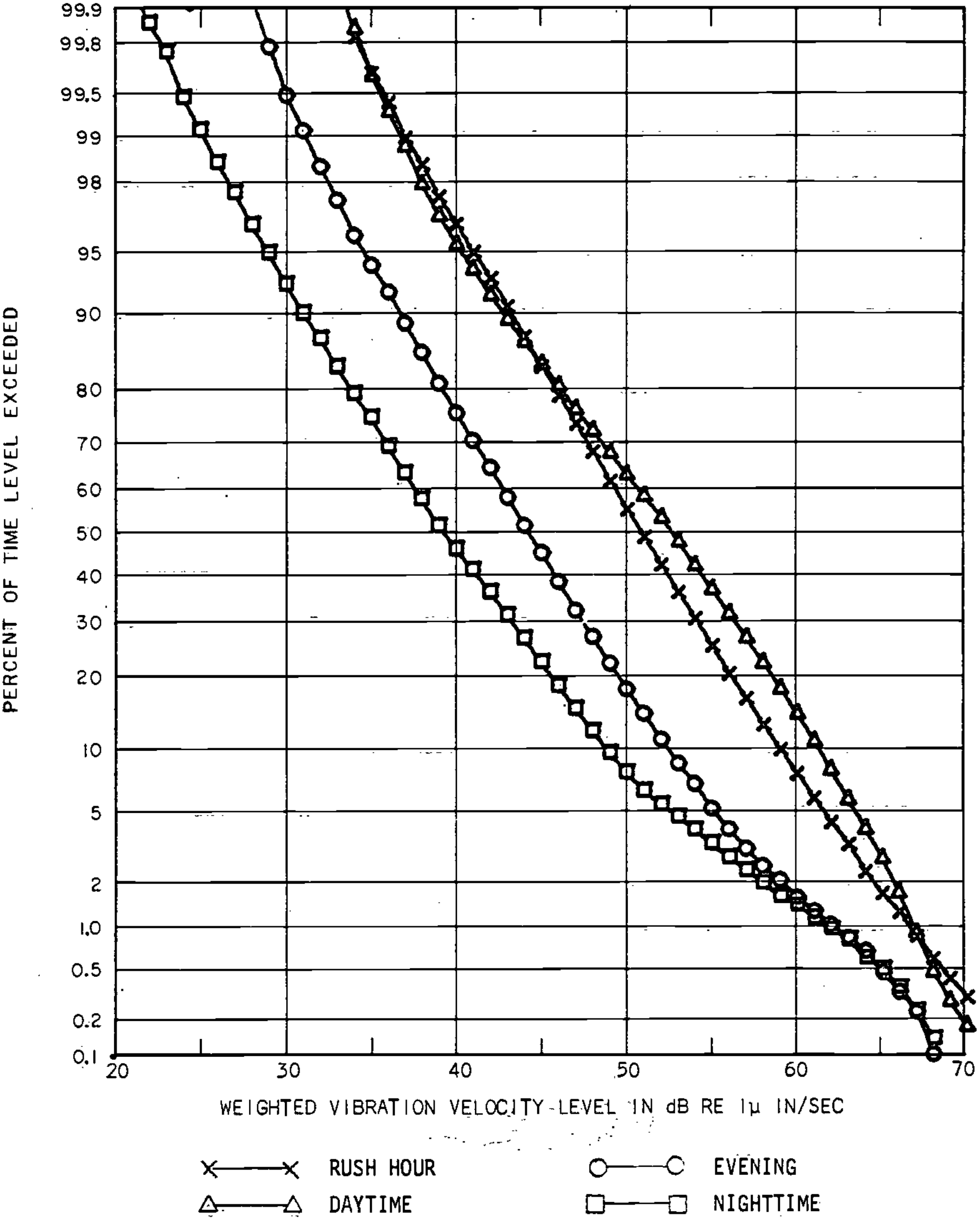

FIGURE B-49 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 104

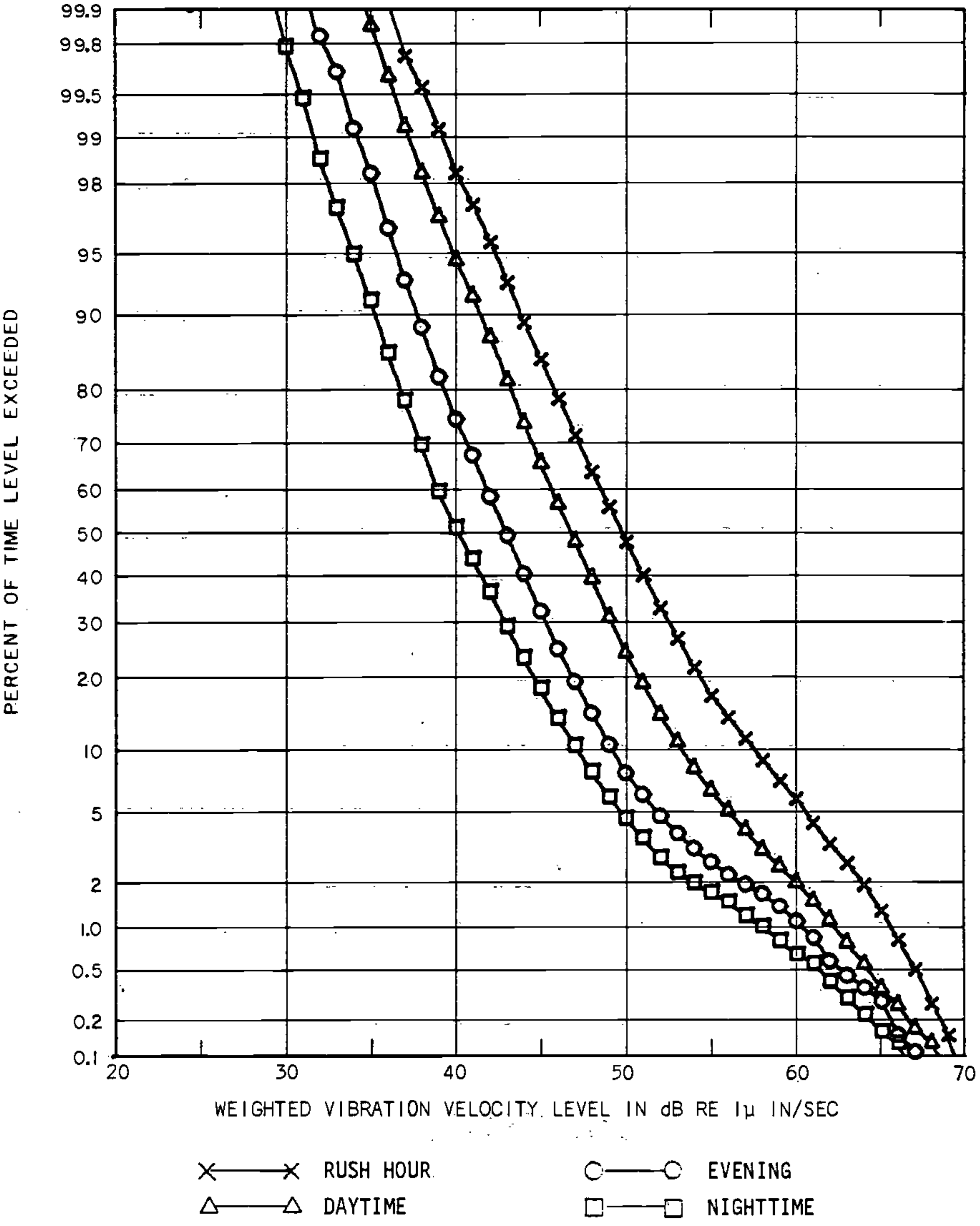

FIGURE B-50 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 105

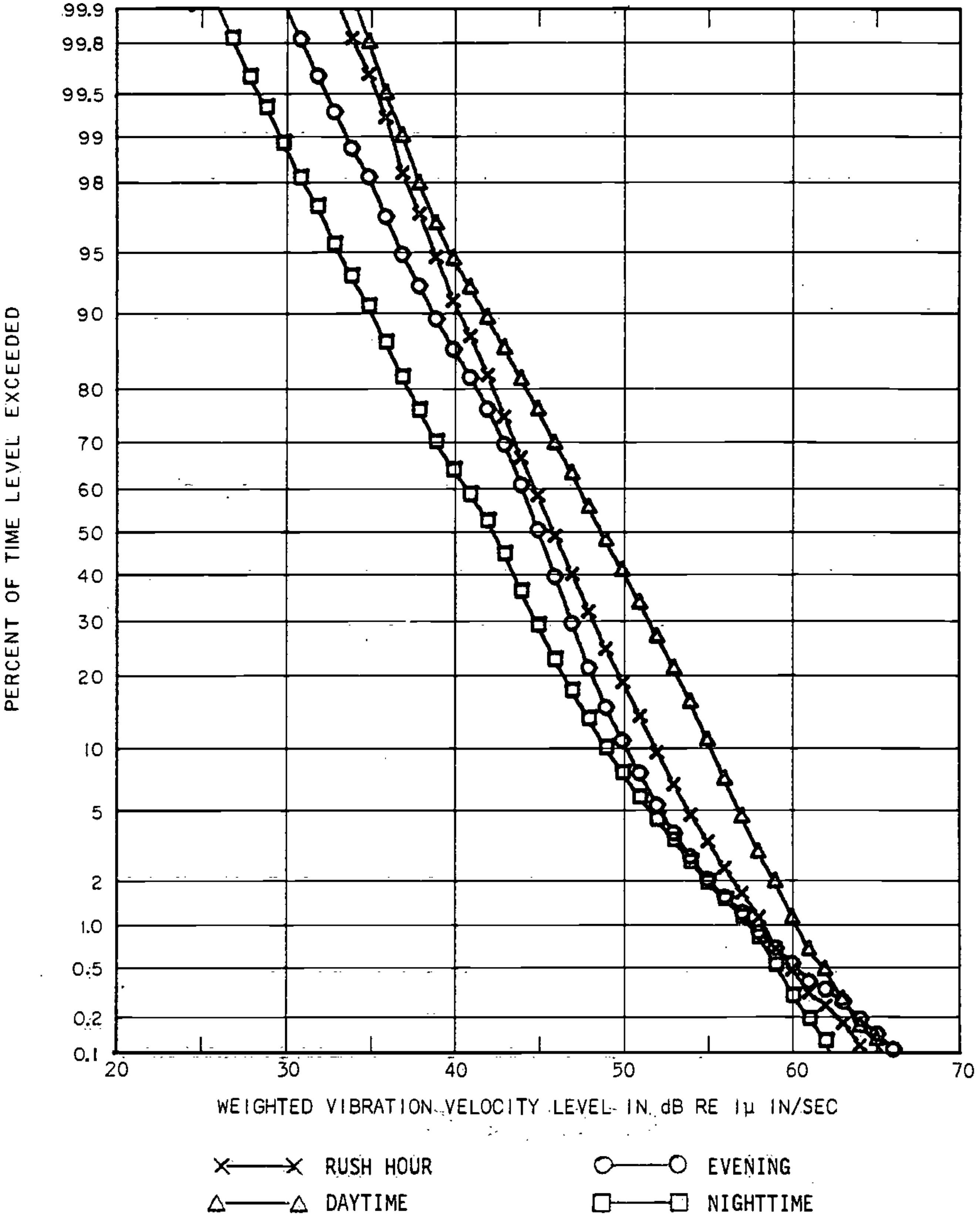

FIGURE B-51 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 106

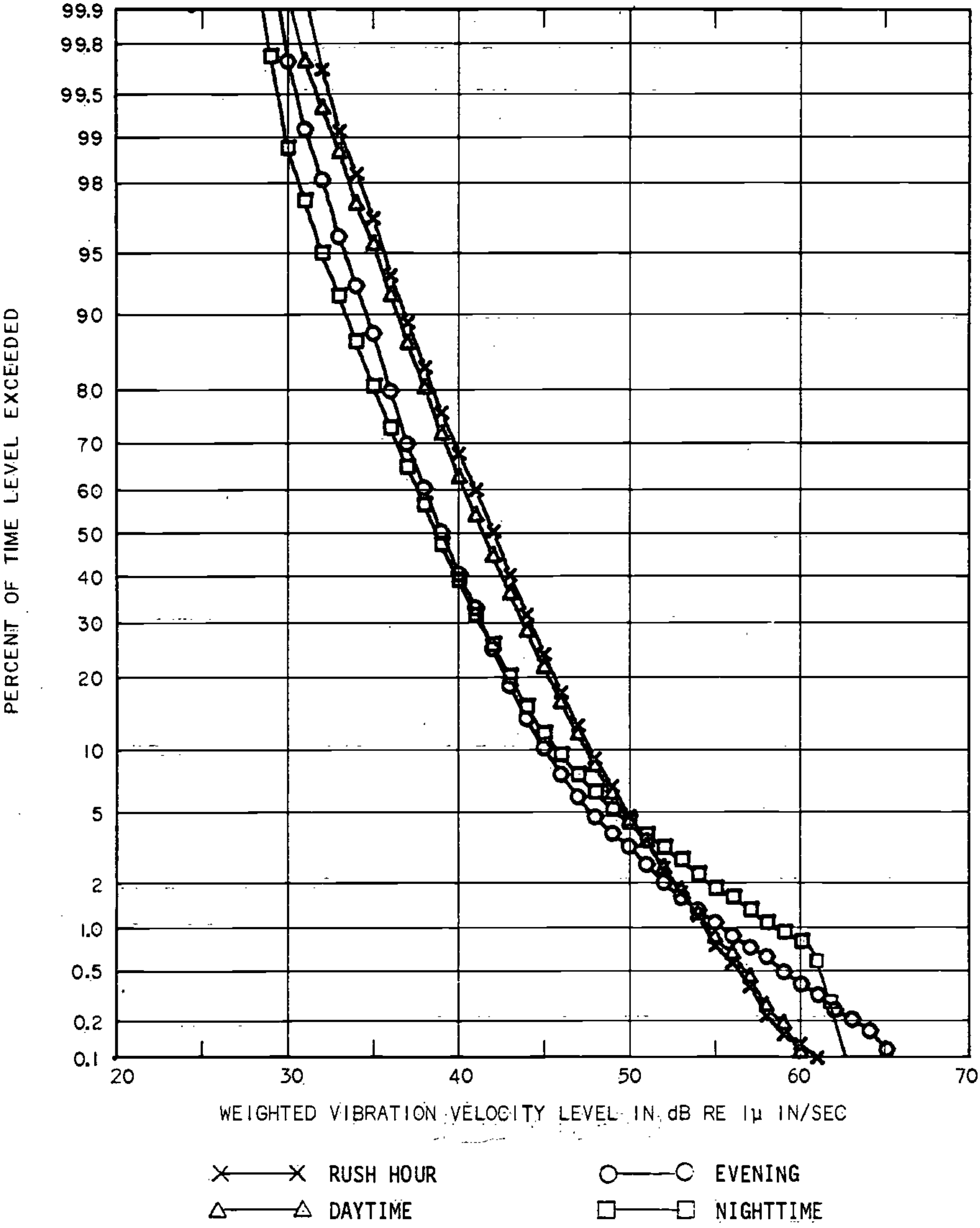

FIGURE B-52 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 107

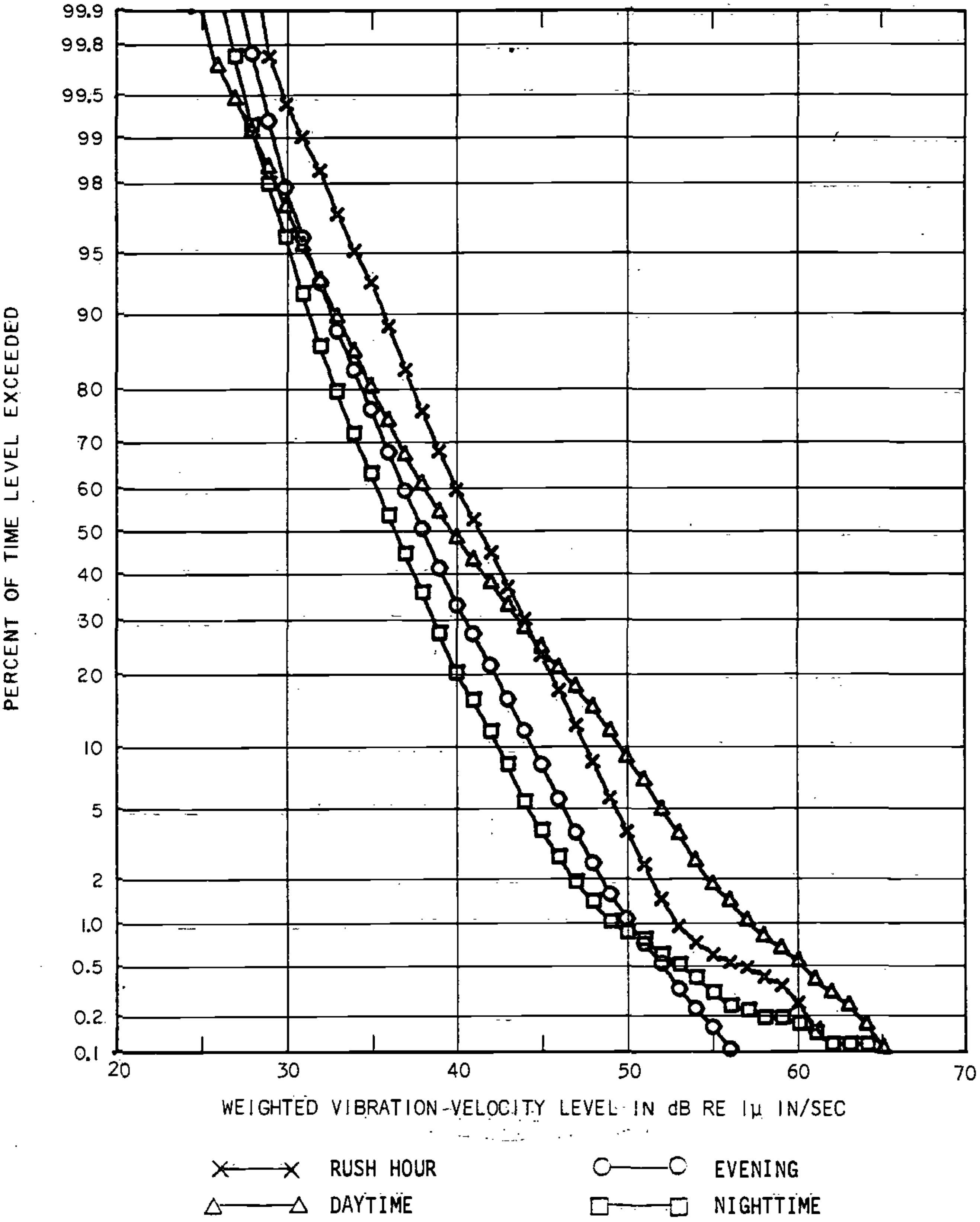

FIGURE B-53 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 108

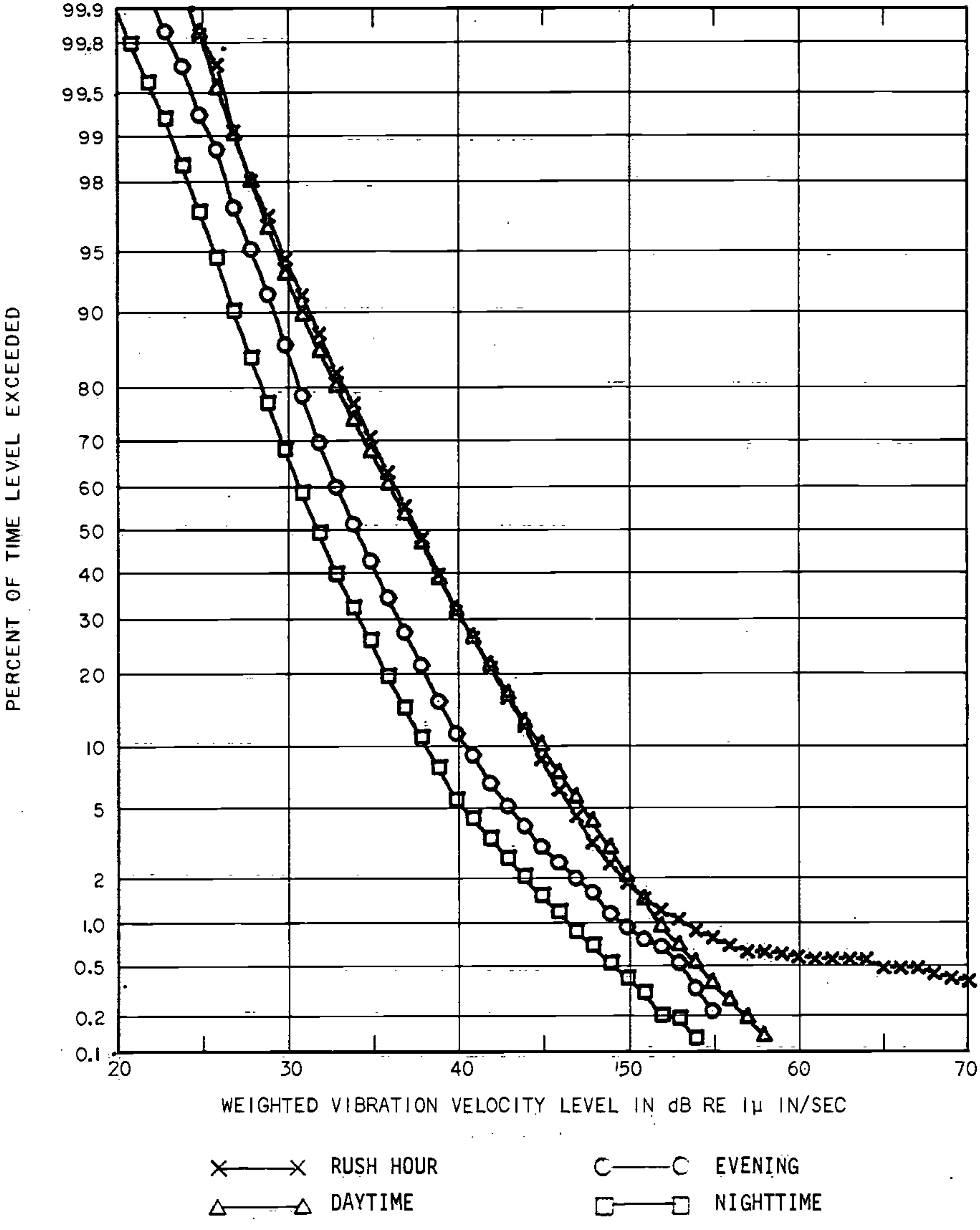

FIGURE B-54 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 109

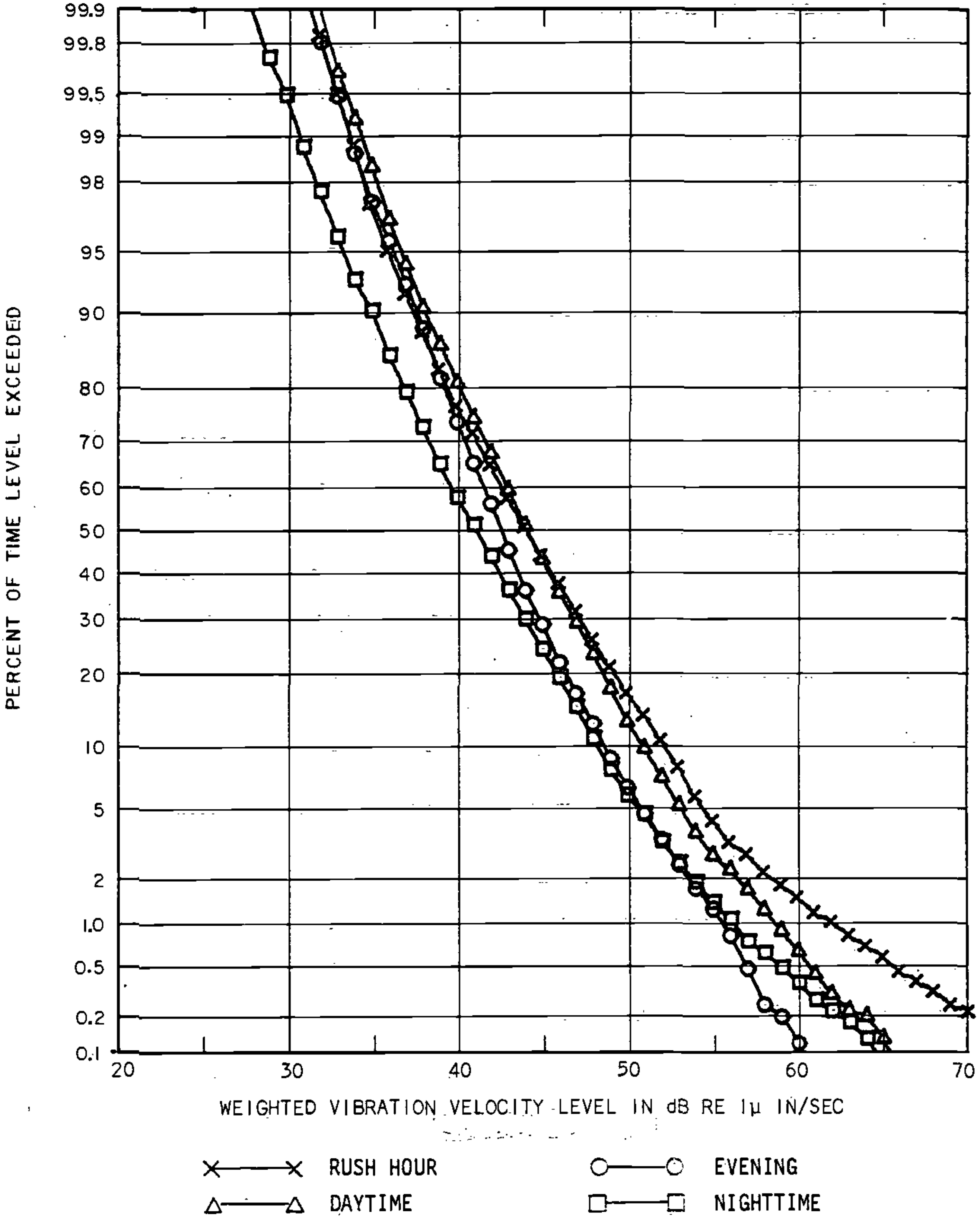

FIGURE B-55 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 110

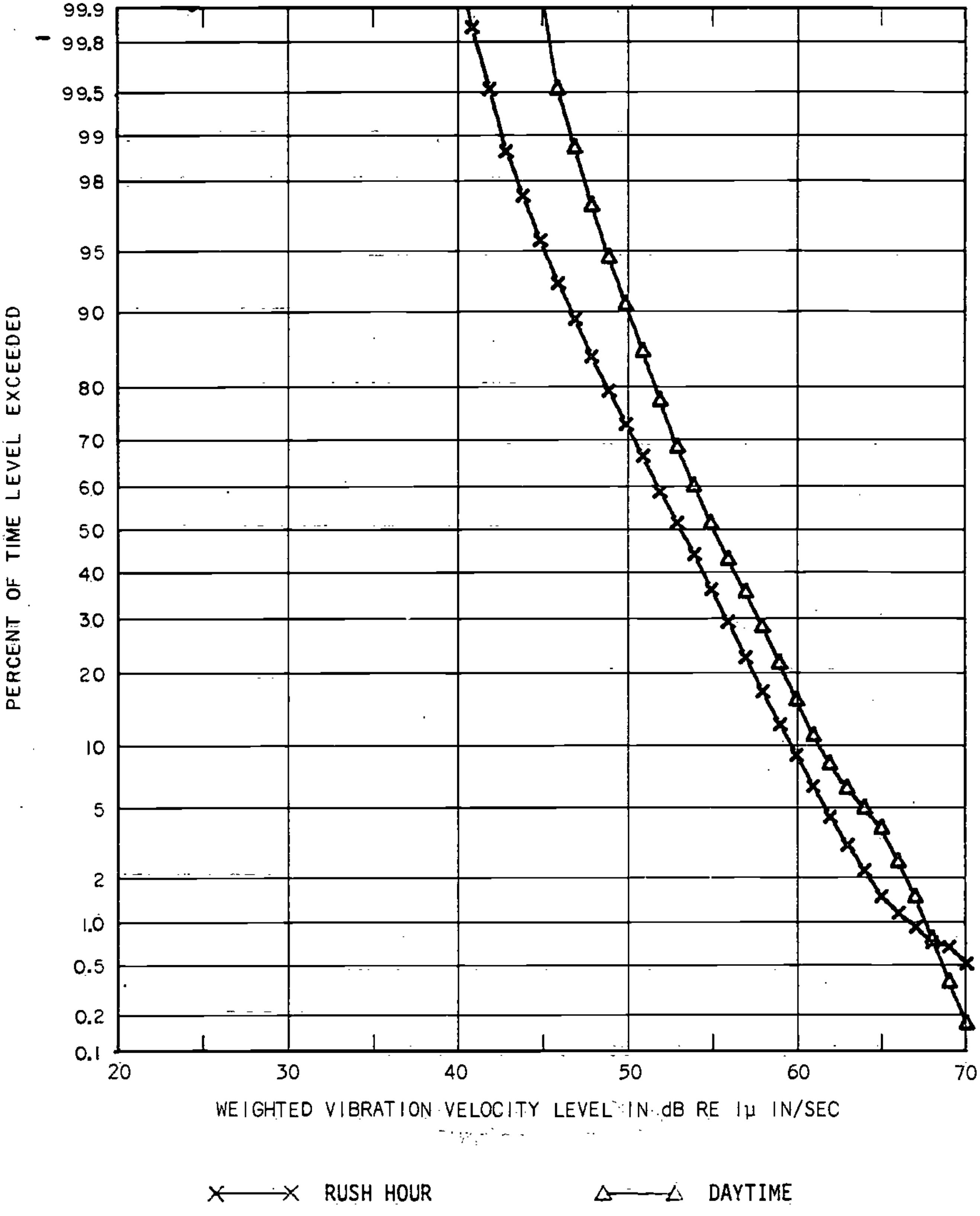

FIGURE B-56 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 111

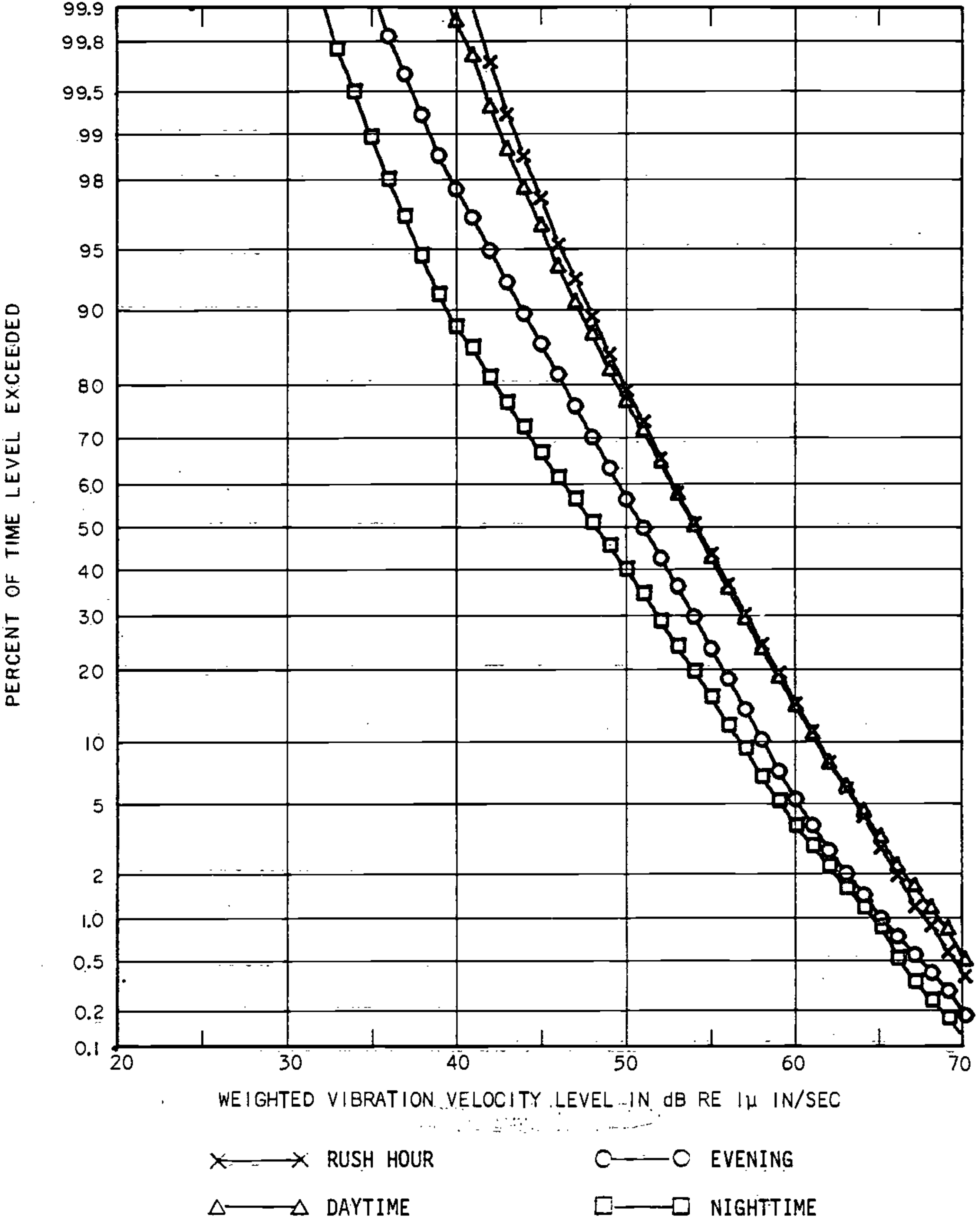

FIGURE B-57 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 112

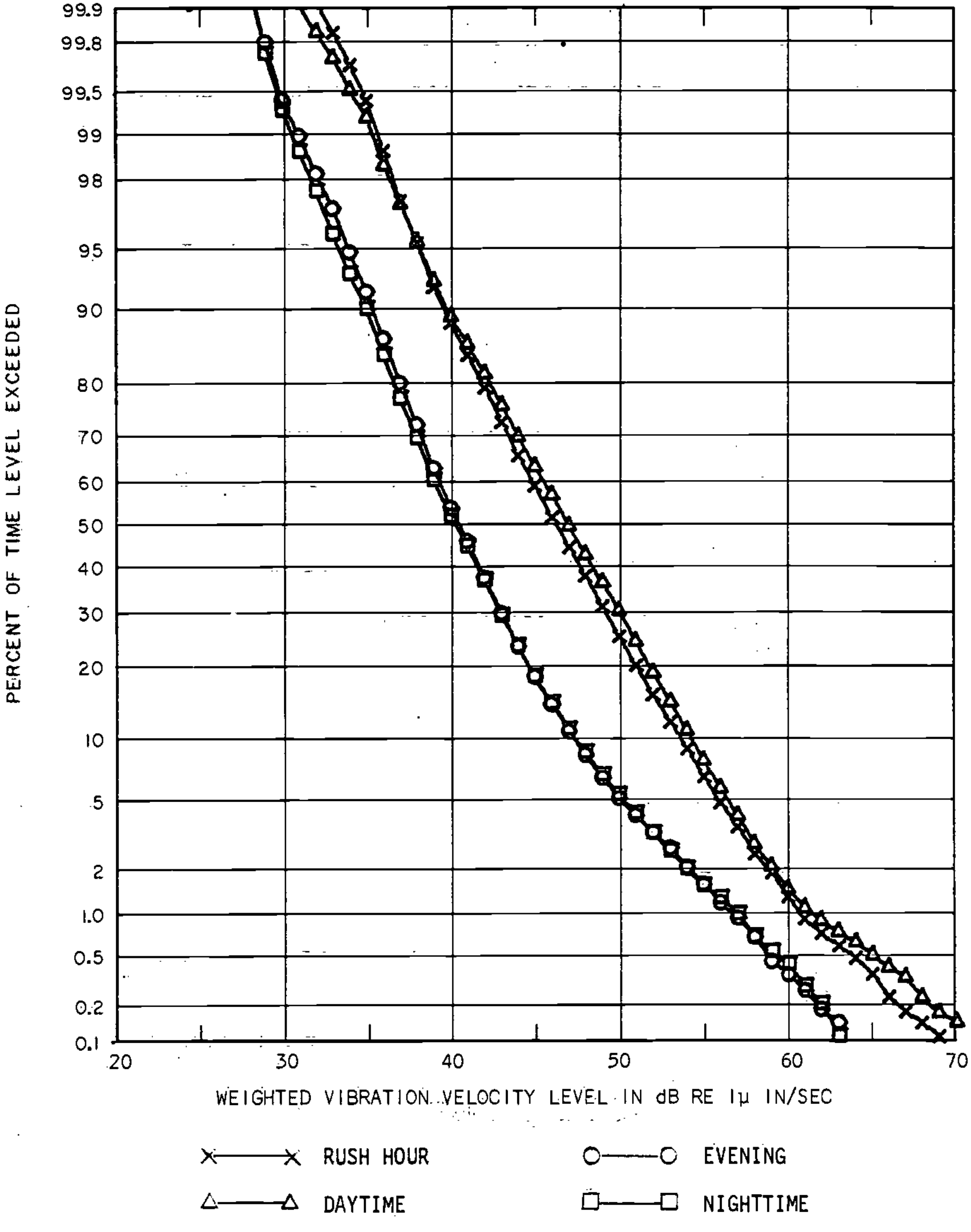

FIGURE B-58 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 113

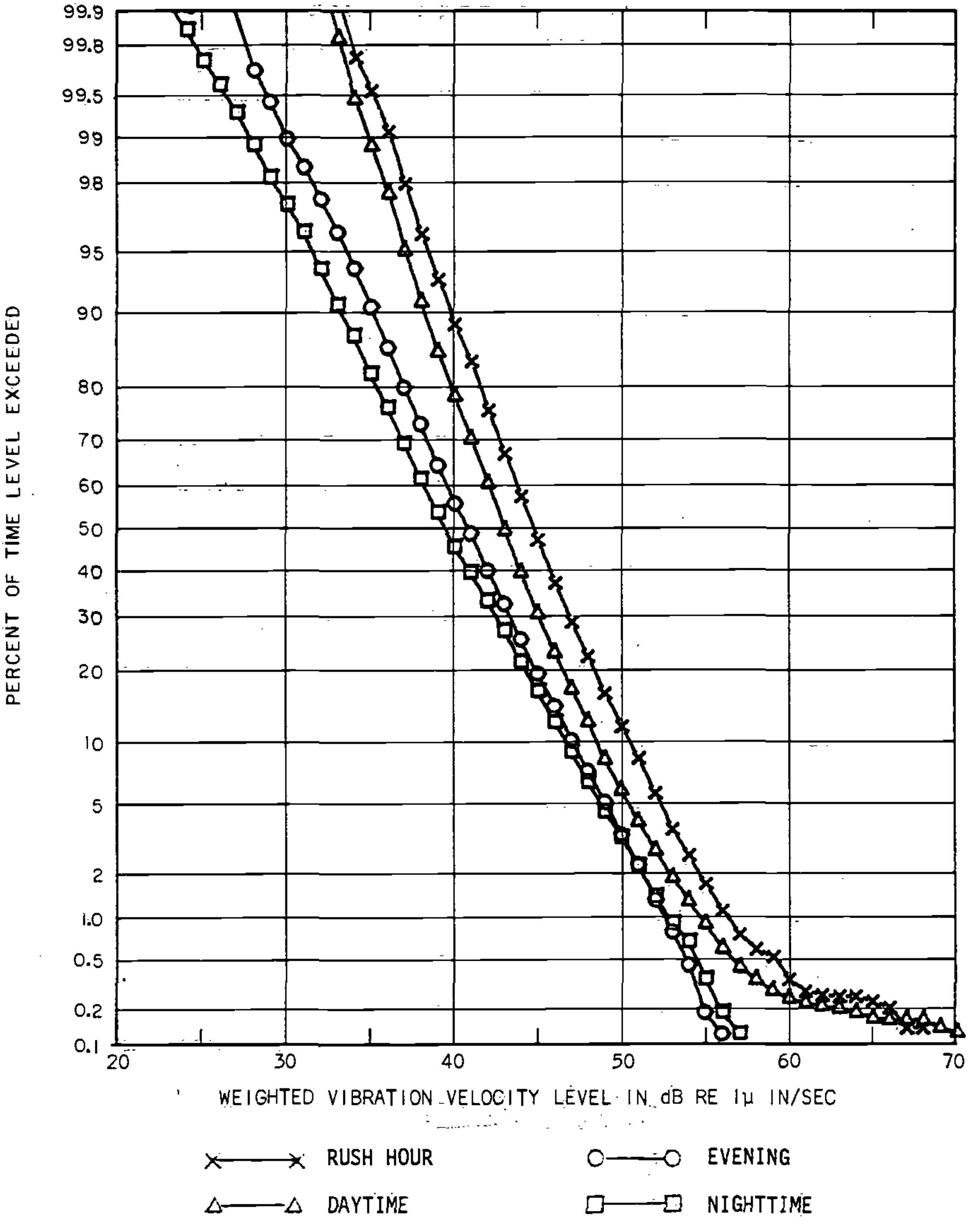

FIGURE B-59 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 114

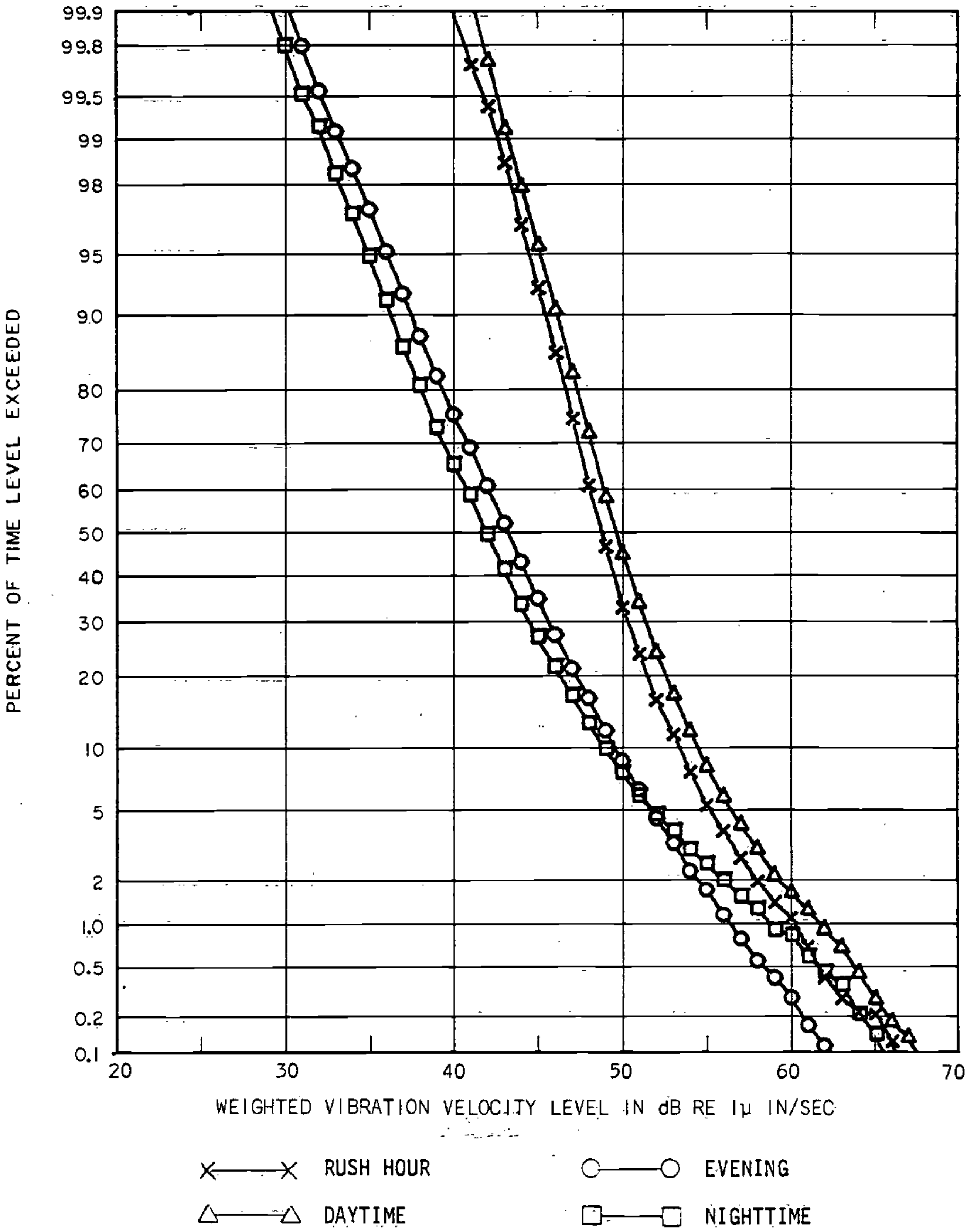

FIGURE B-60 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 115

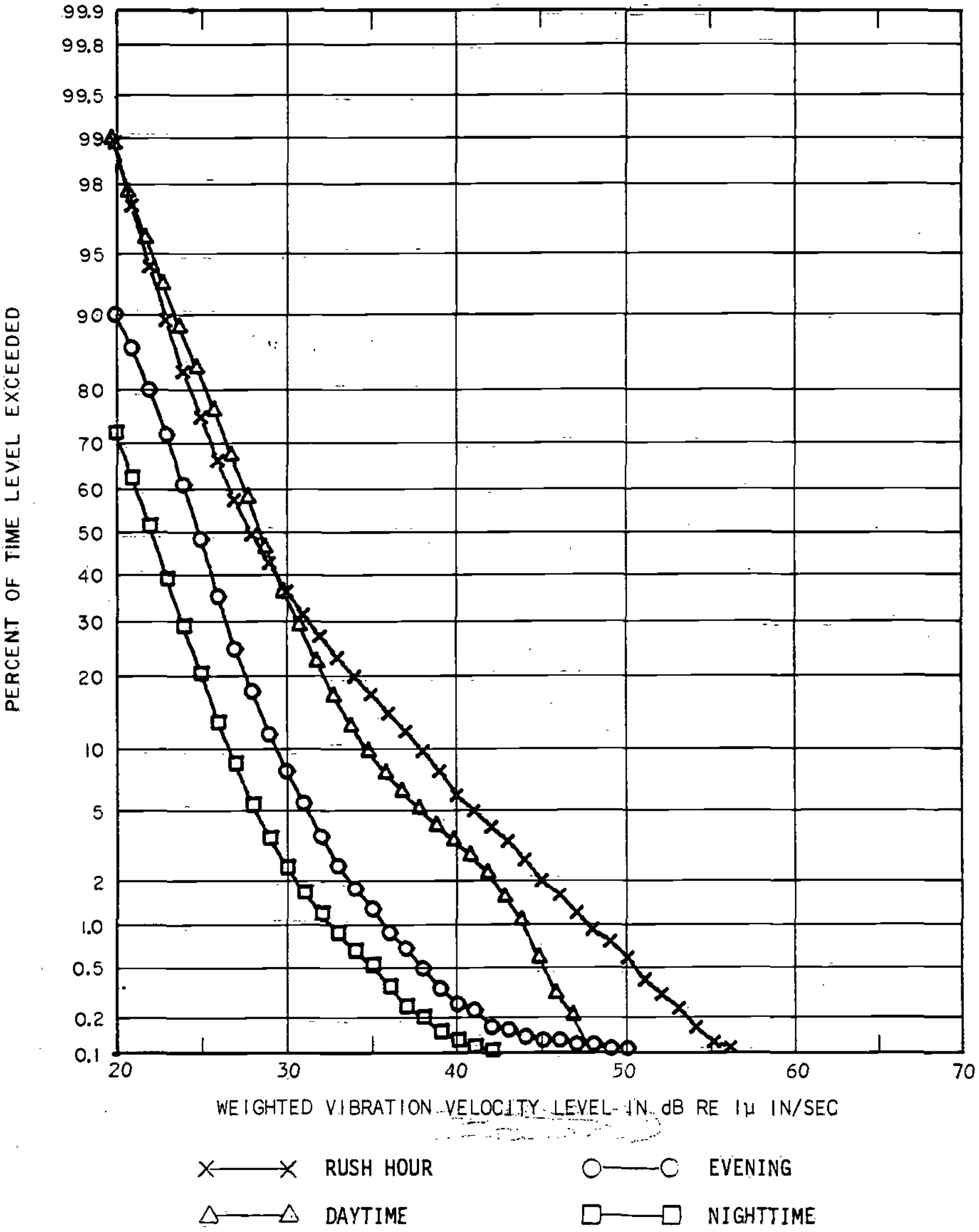

FIGURE B-61 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 116

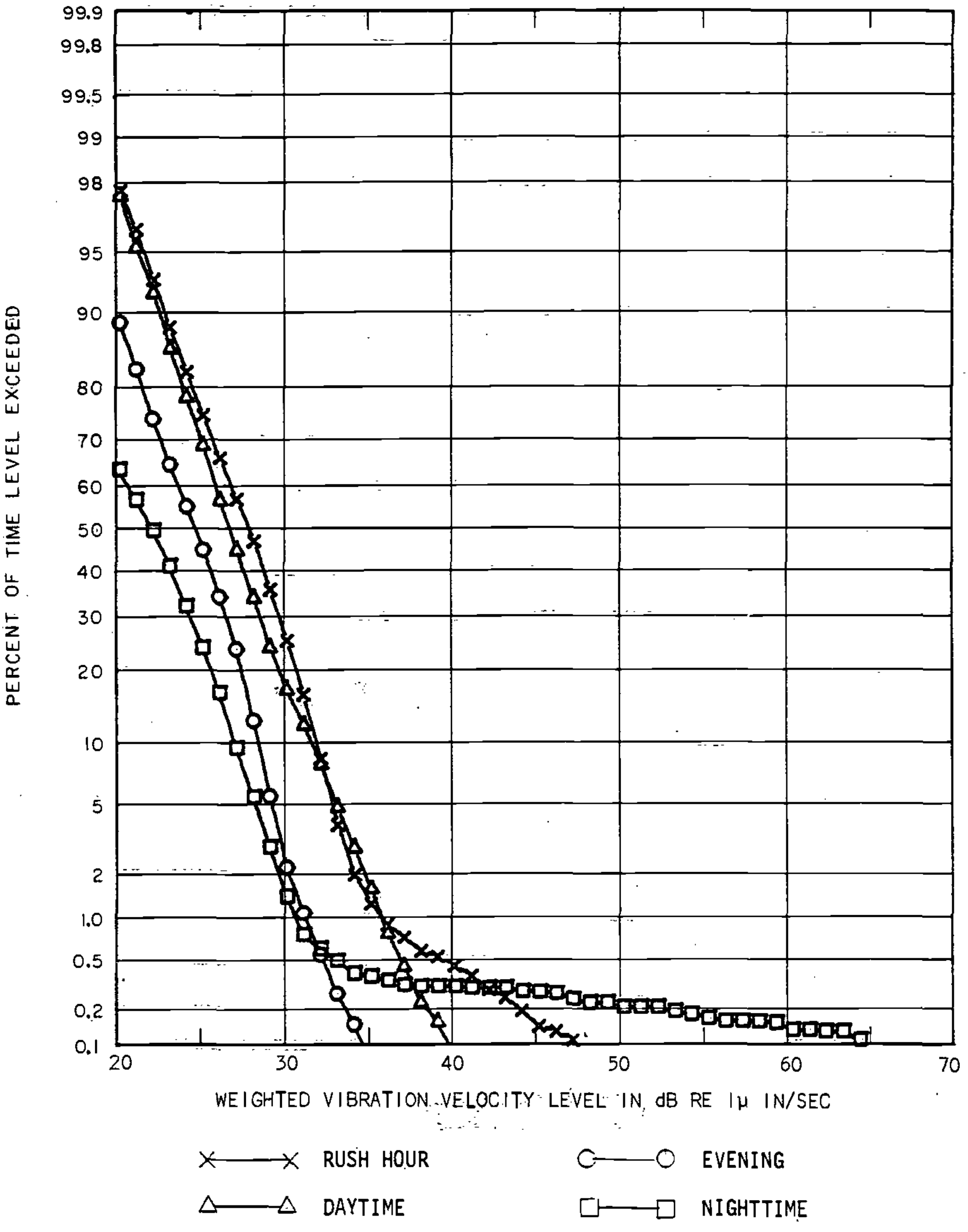

FIGURE B-62 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 117

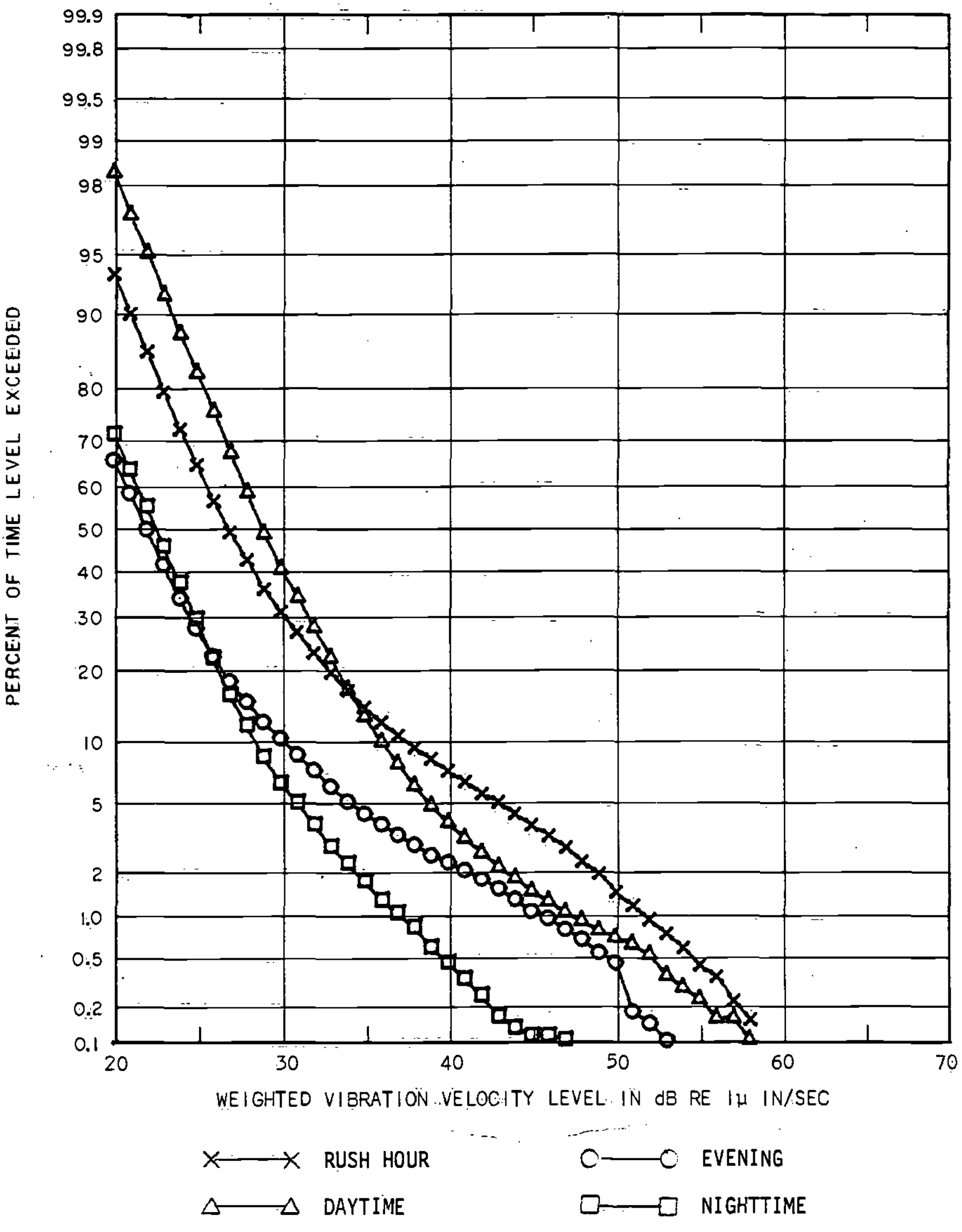

FIGURE B-63 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 118

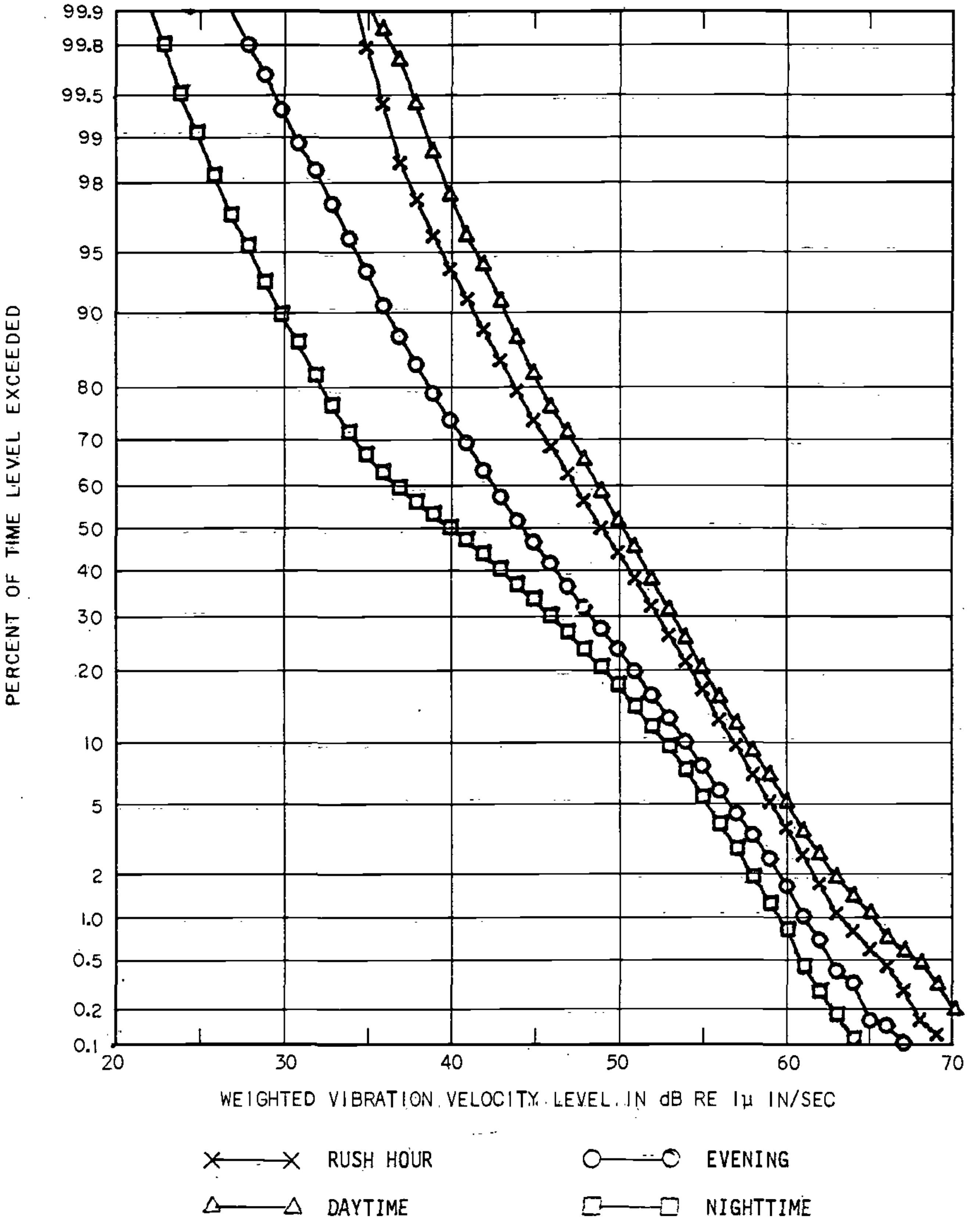

FIGURE B-64 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 119

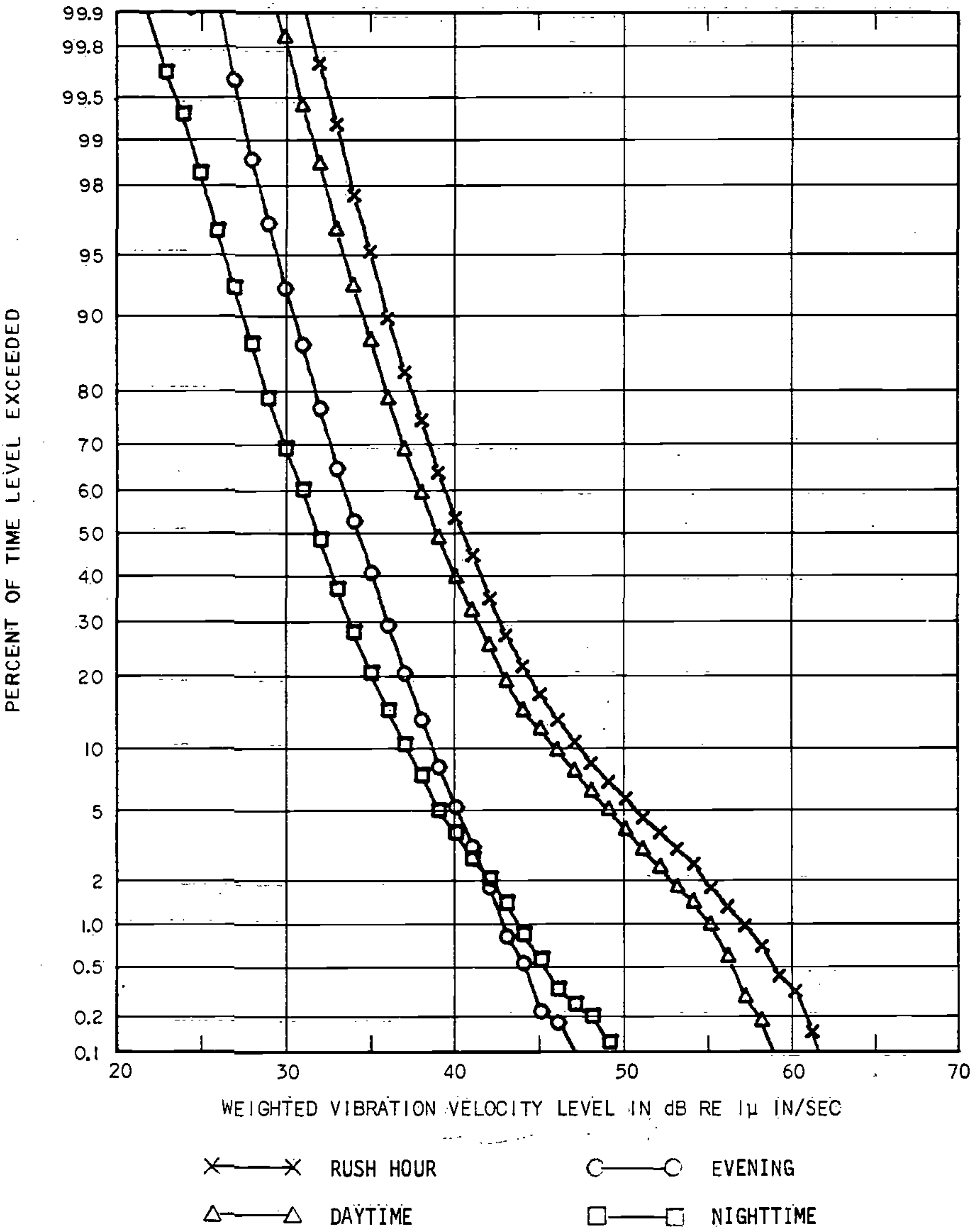

FIGURE B-65 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 120

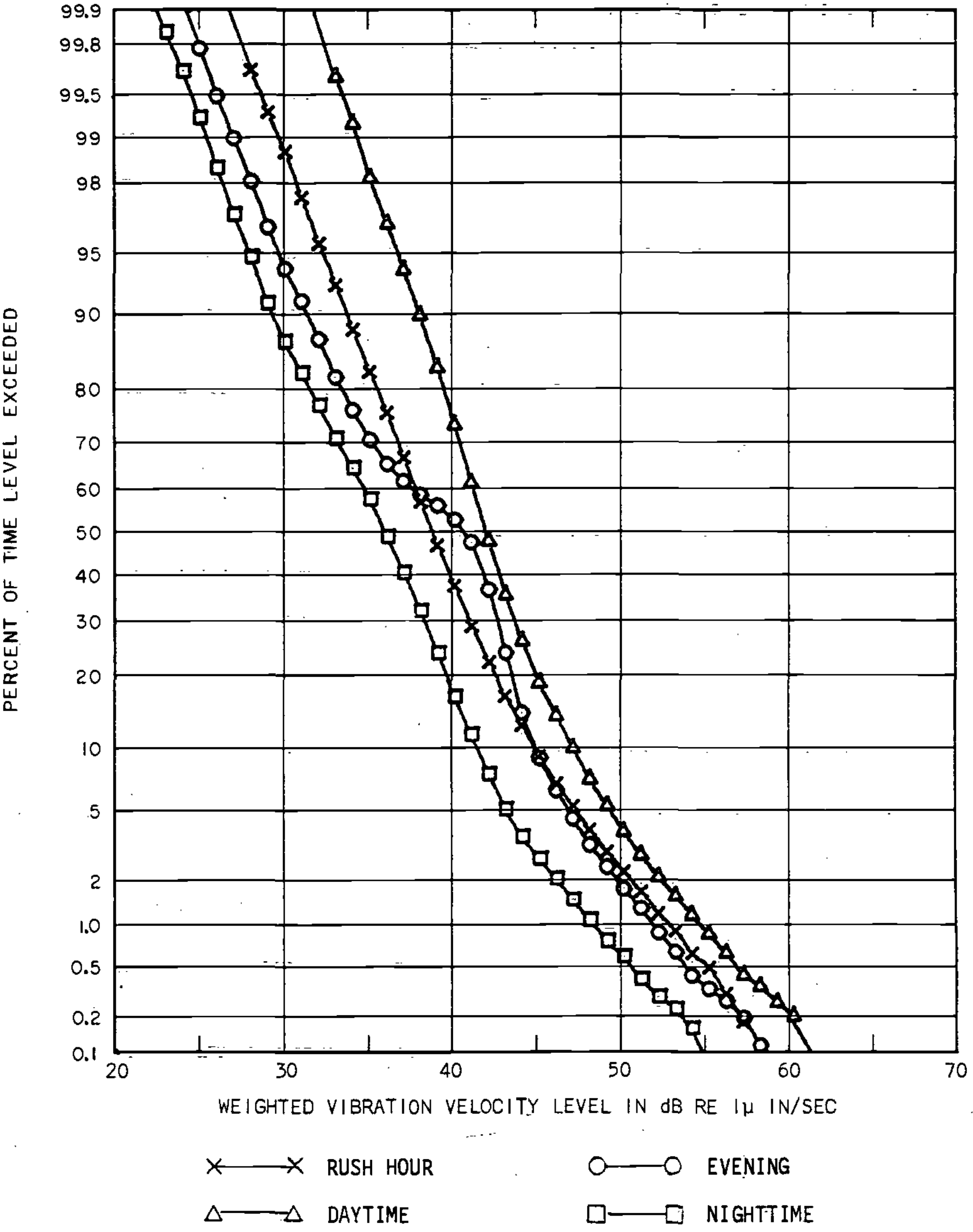

FIGURE B-66 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 121

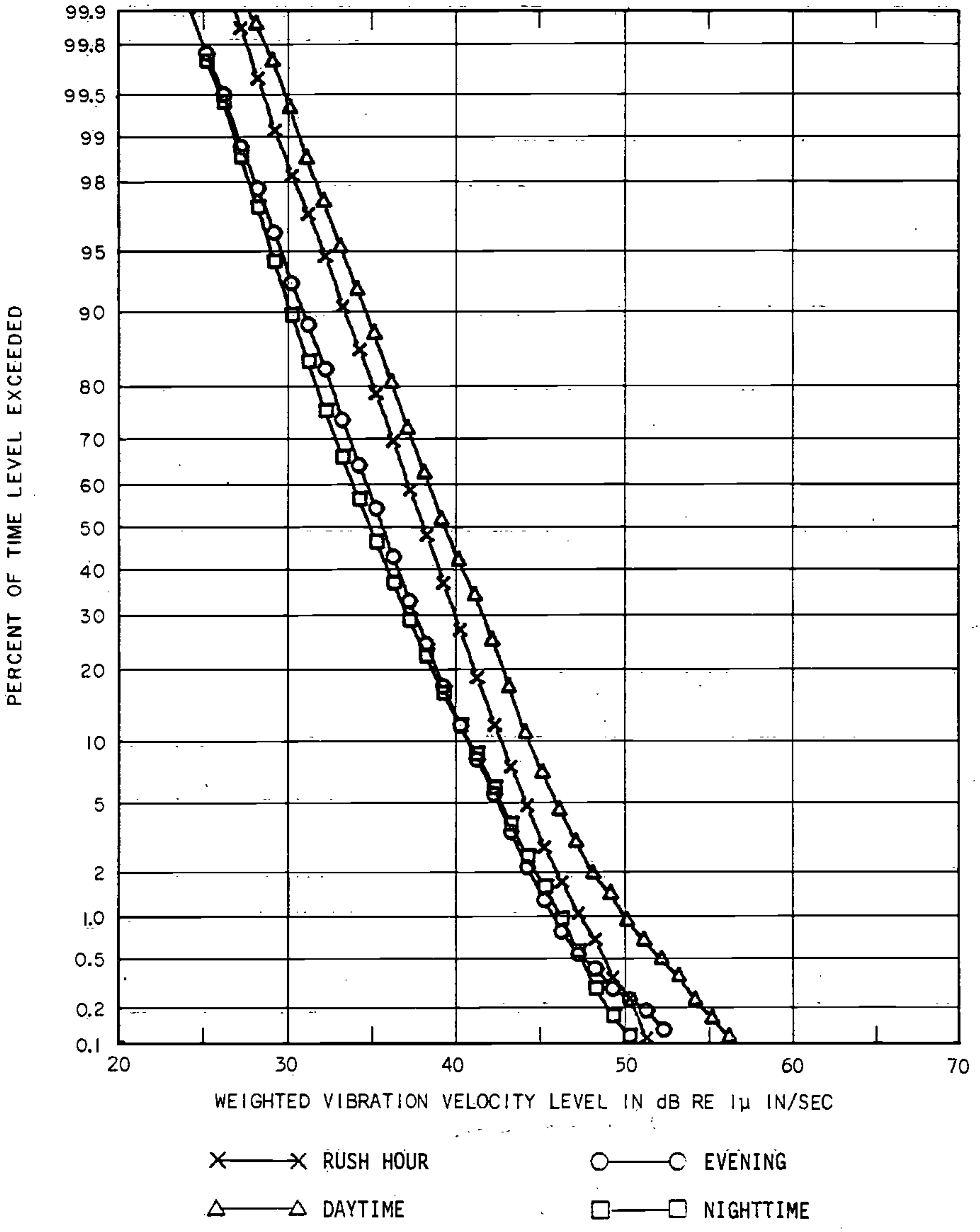

FIGURE B-67 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 122

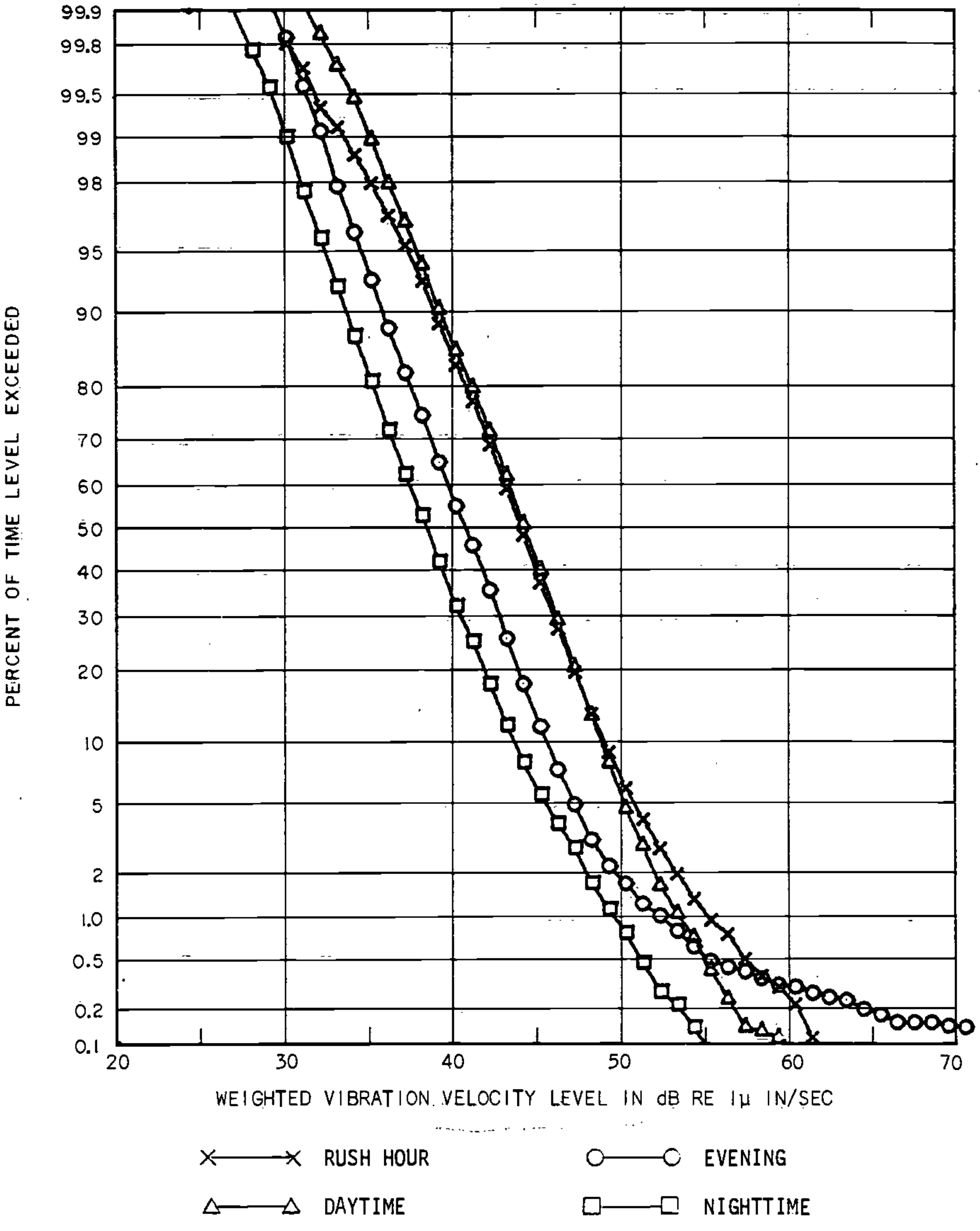

FIGURE B-68 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 123

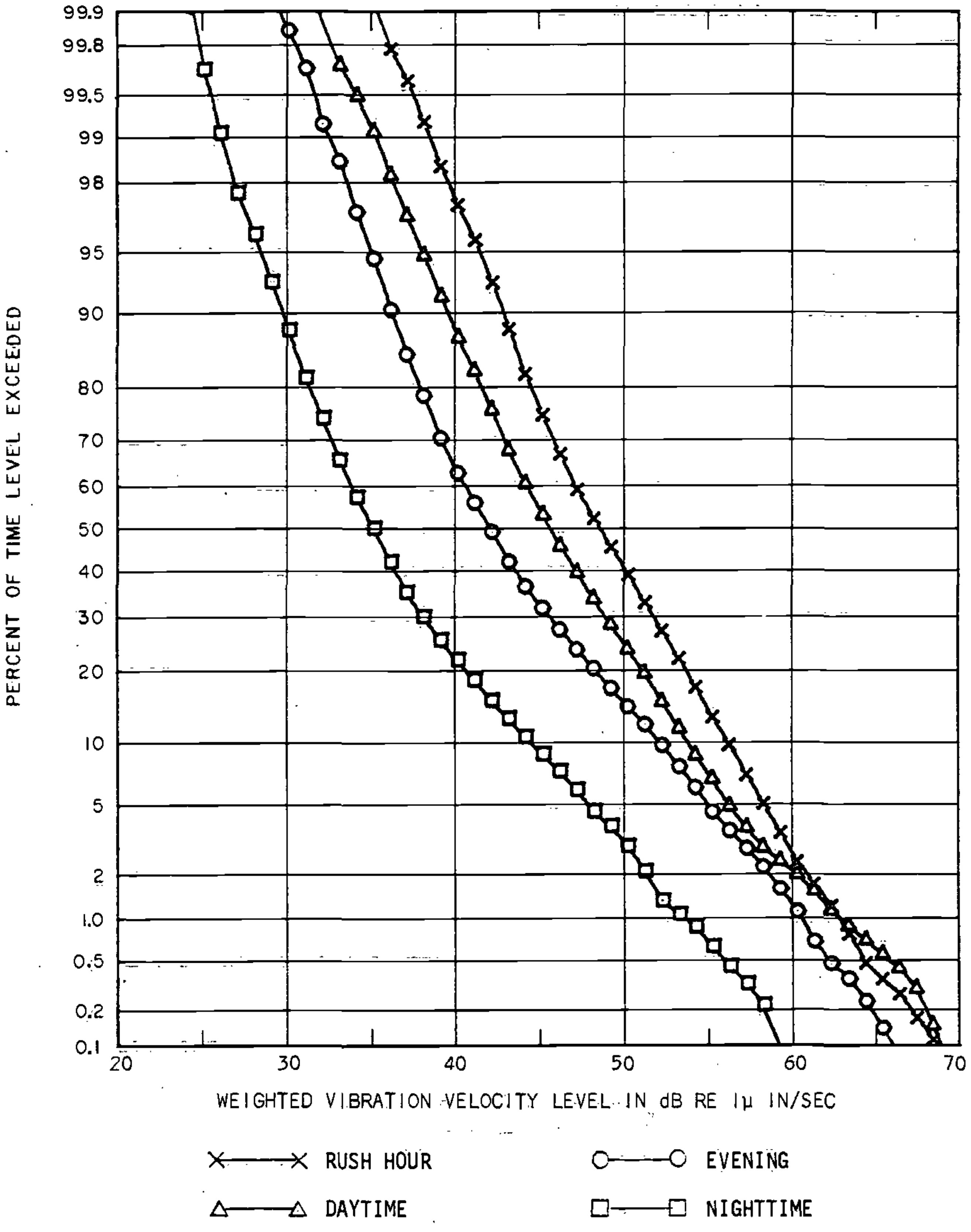

FIGURE B-69 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 124

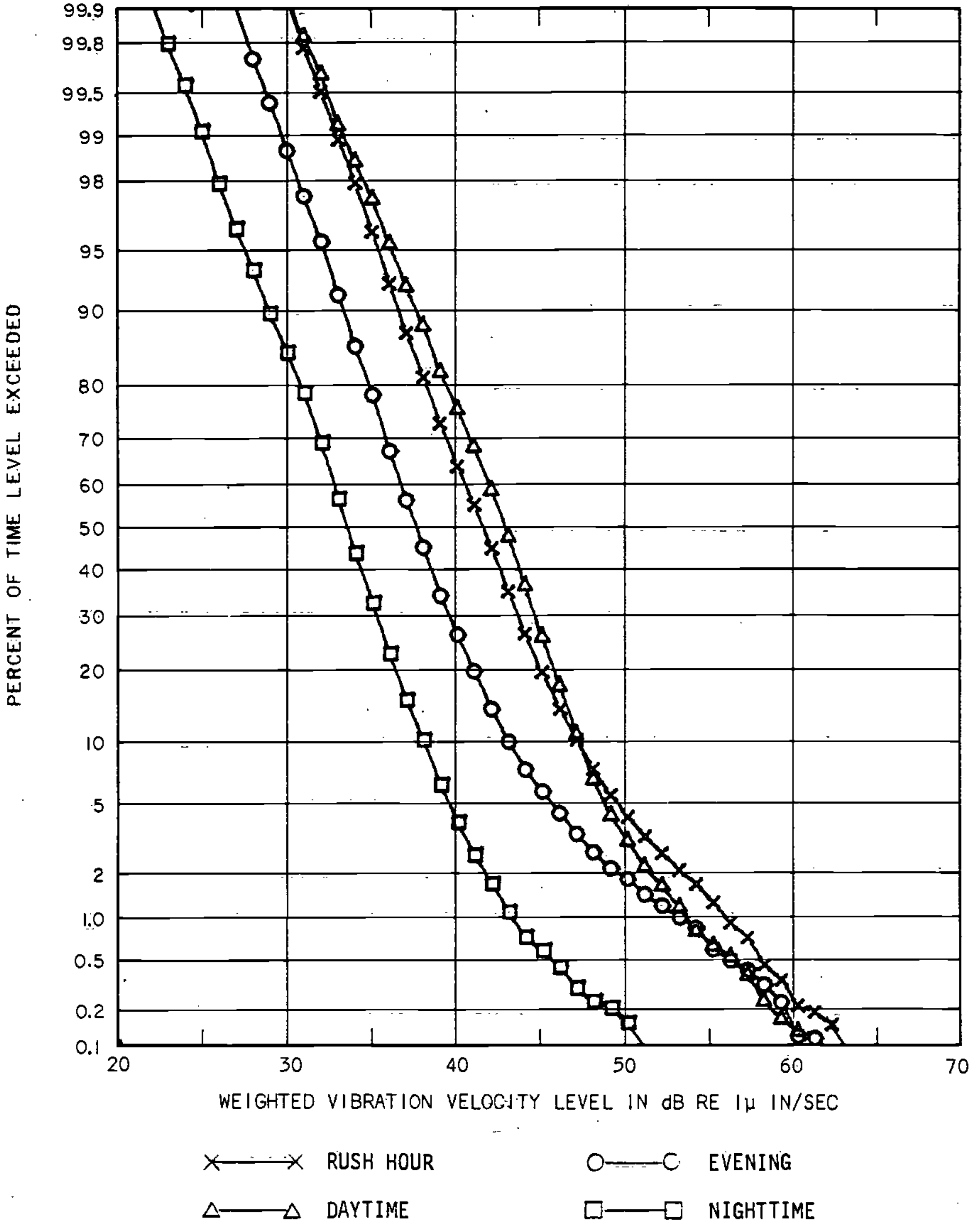

FIGURE B-70 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 125

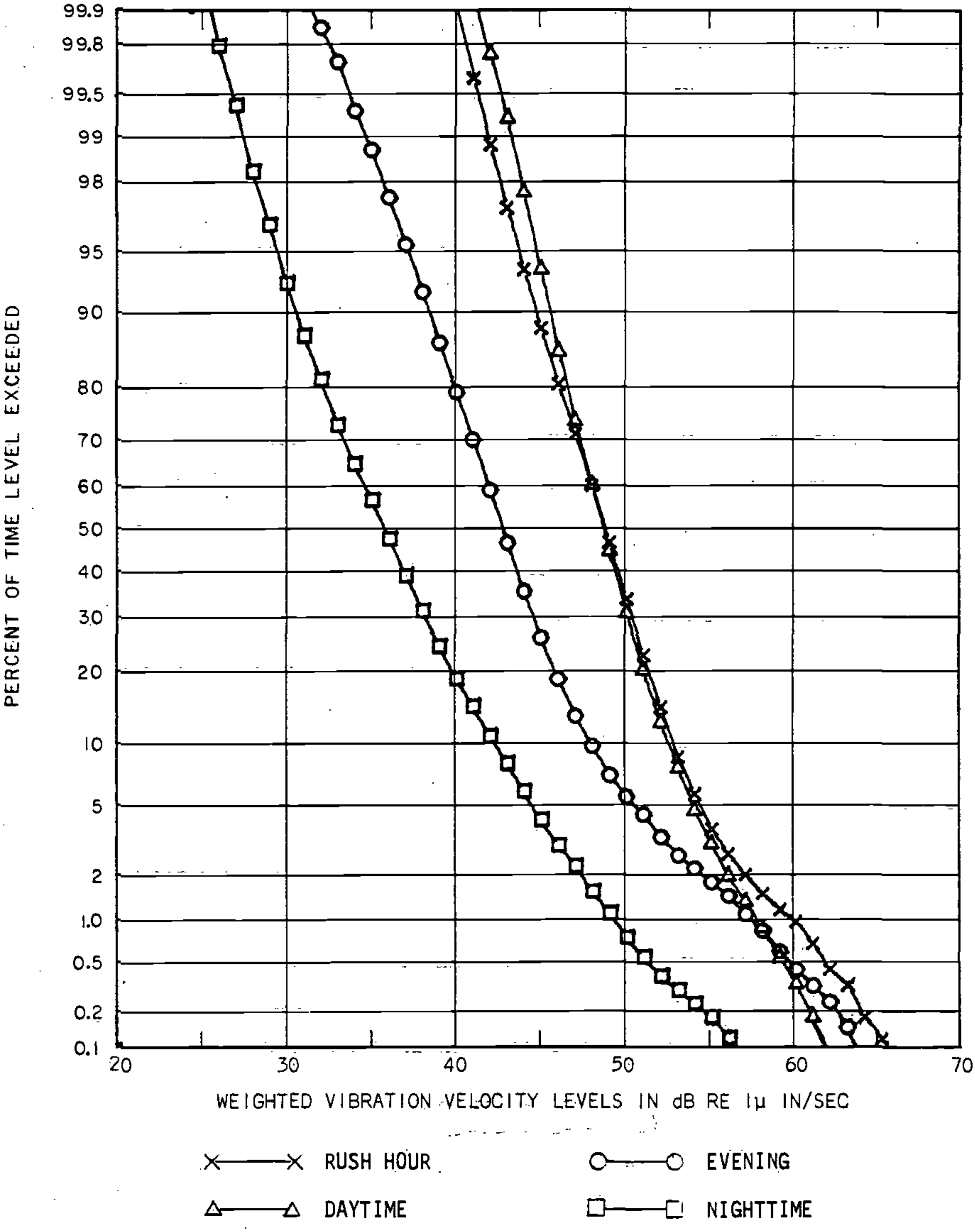

FIGURE B-71 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 126

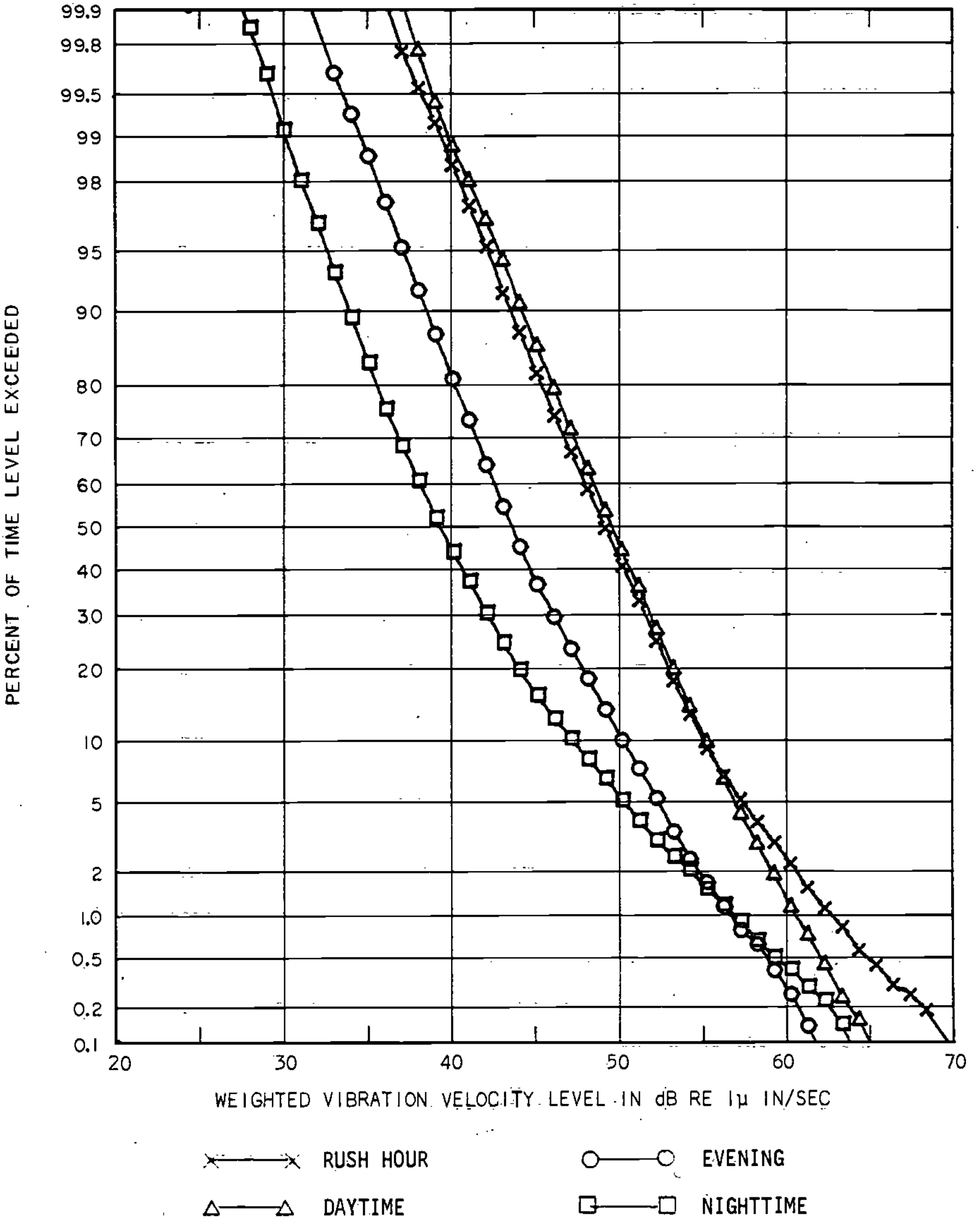

FIGURE B-72 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 127

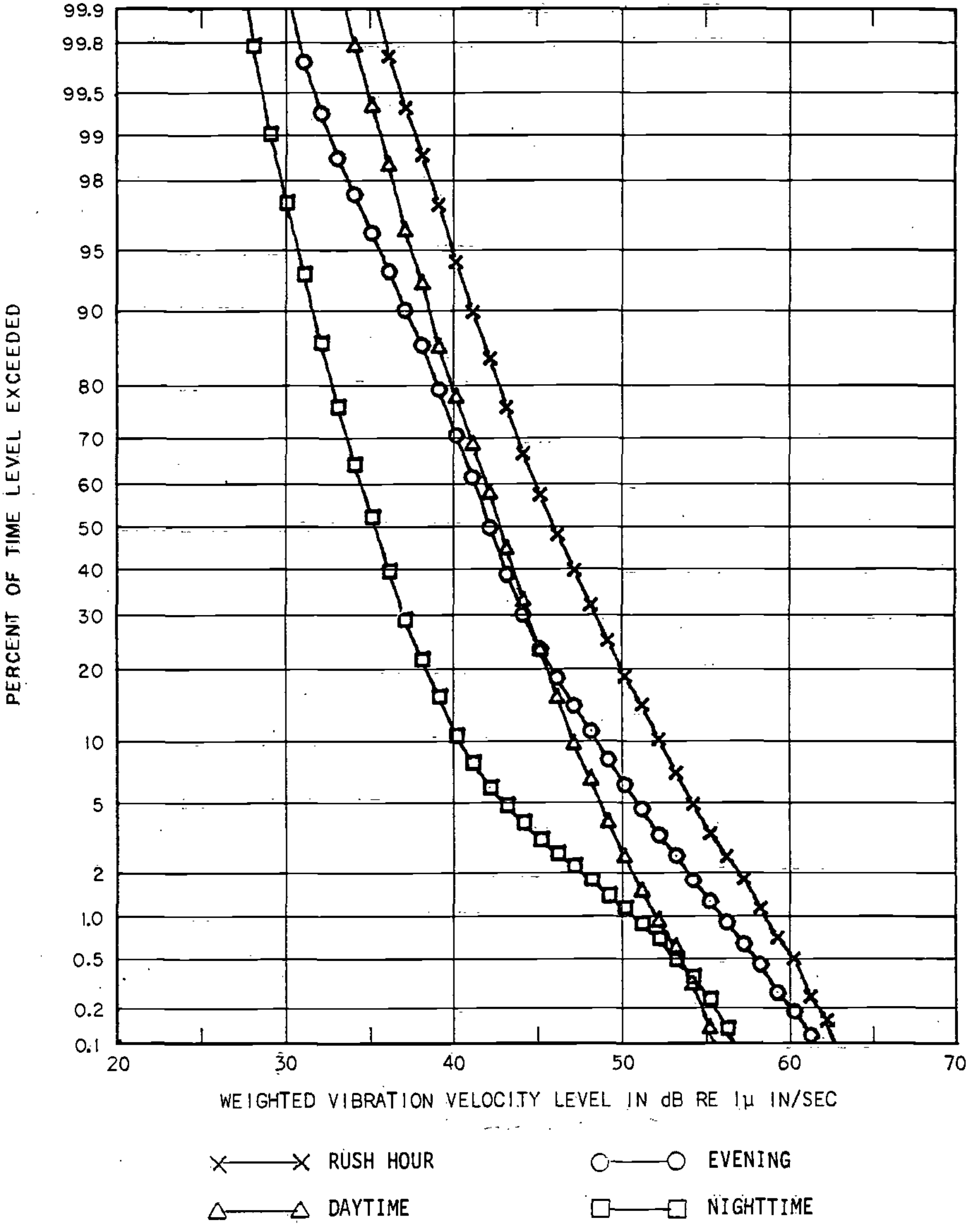

FIGURE B-73 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 128

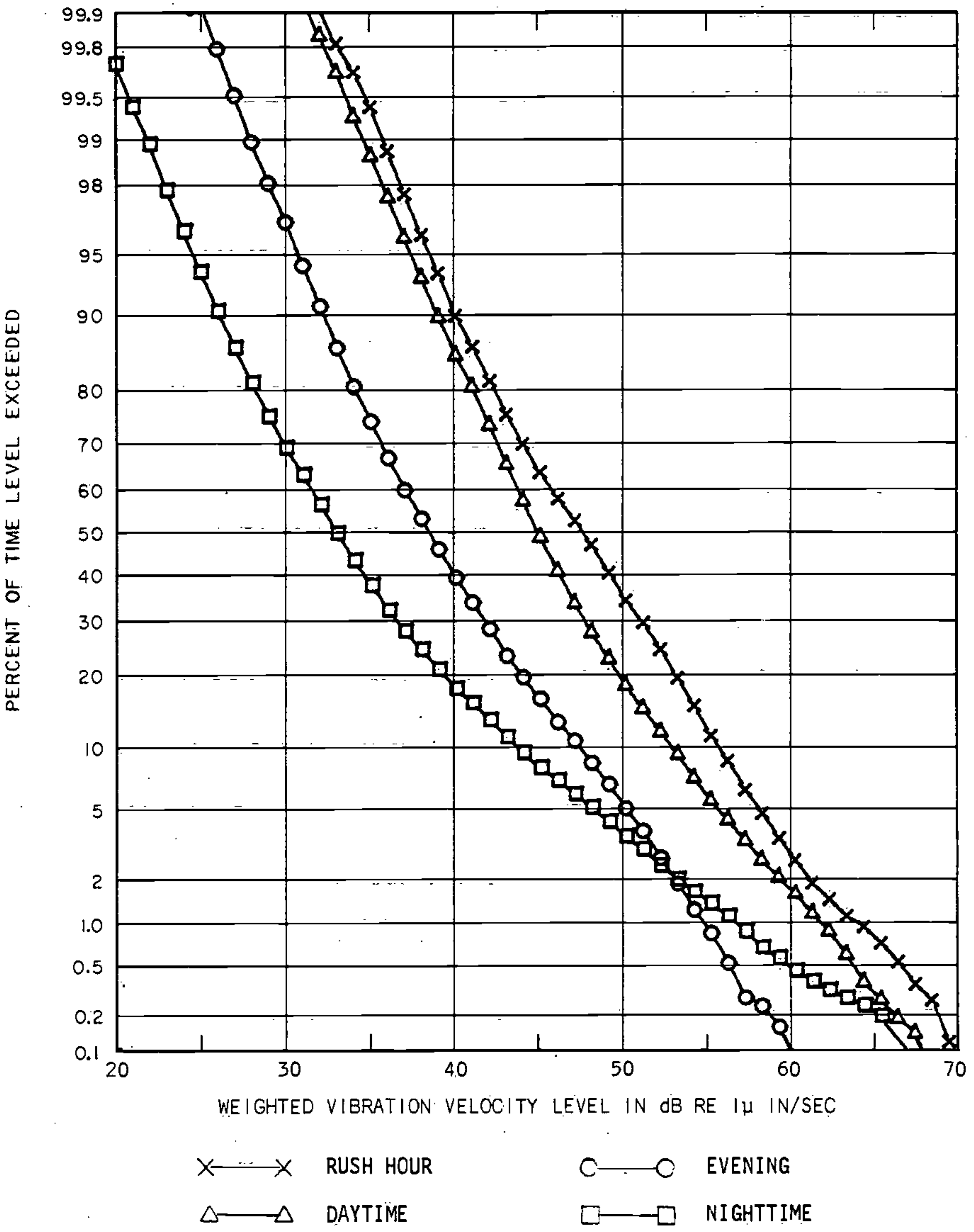

FIGURE B-74 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 129

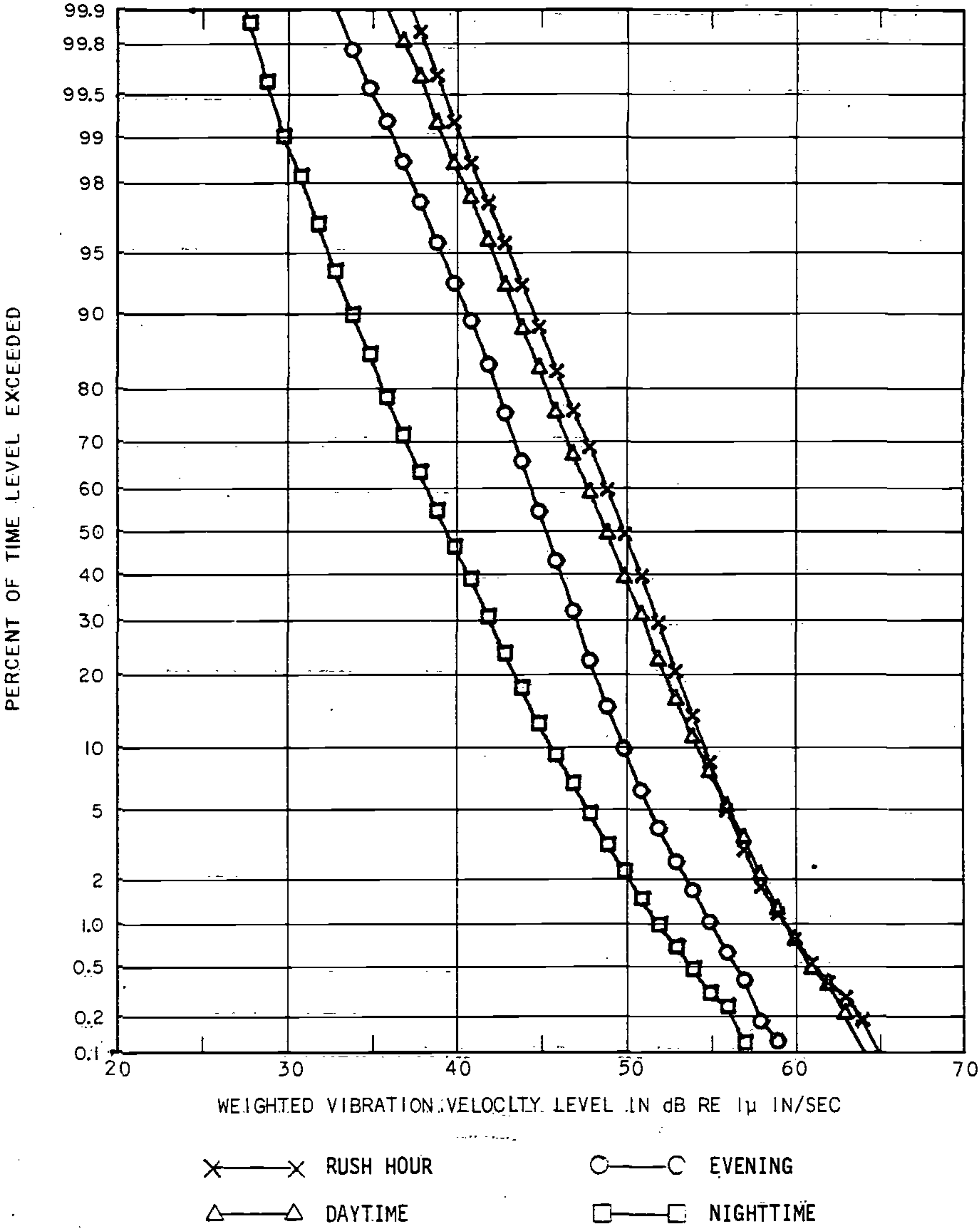

FIGURE B-75 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 130

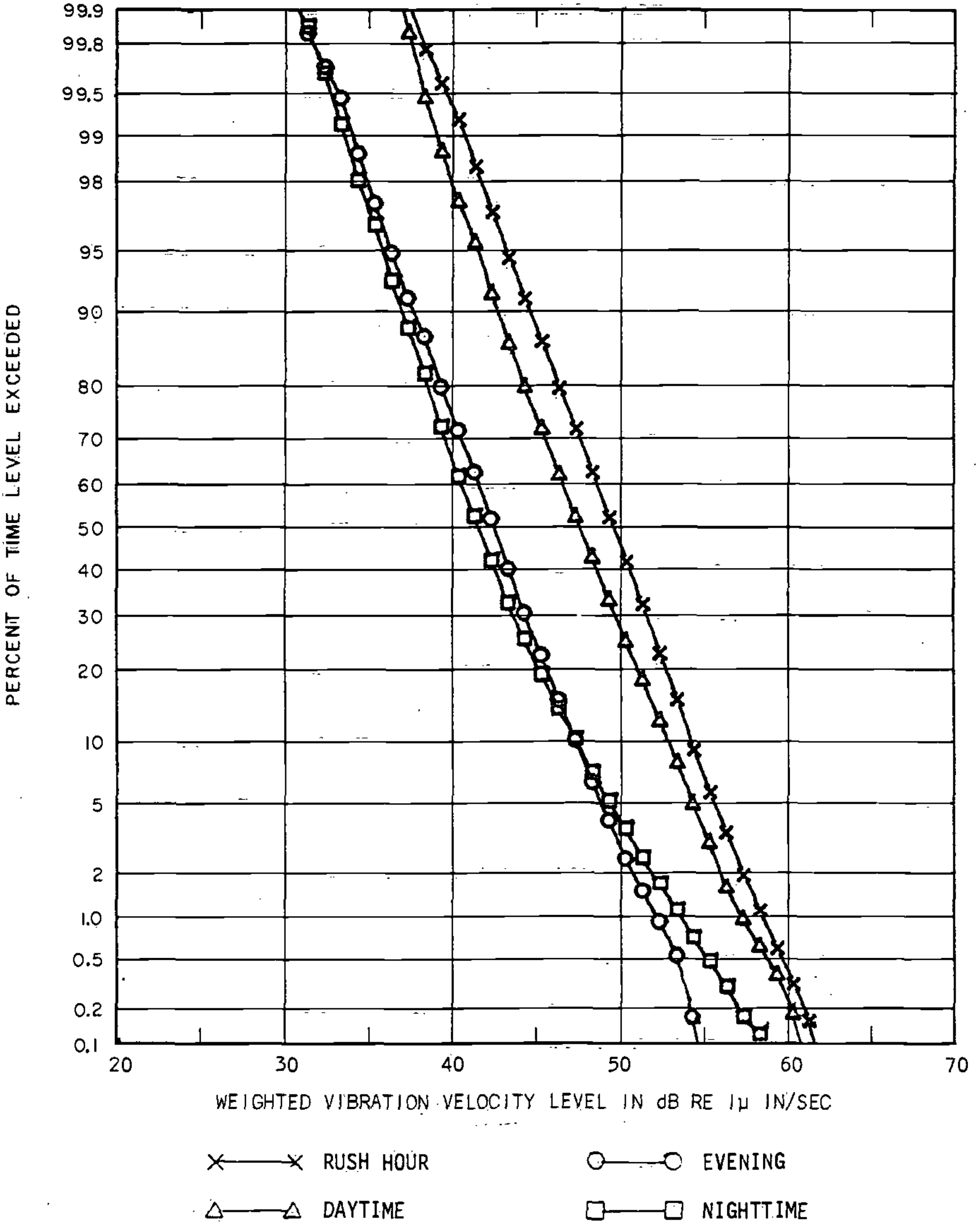

FIGURE B-76 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 131

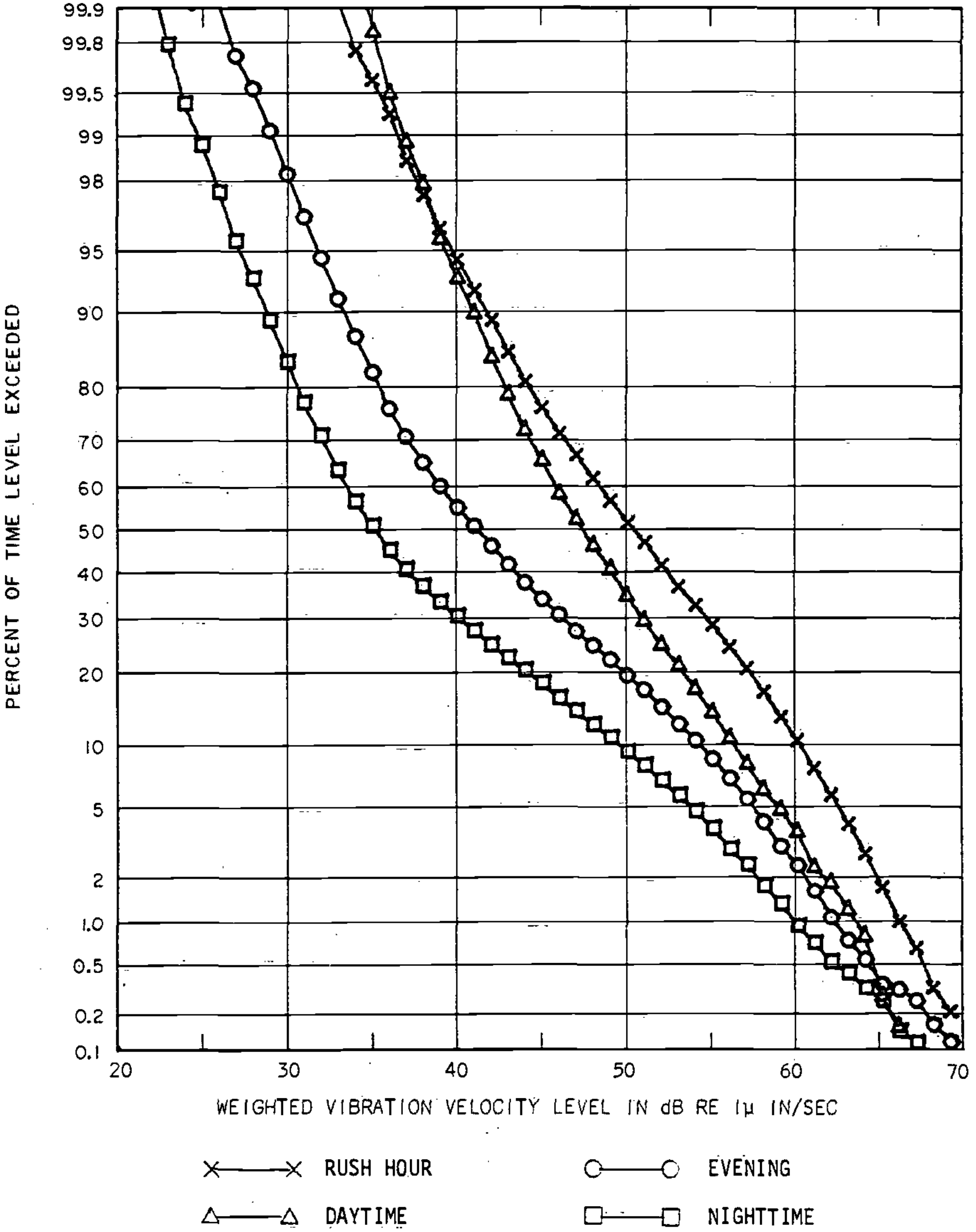

FIGURE B-77 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 132

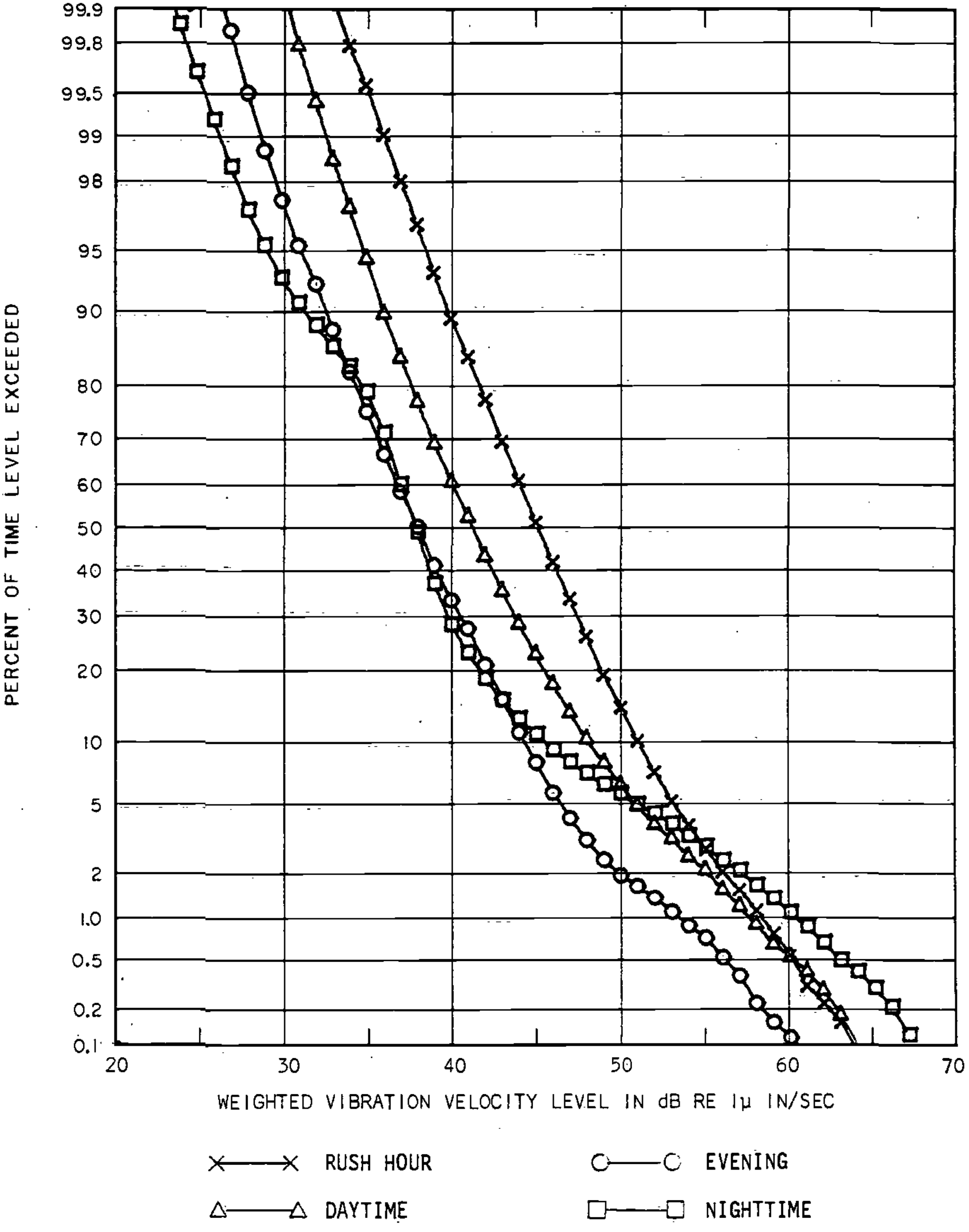

FIGURE B-78 STATISTICAL DISTRIBUTION OF THE WEIGHTED VIBRATION VELOCITY LEVELS AT LOCATION 133

APPENDIX C

MODELLING OF PRESSURE TRANSIENTS DUE TO FAN AND VENT SHAFT PASSAGE

Appendix C Modelling of Pressure Transients due to Fan and Vent Shaft Passage

Because car interior pressure transients occurring during passage of line vent and fan shaft structures are anticipated to be very high, the prediction techniques which we normally use for predicting car interior pressure transient magnitudes were upgraded and implemented on our computer. These prediction techniques are based on theoretical models which have been developed over the last ten years by Wilson, Ihrig & Associates and are supported by measurements at BART and at the Washington Metropolitan Transit Authority.

The model used for prediction of pressure transients at the Metro Rail system is discussed below. The model is intended to accurately determine the time variation of the pressure transient and includes the effects of non linear interaction with reflected waves from far field cross passages and vent shafts. As such, the model is the most accurate that can be attained short of those based on the method of characteristics, but has the added advantage of being relatively inexpensive to implement.

C.1 Components of the Fan and Vent Shaft Pressure Transient

The pressure transient created during the passage of a fan or vent shaft consists of two major components. The first component consists of a pressure rise necessary to overcome the steady state negative static pressure existing in the neighborhood of a train prior to passage of a fan or vent shaft. As the train passes the fan or vent shaft, these steady state pressures must rise to match, approximately, the atmospheric pressure, thus resulting in a pressure rise as the train leaves the tunnel section prior to passage of the fan or vent shaft. As the train passes the fan or vent shaft and enters the tunnel section beyond, the train encounters still air, and can be considered as a train entering a blunt portal. As the train progresses into the tunnel beyond the fan or vent shaft, the pressure transient rises rapidly due to friction along the train and, in the absence of any reflective cross passages or vent shafts in the far field ahead of the train, the pressure rise will continue until the train tail enters the tunnel. Since a six-car train is approximately 450 ft long, the duration of this type of pressure transient will be about 4.5 seconds for a train at speed 70 mph. This duration will be achieved provided that reflective discontinuities such as open cross passages or fan or vent shafts are located more than 2500 ft from the fan or vent shaft location. Note that the tunnel lengths between line vents and stations are typically about one mile - twice that required to consider the tunnel as infinite.

Prior to the train passing the fan or vent shaft, the pressure field in the neighborhood of the train can be thought of as steady state incompressible flow. In order to simplify the analysis, the tunnel length is assumed to consist of the subway tunnel length between the station and/or preceding vent shaft and the vent shaft about to be passed. More detailed analyses can be performed, however for purposes of prediction this approach is reasonably accurate. The theory used for predicting the steady state pressure transients is essentially that used in the Subway Environmental Design Handbook except that the notation and implementation are different. Both rely on incompressible flow and use of friction factors for the train and the tunnel wall. In this regard, the present method differs little from that used in the past.

Prior to vent passage, the steady state pressures within the vehicle are generally below atmospheric due to pressure drops and friction along the side of the train. This negative pressure must be overcome as the train enters the fan or vent shaft area and the time period required for this is assumed to be equivalent to the time required for the nose of the train to pass the fan or vent shaft area for the lead car. However at the trailing car, the interior car pressure begins to rise as soon as the train nose enters the fan or vent shaft area and continues to rise until the trailing car passes the fan or vent shaft. Thus the time period required for overcoming the negative trailing car interior pressure is essentially the time required for the train to completely pass the fan or vent shaft. These time periods may be lengthened by incorporation of transition sections, or flaring, between the vent proper and the line tunnels, in both directions.

The second major part of the pressure transient consists of the entry into the tunnel beyond the fan or vent shaft. For purposes of modelling, the resulting pressure rise is assumed to be equivalent to that which would be produced by a train entering a blunt portal, as mentioned above. This entry pressure transient model consists of a near field flow coupled with a far field. The near field flow about the train during entry into the tunnel section is modelled as an incompressible flow and includes the effect of air inertia in the annulus between the train and the tunnel wall. Again, this approach is essentially equivalent to the model used by the Subway Environmental Design Handbook, although it has been derived essentially independently. This representation is appropriate for the relatively low Mach numbers associated with rapid transit train speeds. For higher speeds, such as trains operating at 150 mph, this incompressible flow assumption would be open to question. The far field flow conditions ahead of the train are modelled as a compressible column of air capable of supporting propagating waves. These waves may be partially or totally reflected and are returned to the train. To implement the far field model, the relationship between induced pressure ahead of the train and change in flow ahead of the train is assumed to be linear. Reflective discontinuities such as a cross passage or fan or vent shaft or exit portal are modelled by a time delay representation.

Tunnel friction ahead of the train is ignored, because the air flow velocity ahead of the train is very low during the transient. This latter assumption is valid for the first few reflections from a far field cross passage or portal. To elaborate, the relationship between the forward static pressure ahead of the train and the induced airflow velocity ahead of the train is controlled by the acoustic impedance of the air, so that a very high pressure must be induced in order to achieve a significant air velocity in the tunnel ahead of the train. Thus the pressures due to compressive loading of the air column ahead of the train are very much higher than the pressures due to tunnel wall friction ahead of the train or portal losses. Again, this assumption loses validity after a number of reflections from the far field have occurred, that is, when the air velocity ahead of the train has increased to significant levels and the pressures ahead of the train have been reduced by these reflections. A more detailed discussion of this interaction is given in the Handbook of Urban Rail Noise and Vibration Control.

Finally, appropriate matching conditions are used to couple the far-field compressible flow representation with the non-linear near-field incompressible flow in the vicinity of the train. These reflected waves from the far field interact at the train nose, and are reflected non-linearly back into the far field. Thus the model accounts for non-linear multiple reflection between the far field reflector and the train nose.

The pressure transient prediction procedure used in the Subway Environmental Design Handbook assumes that the air column is incompressible throughout the subway system, not just in the vicinity of the train. Furthermore, the SEDH prediction procedure accounts for the reflection of waves from the far field by simple linear super-position of the reflected wave amplitude on the interior car pressures. Because of this the method which we employed for the Metro Rail pressure transient prediction is superior in two respects to the method used in the SEDH for modeling of the pressure transient magnitude over relatively short durations. The pressure transient prediction model used in the SEDH is however representative of the average pressure transient profiles and is perhaps quite capable of predicting the average airflow velocity throughout the subway system as a result of the train's "piston action."

C.2 Model Parameters

The parameters used in the above model include:

- blockage ratio
- tunnel wetted perimeter
- train wetted perimeter
- tunnel cross-section area
- tunnel length
- train length
- train speed
- tunnel wall friction factor
- train skin friction factor
- train nose loss factor
- train tail loss factor
- entry and exit portal loss factors

Reflective cross passages and/or portals or vent shafts are modeled by specifying a reflection coefficient together with a time delay associated with each travel path within the subway ahead of the train. A travel path consists of the path traversed by the wave through a cross passage to the adjacent tunnel and reflections from portals and/or vent shafts. For instance, the shortest travel path would consist of the path from the train nose to the first reflector, which may be a cross passage, and the return path back to the train nose. Another travel path might consist of the path through the cross passage to the adjacent tunnel, down the adjacent tunnel to another reflector, and then back through the cross passage and again back to the train nose. At each of the discontinuities, such as the cross passage, a reflection and/or transmission coefficient must be computed and used to infer an overall reflection coefficient for the travel path. These reflection and transmission coefficients are determined by the methods outlined in the Subway Environmental Design Handbook. However, because the travel path may include multiple reflections between cross passages and vent shafts before the wave actually arrives back to the train, the composite reflection coefficient for this particular travel path is considerably more complicated than indicated by the simple formulas in the SEDH manual. Since the model is concerned primarily with the first several seconds of the pressure transient, only a limited number of travel paths may be involved in the pressure transient signature. In fact, the primary path which consists of a reflection from the nearest cross passage or vent shaft or portal is the most significant contributor to the pressure transient since the secondary or multiple path travel times are of such duration as to cause a reflected wave to arrive back at the train after the train tail has entered the tunnel section, at which time the model ceases to have validity.

The model can accommodate train speed variation at constant acceleration. However, an accelerating speed profile was not used for studying the fan or vent shaft passbys of the Metro Rail system.

C.3 Model Output

The output of the steady state pressure prediction model used for determining pressures prior to passage of the fan or vent shaft include the pressure ahead of the train nose, the static tunnel wall pressure immediately behind the train nose, the static tunnel pressure immediately ahead of the train tail, and finally the static tunnel wall pressure behind the train tail. Additionally, the steady state model gives the air velocity ahead of the train as well as the annular air velocity.

The entry pressure transient prediction model used for modeling the pressure transients immediately following passage of the fan or vent shaft produces an estimate of pressures and air velocities at one-tenth second time intervals following entry into the tunnel section. These pressures and velocity estimates consist of the static tunnel wall pressure ahead of the train nose, and the static tunnel wall pressure in the annulus behind the train nose. The air velocity estimates consist of the air velocity ahead of the train, and the annular air velocity. Since the pressure and velocity is given as a function of time in one-tenth second intervals, the data may be plotted as a function of time for a visual representation of the pressure transient profile.

The results of the steady state pressure and the entry pressure transient prediction formulas are combined to produce the composite pressure transient signature as discussed above. This is essentially done by hand or by calculator. These final data are then divided by the duration of the pressure transients to determine the approximate rate of rise of the pressure transient for comparison with criteria.

C.4 Model Implementation

The steady state prediction model and the entry pressure transient model are incorporated in two Fortran programs which have been implemented on the WIA computer system. The computation time for both of these programs is essentially negligible. The dynamic entry pressure transient prediction program uses Runga-Kutta numerical integration techniques to integrate a non-linear ordinary differential equation. Both of these programs could conceivably be combined into one prediction program to model the fan or vent shaft passage, however this has not yet been done.

The entry pressure transient prediction program can be upgraded to include the effect of a flared tunnel entry. This may be useful in the future if the SCRTD wishes to study the effect of flared transitions at the fan or vent shaft locations to reduce the effect of pressure transient magnitude and rate of rise during passage.

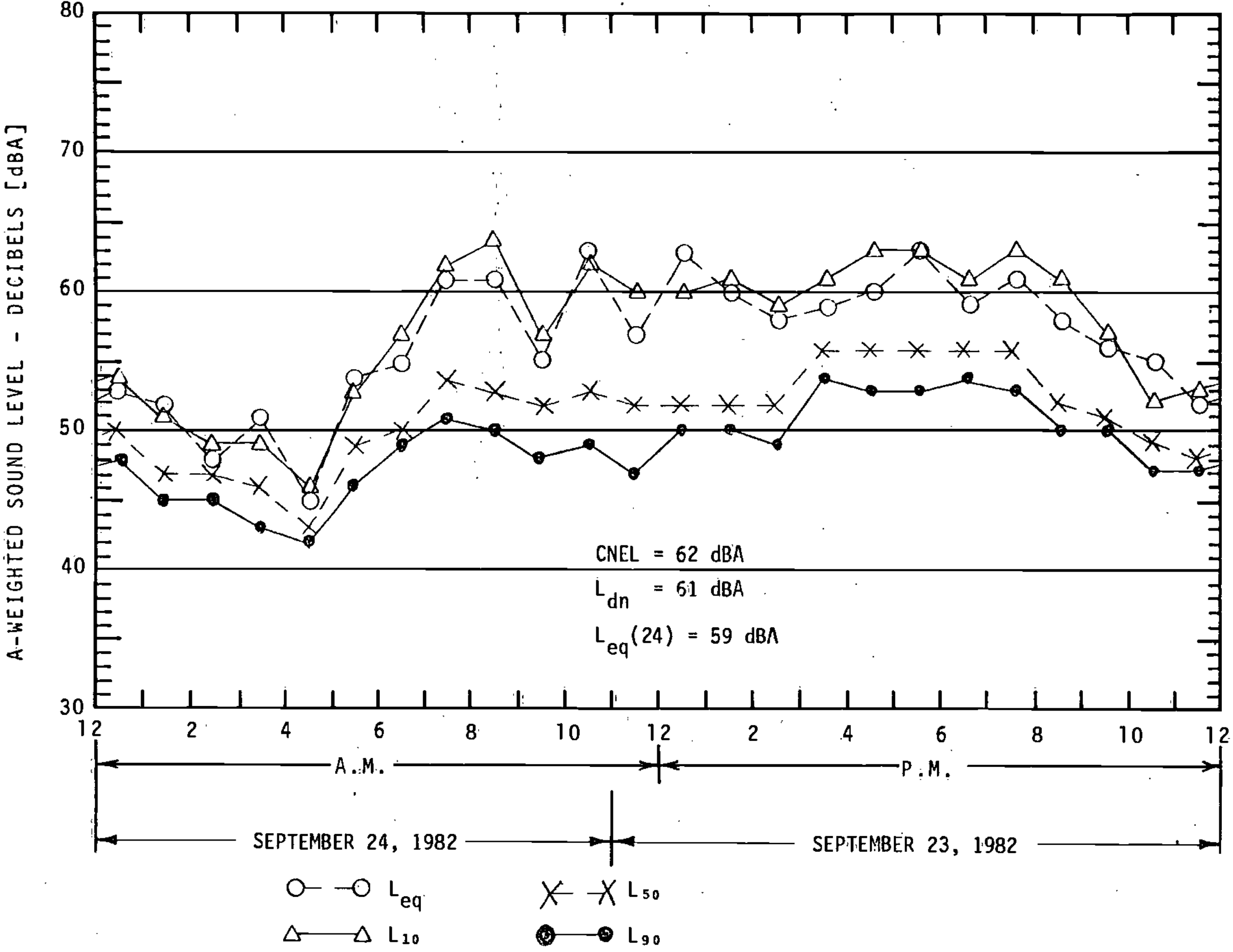

FIGURE 2.3-17 TIME HISTORY OF THE NOISE LEVEL MEASURED AT LOCATION 129A, OVER THE 24-HOUR PERIOD BEGINNING 11:00 A.M., THURSDAY, SEPTEMBER 23, 1982

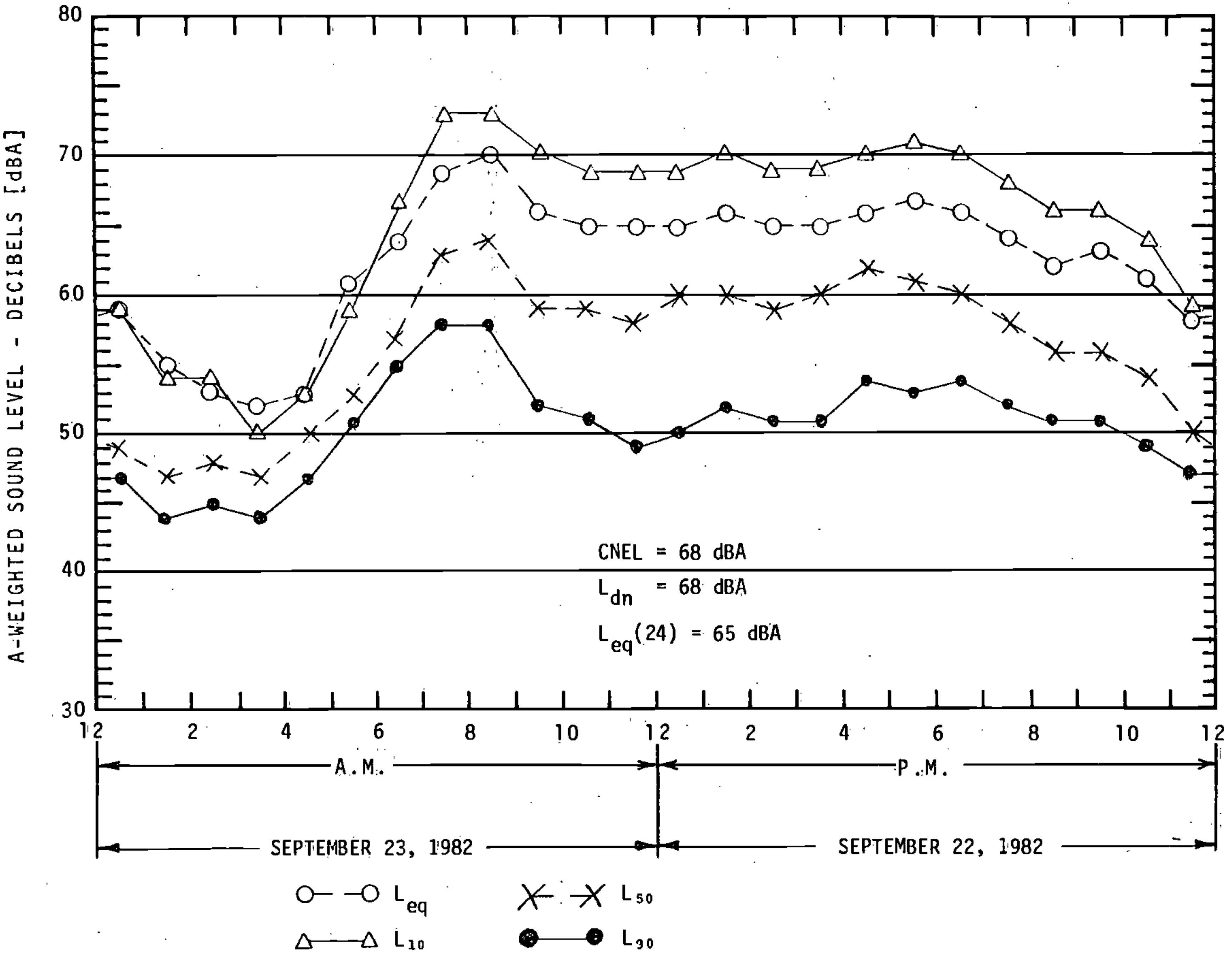

FIGURE 2.3-18 TIME HISTORY OF THE NOISE LEVEL MEASURED AT LOCATION 132, OVER THE 24-HOUR PERIOD BEGINNING 12 NOON, WEDNESDAY, SEPTEMBER 22, 1982

2.4 EXISTING VIBRATION LEVELS

The perception of vibration by people has been discussed extensively in the literature, however, most of the criteria are based on the results obtained from steady-state sinusoidal vibration excitation in laboratory environments. Relatively little information is available on the response of humans to low level random vibration or to transient vibration levels. Recently more information on this type of vibration has been obtained from the results of measurements and subjective evaluations of transit train vibration in Toronto, Washington, D.C., San Francisco and Atlanta.

A number of scales for evaluating the effect of vibration on man have been devised. Units such as Pal and Trem have been presented for establishing scales of response to vibration similar to the A-weighted sound level or the various loudness scales which have been used for the determination of subjective response to noise levels. None of the scales have been widely accepted in evaluating human response to vibration levels and, in general, the criteria for response are presented as charts with ranges of response as a function of vibration frequency. As for the subjective response to noise, the human sensitivity to vibration varies with frequency. Therefore, the frequency must be taken into consideration in assessing annoyance due to vibration. A number of studies have indicated that at frequencies above approximately 12 to 16 Hz, sensitivity to vibration is primarily determined by the velocity amplitude and is relatively independent of frequency. Since the frequency range over which human sensitivity is approximately proportional to velocity amplitude covers the range of principal vibration components from transit trains and since the noise level generated by the vibration of buildings' surfaces is approximately proportional to vibration velocity level, it is appropriate to present vibration criteria and data in terms of velocity level.

A curve of human response to vibration has evolved from the studies which have been done and has been documented in the International Standards Organization document 2631 and Draft ANSI Standard S3.29-198X. Additional information on human sensitivity to vibration is contained in the CHABA Publication, "Guidelines for Preparing Environmental Impact Statements on Noise" which has utilized much of the information contained in the ISO Standard. These standards and publications do indicate that below about 12 to 16 Hz the sensitivity to vibration velocity is somewhat lower. This is characterized in Figure 2.4-1 which indicates human response to building vibration. The curve shape is based on information in the CHABA publication and in this report will be know as CHABA weighting. These curves show the vibration perception level ranges in decibels, dB, re 1.0 micro in/sec, as a function of frequency in Hertz, Hz.

The existing exterior vibration sources include automobiles, trucks, buses, underground mechanical equipment, and on a local scale, pedestrians. Most of the vibration sources, except stationary mechanical equipment operating continuously, create transient vibration levels. The observed level of vibration at a particular location is the summation of the vibrations created by all the various sources, near and far. This is analogous to ambient community noise which represents the summation of many noise sources.

For this survey, the vibration level data were taken simultaneously with, and at the same locations as, the sound level data. Vibration acceleration was measured using a piezoelectric accelerometer, with a signal recorded on one channel of the data tape recorder.

The data were analyzed to obtain a single-number velocity level weighted in such a way to approximate the CHABA weighting shown in Figure 2.4-1. To obtain the weighted velocity level from the acceleration data, an electronic integrator and filter approximating the inverse of the CHABA weighting were used.

Although the CHABA weighting is not a standardized measurement, the resultant weighted velocity level is a good single-number indication of the human response to vibration. Figure 2.4-1 indicates that weighted vibration velocity levels below about 69 dB overall level are generally imperceptible or just perceptible as vibration to the average person under normal conditions.

The weighted vibration velocity levels obtained in this manner were statistically analyzed to obtain the same statistical parameters used to describe the existing noise levels; L_{99}, L_{90}, L_{50}, L_{10}, L_1, and L_{EQ}.

Table 2.4-1 presents a complete tabulation of the statistical analysis of the weighted vibration velocity levels observed at each measurement site. In general those locations with the highest noise levels also have the highest vibration levels and vice versa, since in most cases, trucks and buses which produce high noise levels also produce high vibration levels. However, this correlation is not always true since airplanes, motorcycles, and some cars can produce high noise levels but not necessarily high vibration levels.

Review of the vibration data indicates that as for the noise data there is a considerable range of levels at different locations over the length of the alignment. The lowest vibration levels were observed at Locations 32, 33, 34, 35, 37, 116, 117 and 118 which are located away from nearby vibration producing activities, especially during the evening and nighttime measurement periods. These locations are located on or near the Santa Monica Mountains which in addition to having few nearby vibration producing activities may also be on or near rock. Although rock transmits vibration more efficiently than soil, it takes a greater vibration energy level at the source to produce the same vibration amplitude at the receiver.

There are a number of locations where the L_1 vibration velocity level exceeds 69 dB. This means that for approximately 6 seconds in 10 minutes the vibration from passing vehicles was at least barely perceptible at the measurement location. Vibration at other locations with the L_1 vibration velocity level less than 69 dB should not be perceptible as mechanical motion. Excluding Locations 32, 33, 34, 35, 37, 116, 117 and 118, the weighted vibration velocity L_{eq} ranges from 34 to 641 dB which is typical of commercial and residential areas near heavily traveled streets and boulevards. Comparing these data with that obtained during previous environmental vibration studies performed by WIA indicates that the vibration levels are typical of other large cities (such as Baltimore and Chicago).

Appendix B presents statistical distribution plots showing the detailed statistical distribution in terms of the weighted vibration velocity level exceedance as a percentage of time for all of the measurement locations along the alignment. These plots are analogous to those plotted for noise level exceedance in Appendix A. As with the noise plots, these charts allow graphic comparison of the vibration velocity statistical distributions along different sections of the Metro Rail alignment.

To provide some indication of the frequency content of the measured ground-borne vibration, five representative examples of the vibration levels were statistically analyzed by 1/3 octave bands. For the statistical analysis the unweighted vibration velocity level as a function of time was analyzed in each of the

1/3 octave bands from 3.15 Hz through 1000 Hz. The results of these are shown on Figures 2.4-2 through 2.4-6. Although several analyses indicate somewhat similar overall vibration velocity levels, each of the charts show a somewhat different shape for the frequency spectrum.

TABLE 2.4-1 WEIGHTED OVERALL VIBRATION VELOCITY LEVELS[1] MEASURED AT LOCATIONS ALONG THE METRO RAIL ALIGNMENT - SEPTEMBER 21 THROUGH OCTOBER 1, 1981

Location Number	Time of Day	Date (September or October 1981)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_1	L_{eq}
1	Rush Hour	28	41	44	48	52	57	49
	Day	28	45	48	51	54	58	52
	Evening	28	37	39	42	48	52	44
	Night	28	34	37	40	46	52	43
2	Rush Hour	22	46	49	54	60	66	56
	Day	21	48	51	54	60	67	57
	Evening	22	47	48	52	58	66	55
3	Rush Hour	22	44	47	52	59	68	57
	Day	21	44	48	52	61	69	57
	Evening	22	38	41	46	55	68	54
4	Rush Hour	22 & 28	40	42	46	51	57	48
	Day	21 & 28	42	44	47	51	57	49
	Evening	22 & 28	34	36	39	44	53	43
5	Rush Hour	23 & 28	42	44	49	57	62	53
	Day	21	43	45	49	53	58	50
	Evening	21 & 28	36	38	41	46	55	44
	Night	22	39	41	44	47	52	45
6	Rush Hour	21	49	52	58	64	70	61
	Day	21	49	53	56	62	69	59
	Evening	21	44	48	53	58	68	58
7	Rush Hour	21 & 1	44	46	54	61	70	59
	Day	21 & 29	45	48	54	60	67	57
	Evening	21	40	42	46	56	66	53
	Night	21	38	39	42	49	58	48
8	Rush Hour	21 & 1	51	53	57	63	72	61
	Day	21 & 29	49	52	55	61	68	58
	Evening	21	44	46	50	54	64	53
	Night	21	46	48	50	56	67	55

[1] Corrected for Human Perception Curve (see text)

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September or October 1981)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_1	L_{eq}
9	Rush Hour	21	44	46	49	55	60	52
	Day	22	40	41	45	51	58	48
	Evening	21	40	41	45	51	55	47
	Night	21	39	42	46	51	61	50
10	Rush Hour	21 & 1	47	50	55	62	67	58
	Day	22 & 29	44	46	50	56	61	53
	Evening	21	42	45	50	56	59	52
	Night	21	42	44	48	54	61	51
11	Rush Hour	21 & 1	40	42	46	54	63	52
	Day	22 & 29	38	41	44	48	54	46
	Evening	21	40	41	45	52	60	50
	Night	22	37	39	42	46	51	44
12	Rush Hour	23	42	44	49	54	62	52
	Day	22	40	44	47	51	56	48
	Evening	23	42	46	50	56	62	52
13	Rush Hour	23	40	43	47	54	59	50
	Day	22	33	36	42	50	56	46
	Evening	23	31	33	40	46	56	44
	Night	23	37	40	43	48	58	47
14	Rush Hour	10/1	35	38	43	51	60	49
	Day	29	36	39	44	51	59	49
15	Rush Hour	23	38	42	46	52	61	50
	Day	23 & 29	34	38	44	51	62	49
	Evening	23	26	30	37	45	54	44
	Night	25	22	24	28	39	50	38
16	Rush Hour	24	43	45	49	56	64	53
	Day	23	43	46	50	56	62	53
	Evening	23	35	39	45	52	62	50
17	Rush Hour	24	39	43	49	58	68	55
	Day	23	38	42	47	54	68	55
	Evening	23	38	41	46	52	59	49
	Night	23	32	35	44	55	67	53
18	Rush Hour	23	38	40	44	49	55	46
	Day	23 & 30	32	36	41	46	50	43

TABLE 2.4-1 (CONTINUED)

			Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
Location Number	Time of Day	Date (September or October 1981)	L_{99}	L_{90}	L_{50}	L_{10}	L_{1}	L_{eq}
19	Rush Hour	22 & 30	37	41	44	49	56	47
	Day	22 & 30	36	40	43	50	56	46
	Evening	22	37	39	43	47	54	45
	Night	23	36	39	42	46	54	44
20	Rush Hour	23	40	42	46	49	54	47
	Day	23 & 29	40	43	47	51	55	48
	Evening	23	39	42	44	50	54	49
21	Rush Hour	22	42	46	52	57	62	54
	Day	30	34	40	52	59	65	55
	Evening	22	39	42	49	57	65	54
	Night	25	30	32	39	57	68	55
22	Rush Hour	22	44	46	48	51	55	49
	Day	22	41	43	45	49	54	47
	Evening	22	42	44	46	50	56	48
	Night	24	40	42	44	48	53	46
23	Rush Hour	24 & 30	33	38	42	46	54	45
	Day	23 & 30	36	39	42	46	52	43
	Evening	23	35	37	40	44	54	43
	Night	24	35	38	41	45	51	43
24	Rush Hour	24	44	47	53	59	64	56
	Day	24	39	43	50	58	68	55
	Evening	24	38	41	49	58	64	54
	Night	24	31	34	43	54	60	50
25	Rush Hour	24 & 30	35	40	46	51	55	48
	Day	24 & 30	36	40	45	51	56	48
	Evening	24	30	34	41	49	54	45
	Night	24	36	39	44	51	55	47
26	Rush Hour	24	42	45	49	53	56	50
	Day	24	42	45	50	54	59	51
	Evening	24	35	39	45	52	57	48
27	Rush Hour	24	41	44	49	55	62	52
	Day	24	42	45	50	56	62	53
	Evening	24	35	40	46	53	57	49
	Night	24	29	33	42	52	59	48

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September or October 1981)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_{1}	L_{eq}
28	Rush Hour	28	38	43	49	54	58	50
	Day	28	38	42	49	54	58	51
	Evening	28	32	38	46	54	61	50
	Night	28	26	29	36	49	55	44
29	Rush Hour	24	42	47	55	64	70	60
	Day	24 & 24	43	47	53	60	65	56
	Evening	24	40	43	50	61	67	57
30	Rush Hour	29	42	45	50	56	62	53
	Day	24	46	48	53	58	67	59
	Evening	24 & 24	40	42	46	55	62	52
31	Rush Hour	24	36	38	41	44	48	42
	Day	24	36	39	42	47	53	44
	Evening	24	35	37	41	46	53	43
	Night	24	34	37	41	46	53	44
32	Rush Hour	29	36	38	41	44	48	41
	Day	25	32	34	37	41	45	38
	Evening	29	25	27	32	38	45	35
	Night	29	22	24	29	34	46	34
33.	Rush Hour	29	36	37	40	43	46	41
	Day	25	32	35	38	45	56	44
	Evening	29	27	29	32	35	38	33
34	Rush Hour	29	34	37	40	44	47	41
	Day	25	25	28	32	38	45	35
	Evening	29	20	22	26	32	39	29
	Night	30	18	20	24	29	35	26
35	Rush Hour	29	22	24	29	36	49	36
	Day	25	24	26	32	42	44	39
	Evening	29	21	24	28	34	44	33
	Night	29	18	20	24	28	31	25
36	Rush Hour	29	30	32	35	47	55	43
	Day	29	36	38	41	46	54	44
	Evening	29	32	33	35	40	55	42
	Night	29	32	33	35	40	55	43

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September or October 1981)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_{1}	L_{eq}
37	Rush Hour	29	22	25	29	34	41	32
	Day	29	22	24	27	30	43	31
	Evening	29	20	21	23	26	45	35
	Night	29	20	22	24	27	32	27
38	Rush Hour	28	37	39	42	46	50	43
	Evening	28	33	36	39	44	52	42
	Night	29	30	32	35	40	54	41
39	Rush Hour	28	39	42	48	53	60	50
	Day	28	36	41	47	54	63	52
	Evening	28	29	32	40	48	61	48
40	Rush Hour	28	42	44	46	50	56	48
	Day	28 & 30	43	45	49	55	62	53
	Evening	28 & 29	39	41	44	49	57	47
	Night	30	36	37	41	46	51	43
41	Rush Hour	28	48	52	57	64	72	61
	Day	28	47	51	56	64	74	62
	Evening	28	40	44	51	59	67	56
	Night	29	38	40	46	58	71	56
42	Rush Hour	28	44	46	51	58	67	55
	Day	28	46	48	52	57	64	55
	Evening	28	42	46	50	57	64	54
	Night	29	39	41	46	52	58	49
43	Rush Hour	28	47	50	54	60	66	57
	Day	28	43	46	53	60	67	57
	Evening	28	45	48	54	63	69	59
	Night	29	41	43	48	58	66	55
44	Rush Hour	28	45	47	49	56	63	53
	Day	28	43	45	49	56	62	52
	Evening	28	50	51	52	56	64	54
	Night	29	46	48	50	53	55	51
45	Rush Hour	28	46	48	52	56	61	54
	Day	28	48	49	50	54	58	52
	Evening	28	36	39	43	49	57	47
	Night	28	35	38	42	48	56	45

TABLE 2.4-1 (CONTINUED)
WEIGHTED OVERALL VIBRATION VELOCITY LEVELS[1]
MEASURED AT LOCATIONS ALONG THE METRO RAIL
ALIGNMENT ALTERNATIVES - SEPTEMBER 20 THROUGH
SEPTEMBER 24, 1982

Location Number	Time of Day	Date (September 1982)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_1	L_{eq}
101	Rush Hour	20 & 21	42	46	51	57	66	55
	Day	20 & 21	43	46	51	57	64	54
	Evening	20 & 21	36	39	44	54	65	53
	Night	20 & 22	35	37	41	49	58	47
102	Rush Hour	20 & 21	44	49	55	63	70	59
	Day	21	41	46	52	59	67	56
	Evening	20 & 21	37	41	47	56	67	55
	Night	21 & 22	34	37	43	51	63	51
103	Rush Hour	20 & 21	43	48	55	65	76	64
	Day	20 & 21	43	48	56	64	74	63
	Evening	20 & 21	37	41	45	58	70	56
	Night	21 & 22	34	38	42	50	62	50
104	Rush Hour	20 & 21	37	43	51	58	66	55
	Day	20 & 21	39	45	52	60	67	56
	Evening	20 & 21	31	37	44	52	62	50
	Night	20 & 22	27	32	39	49	62	49
105	Rush Hour	20 & 21	39	44	50	57	66	54
	Day	20 & 21	37	41	47	53	62	51
	Evening	20 & 21	34	38	43	49	59	48
	Night	20 & 21	32	35	40	47	58	46
106	Rush Hour	20 & 23	36	40	46	52	58	49
	Day	21	37	42	48	55	60	52
	Evening	21 & 23	34	39	45	50	57	48
	Night	21 & 24	31	36	42	49	57	45
107	Rush Hour	20 & 21	33	37	42	48	54	45
	Day	21 & 22	33	36	41	47	54	45
	Evening	20 & 22	31	34	39	45	55	45
	Night	21	30	33	39	46	58	45

[1] Corrected for Human Perception Curve (see text)

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September 1982)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_{1}	L_{eq}
108	Rush Hour	20 & 22	31	36	41	48	53	45
	Day	21 & 22	29	34	40	47	54	44
	Evening	20 & 22	29	33	38	44	50	41
	Night	20	28	31	36	42	49	43
109	Rush Hour	21	27	31	38	44	53	49
	Day	21 & 22	27	31	37	45	51	42
	Evening	20 & 21	25	29	34	41	55	44
	Night	21 & 22	23	27	32	38	47	36
110	Rush Hour	22	34	38	44	52	62	51
	Day	22	34	38	44	51	58	48
	Evening	22 & 23	34	38	43	49	56	47
	Night	23	31	35	41	48	56	46
111	Rush Hour	21	42	47	53	60	67	57
	Day	21	47	50	55	61	68	58
112	Rush Hour	21 & 22	44	48	54	61	68	58
	Day	21 & 22	42	47	54	61	68	58
	Evening	21 & 22	39	44	51	58	65	55
	Night	21	35	40	48	56	64	53
113	Rush Hour	21 & 22	36	40	46	53	61	51
	Day	20 & 21	35	40	47	54	61	51
	Evening	20 & 23	31	35	40	47	56	45
	Night	20 & 21	31	35	40	47	56	45
114	Rush Hour	23	36	40	44	50	56	49
	Day	23 & 24	35	38	43	48	54	47
	Evening	23	30	35	41	47	52	44
	Night	23	28	33	39	47	53	43
115	Rush Hour	22	43	45	49	53	60	51
	Day	22 & 23	43	46	49	54	62	52
	Evening	23	33	38	43	50	56	47
	Night	21	32	36	42	49	58	47
116	Rush Hour	21 & 22	20	23	28	35	46	35
	Day	21 & 23	22	24	28	35	44	33
	Evening	21 & 22	17	21	24	29	35	27
	Night	20 & 22	14	17	22	26	33	27

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September 1982)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_1	L_{eq}
117	Rush Hour	22 & 23	21	24	27	31	37	29
	Day	21 & 22	19	22	26	31	36	30
	Evening	21 & 22	18	21	24	27	31	25
	Night	21 & 22	14	17	22	26	30	23
118	Rush Hour	21 & 22	15	21	27	38	52	36
	Day	21 & 22	19	23	29	36	47	36
	Evening	21 & 22	13	16	22	30	45	33
	Night	20 & 22	14	18	22	28	37	29
119	Rush Hour	21 & 22	36	41	49	56	63	53
	Day	21	38	43	50	58	65	55
	Evening	21 & 22	31	36	44	54	61	50
	Night	21 & 23	28	33	40	50	58	47
120	Rush Hour	23	33	36	40	47	57	45
	Day	23	32	34	39	46	55	43
	Evening	23	28	30	34	38	43	36
	Night	23	24	27	32	37	44	34
121	Rush Hour	22 & 23	30	34	38	44	52	42
	Day	21 & 22	35	38	42	47	54	44
	Evening	20 & 22	33	35	38	43	51	41
	Night	20, 21 & 22	28	32	35	39	46	37
122	Rush Hour	21 & 23	29	33	38	42	47	39
	Day	21 & 23	30	34	39	44	50	40
	Evening	20 & 21	27	31	35	40	45	37
	Night	20 & 21	26	30	34	40	46	37
123	Rush Hour	21 & 23	34	38	44	49	55	46
	Day	21 & 22	35	39	44	48	53	46
	Evening	20 & 23	32	36	41	45	52	46
	Night	21 & 22	30	33	38	43	49	40
124	Rush Hour	21 & 23	39	43	48	56	62	52
	Day	21 & 22	35	39	45	53	62	51
	Evening	20 & 23	32	37	42	52	60	48
	Night	21 & 23	27	30	36	46	56	44
125	Rush Hour	21 & 23	33	37	41	47	55	45
	Day	21 & 23	34	38	42	47	53	45
	Evening	20 & 22	30	33	37	43	53	42
	Night	21 & 23	27	29	33	38	43	35

TABLE 2.4-1 (CONTINUED)

Location Number	Time of Day	Date (September 1982)	Weighted Vibration Velocity Levels (dB re 1 micro in/sec)					
			L_{99}	L_{90}	L_{50}	L_{10}	L_1	L_{eq}
126	Rush Hour	22 & 23	43	45	48	52	59	50
	Day	21 & 23	43	46	48	52	58	50
	Evening	20 & 22	35	38	42	47	57	46
	Night	21 & 23	27	30	36	42	49	39
127	Rush Hour	20 & 23	39	43	49	54	61	52
	Day	21 & 23	40	44	49	55	60	52
	Evening	20 & 22	34	38	43	50	56	47
	Night	21 & 23	30	34	39	46	56	45
128	Rush Hour	20 & 23	38	41	46	52	58	49
	Day	21 & 22	36	38	43	48	54	46
	Evening	21 & 22	34	37	42	48	55	45
	Night	20 & 22	28	30	34	39	47	37
129	Rush Hour	20 & 23	36	40	47	55	63	52
	Day	21 & 22	34	39	45	53	61	50
	Evening	20 & 22	28	32	38	47	54	44
	Night	20 & 22	23	27	33	41	43	41
130	Rush Hour	20 & 22	40	45	50	54	59	52
	Day	21 & 22	39	43	49	54	59	51
	Evening	21 & 23	37	41	45	50	55	47
	Night	20 & 22	30	34	39	46	52	43
131	Rush Hour	21 & 22	40	44	49	54	58	51
	Day	22 & 23	39	42	47	52	57	49
	Evening	21	34	37	42	47	52	44
	Night	21 & 22	33	37	41	47	52	43
132	Rush Hour	21 & 22	36	42	50	60	66	56
	Day	22 & 23	36	41	47	56	63	53
	Evening	21 & 23	29	33	41	54	62	50
	Night	21 & 22	25	29	35	49	59	47
133	Rush Hour	21 & 22	36	40	45	51	57	48
	Day	22 & 23	33	36	41	48	57	46
	Evening	21 & 23	29	32	38	44	53	42
	Night	21 & 22	26	32	38	45	60	47

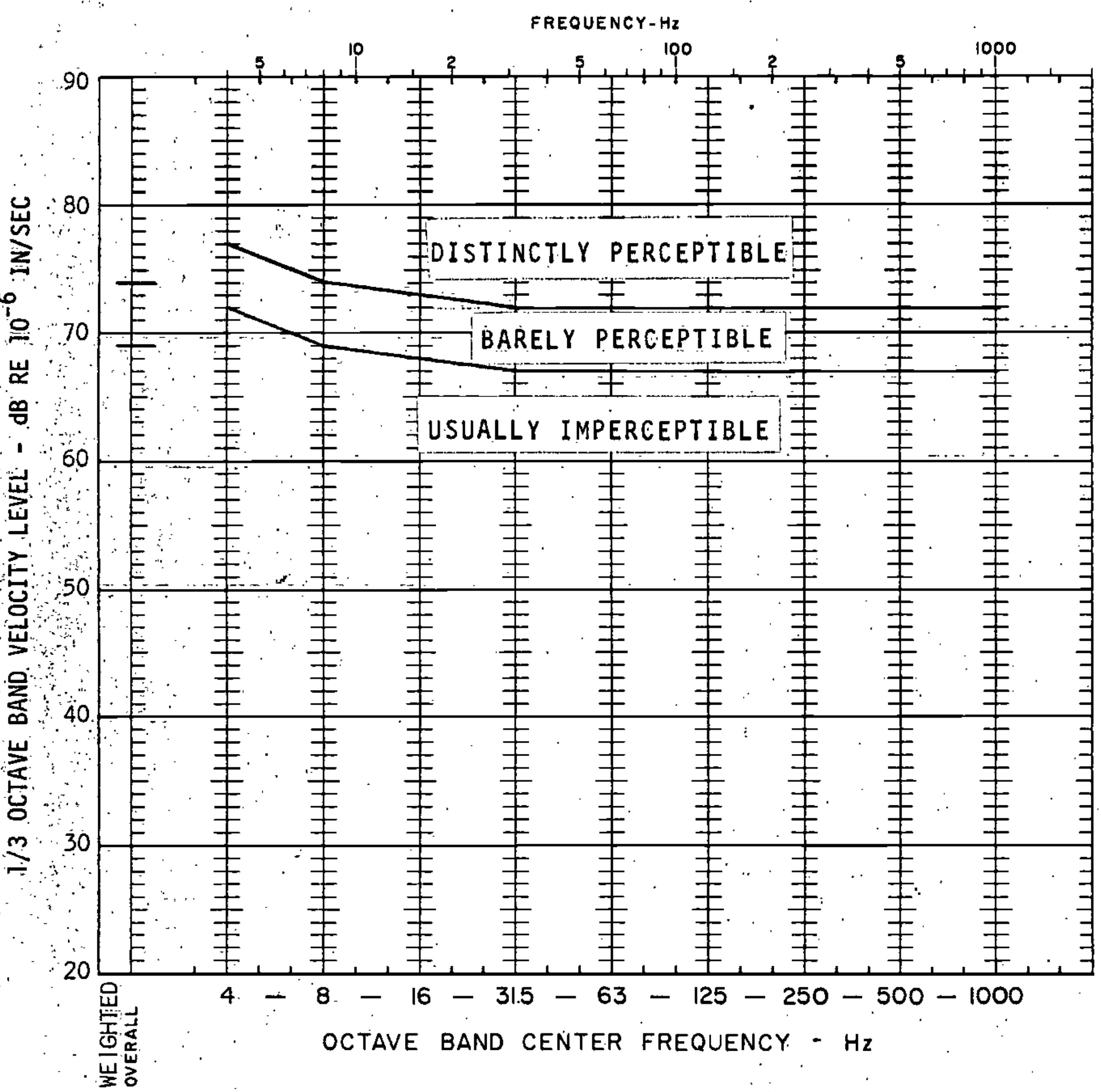

FIGURE 2.4-1 RESPONSE OF PERSONS SEATED OR STANDING TO BUILDING VIBRATION

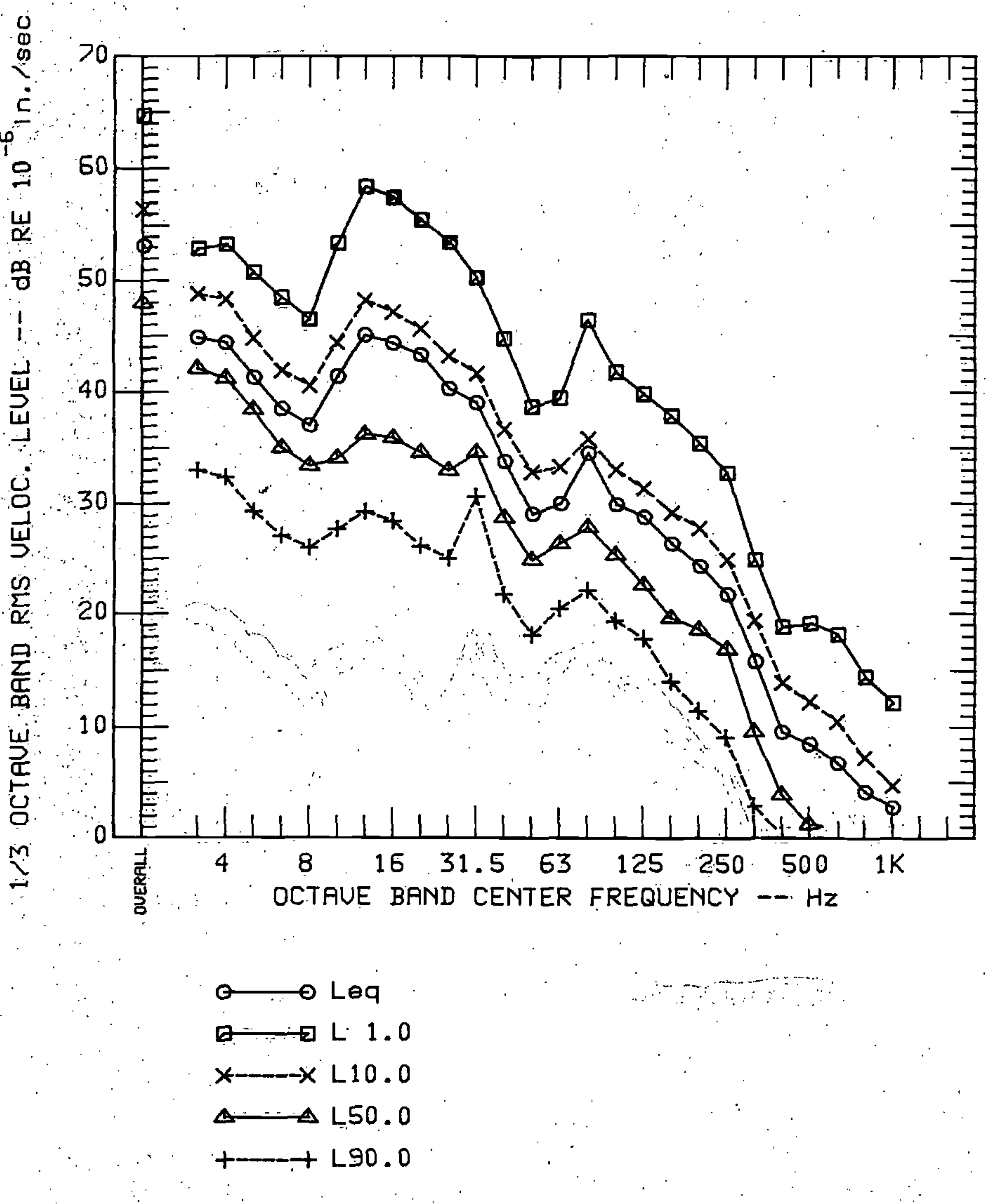

FIGURE 2.4-2 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING RUSH HOUR AT LOCATION 5 ON SEPTEMBER 23, 1981

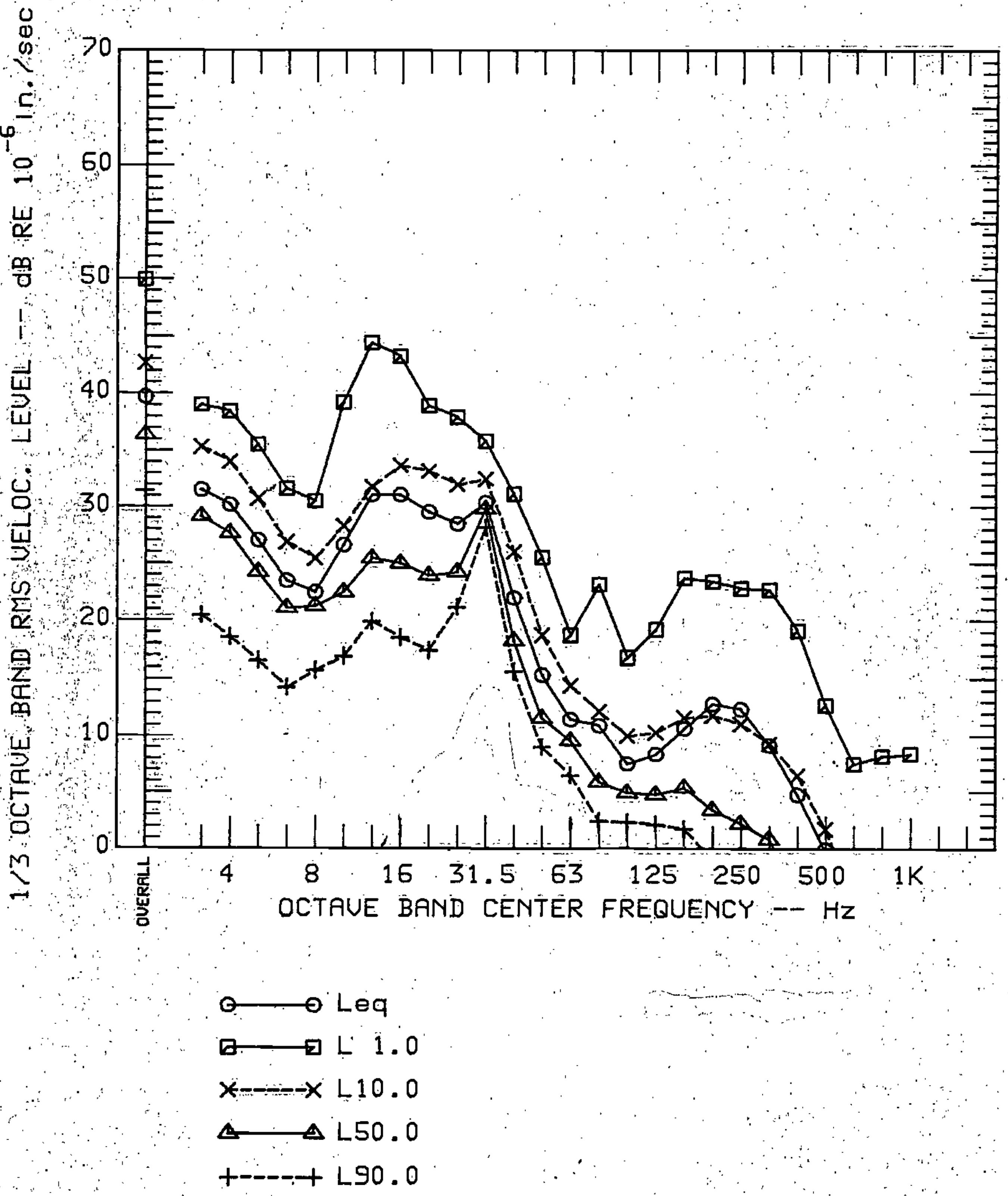

FIGURE 2.4-3 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE EVENING AT LOCATION 5 ON SEPTEMBER 21, 1981

45

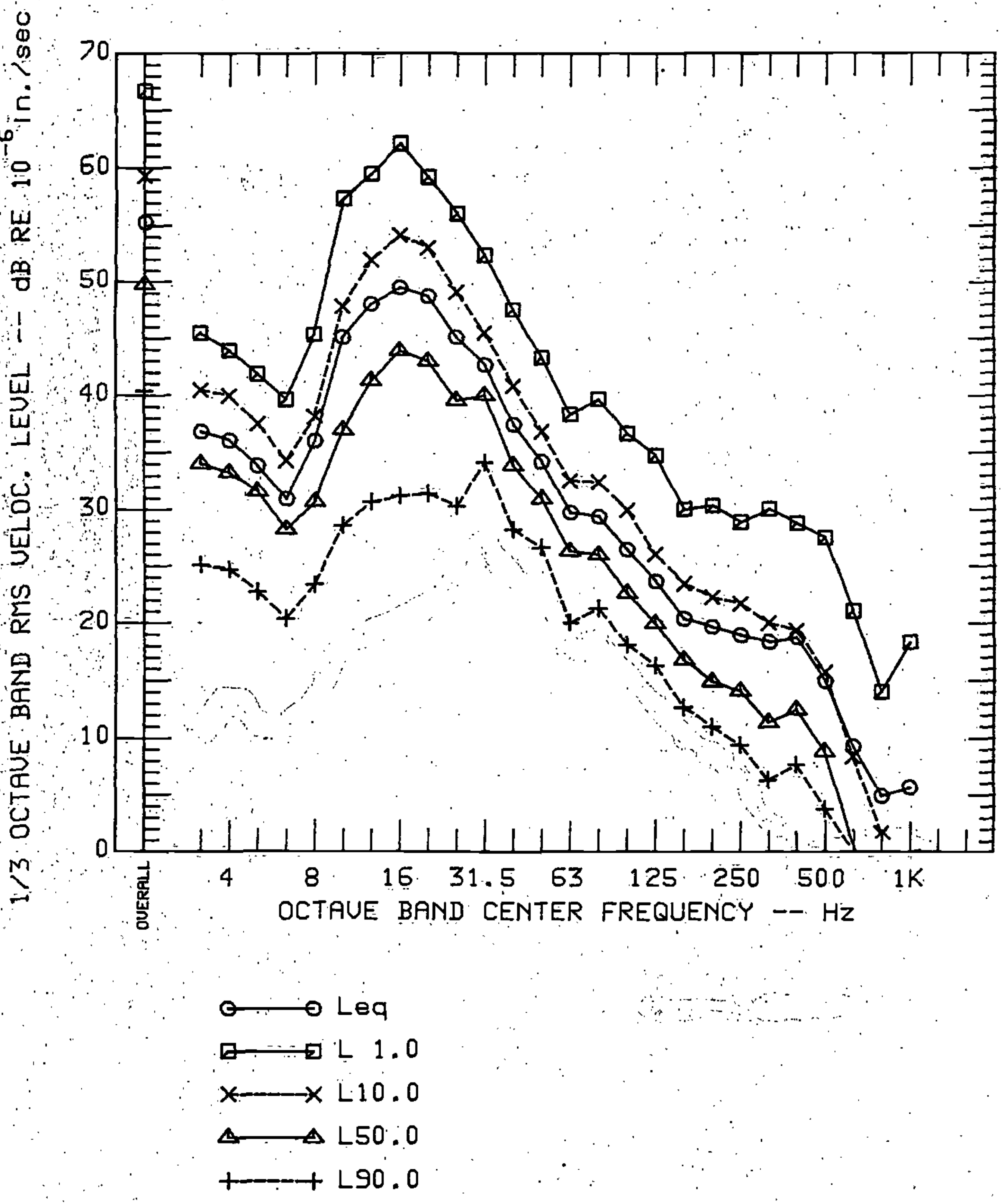

FIGURE 2.4-4 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING RUSH HOUR AT LOCATION 7 ON SEPTEMBER 21, 1981

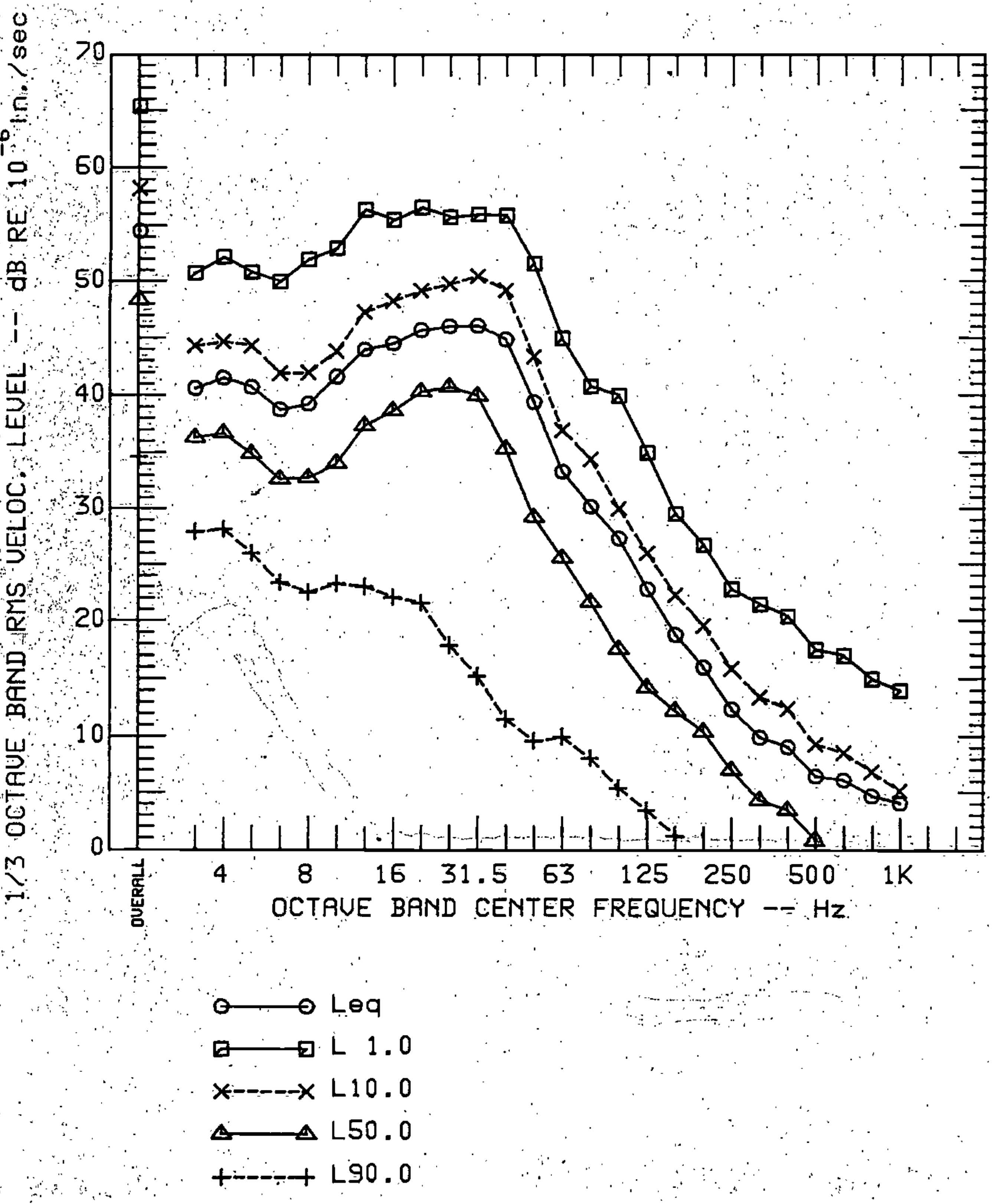

FIGURE 2.4-5 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY AT LOCATION 21 ON SEPTEMBER 30, 1981

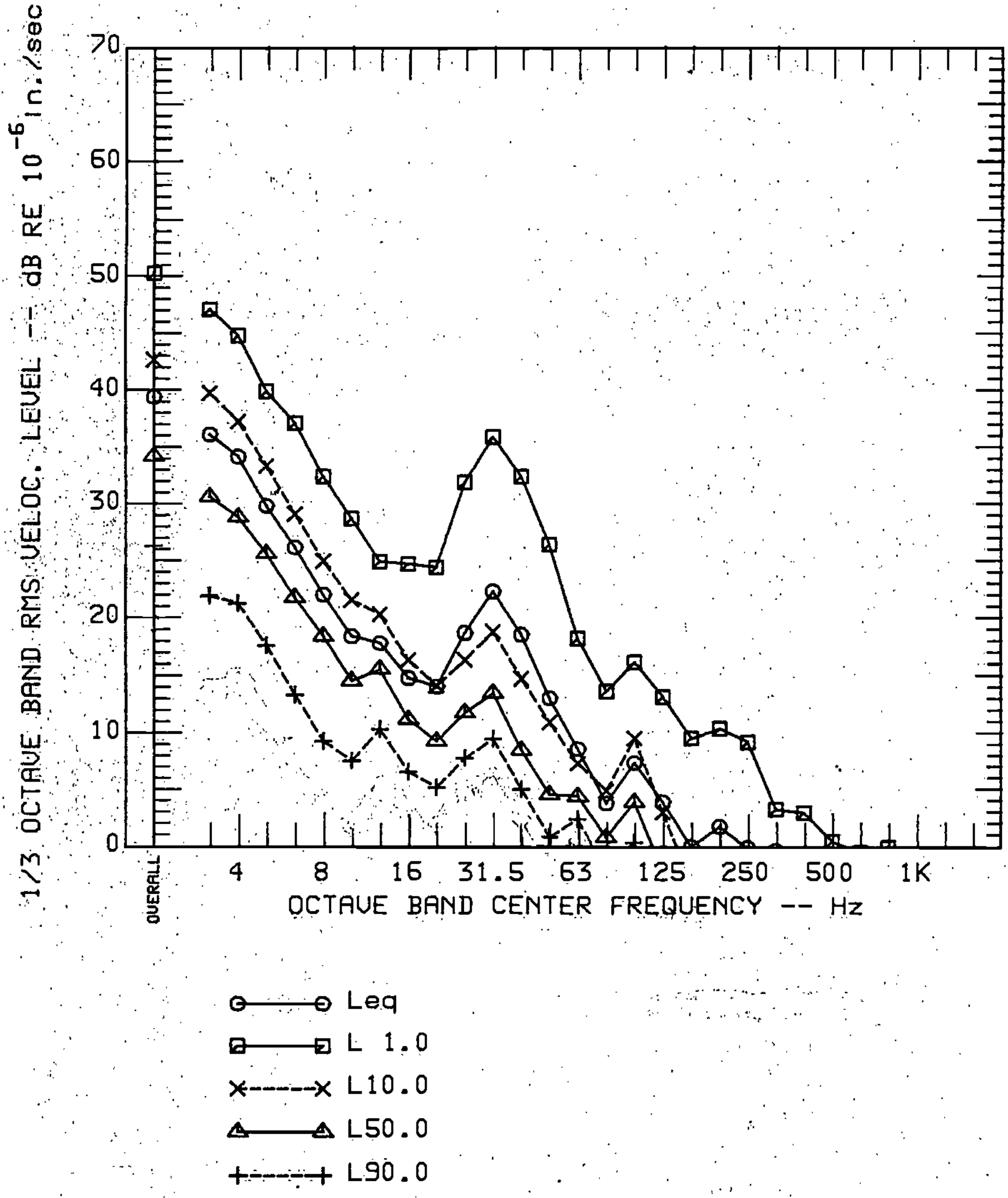

FIGURE 2.4-6 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY AT LOCATION 34 ON SEPTEMBER 29, 1981

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GLOSSARY AND SIGNIFICANCE OF ACOUSTICAL TERMS

1. Glossary of Terms

A-WEIGHTED SOUND LEVEL (dBA):
The sound pressure level in decibels as measured on a sound level meter using the internationally standardized A-weighting filter or as computed from sound spectral data to which A-weighting adjustments have been made. A-weighting de-emphasizes the low and very high frequency components of the sound in a manner similar to the response of the average human ear. A-weighted sound levels correlate well with subjective reactions of people to noise and are universally used for community noise evaluations.

ACCELEROMETER:
A vibration sensitive transducer that responds to the vibration acceleration of a surface to which it is attached. The electronic signal generated by an accelerometer is directly proportional to the surface acceleration.

ACCELERATION LEVEL:
Also referred to as "vibration acceleration level." Vibration acceleration is the rate of change of speed and direction of a vibration. An accelerometer generates an electronic signal that is proportional to the vibration acceleration of the surface to which it is attached. The acceleration level is 20 times the logarithm to the base 10 of the ratio of the RMS value of the acceleration to a reference acceleration. The generally accepted reference vibration acceleration is 10^{-6} g (10^{-5} m/sec).

AMBIENT NOISE:
The prevailing general noise existing at a location or in a space, which usually consists of a composite of sounds from many sources near and far.

BACKGROUND NOISE:
The general composite non-recognizable noise from all distant sources, not including nearby sources or the source of interest. Generally background noise consists of a large number of distant noise sources and can be characterized by L_{90} or L_{99}.

COMMUNITY NOISE EQUIVALENT LEVEL (CNEL):
The L_{eq} of the A-weighted noise level over a 24-hour period with a 5 dB penalty applied to noise levels between 7 p.m. and 10 p.m. and a 10 dB penalty applied to noise levels between 10 p.m. and 7 a.m.

DAY-NIGHT SOUND LEVEL (L_{dn}):
The L_{eq} of the A-weighted noise level over a 24-hour period with a 10 dB penalty applied to noise levels between 10 p.m. and 7 a.m.

DECIBEL (dB):
The decibel is a measure on a logarithmic scale of the magnitude of a particular quantity (such as sound pressure, sound power, sound intensity) with respect to a standardized reference quantity.

ENERGY EQUIVALENT LEVEL (L_{eq}):
The level of a steady noise which would have the same energy as the fluctuating noise level integrated over the time period of interest. L_{eq} is widely used as a single-number descriptor of environmental noise. L_{eq} is

based on the logarithmic or energy summation and it places more emphasis on high noise level periods than does L_{50} or a straight arithmetic average of noise level over time. This energy average is not the same as the average of sound pressure levels over the period of interest, but must be computed by a procedure involving summation or mathematical integration.

FREQUENCY (Hz):
The number of oscillations per second of a periodic noise (or vibration) expressed in Hertz (abbreviated Hz). Frequency in Hertz is the same as cycles per second.

L_1, L_{10}, L_{50}, L_{90} AND L_{99}:
The noise (or vibration) levels that are exceeded for 1%, 10%, 50%, 90% and 99% of a specified time period, respectively. Environmental noise and vibration data are often described in these terms. See section 2. for a more detailed discussion of the statistical distribution terms.

NOISE REDUCTION COEFFICIENT (NRC):
Noise reduction coefficient is a measure of the acoustical absorption performance of a material, calculated by averaging its sound absorption coefficients at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz.

OCTAVE BAND - 1/3 OCTAVE BAND:
One octave is an interval between two sound frequencies that have a ratio of two. For example, the frequency range of 200 Hz to 400 Hz is one octave, as is the frequency range of 2000 Hz to 4000 Hz. An octave band is a frequency range that is one octave wide. A standard series of octaves is used in acoustics, and they are specified by their center frequencies. In acoustics, to

increase resolution, the frequency content of a sound or vibration is often analyzed in terms of 1/3 octave bands, where each octave is divided into three 1/3 octave bands.

REVERBERANT FIELD:
The region in a room where the reflected sound dominates, as opposed to the region close to the noise source, where the direct sound dominates.

REVERBERATION:
The continuation of sound reflections within an enclosed space after the sound source has stopped.

REVERBERATION TIME (RT):
The time taken for the sound-pressure level in a room to decrease to one-millionth (60 dB) of its steady state value after the source of sound energy is suddenly interrupted. It is a measure of the persistence of a sound in a room and of the amount of acoustical absorption present inside the room.

SOUND ABSORPTION COEFFICIENT (α):
The absorption coefficient of a material is the ratio of the sound absorbed by the material to that absorbed by an equivalent area of open window. The absorption coefficient of a perfectly absorbing surface would be 1.0 while that for concrete or marble slate is approximately 0.01 (a perfect reflector would have an absorption of 0.00).

SOUND PRESSURE LEVEL (SPL):
The sound pressure level of a sound in decibels is 20 times the logarithm to the base of 10 of the ratio of the RMS value of the sound pressure to the RMS value of a

reference sound pressure. The standard reference sound pressure is 20 micro-pascals as indicated in ANSI S1.8-1969, "Preferred Reference Quantities for Acoustical Levels".

VELOCITY LEVEL:
Also referred to as the "vibration velocity level." Vibration velocity is the rate of change of displacement of a vibration. The velocity level is 20 times the logarithm to the base 10 of the ratio of the RMS value of the velocity to the reference velocity. In this report the reported vibration velocity levels are all referenced to 10^{-6} in/sec. Above approximately 10 Hz, human response to vibration is more closely correlated to the velocity level than the acceleration level.

WEIGHTED VELOCITY LEVEL:
The vibration velocity level to which a weighting factor has been added. The weighting de-emphasizes the low frequencies in a manner similar to human response to vibration. The weighting used in this report is based on that proposed in Reference 8, however, there is no internationally recognized velocity weighting filter.

2. Statistical Distribution Terms

L_{99} and L_{90} are descriptors of the typical minimum or "residual" background noise (or vibration) levels observed during a measurement period, normally made up of the summation of a large number of sound sources distant from the measurement position and not usually recognizable as individual noise sources. The most prevalent source of this residual noise is distant street traffic. L_{99} and

L_{90} are not strongly influenced by occasional local motor vehicle pass-bys. However they can be influenced by stationary sources such as air conditioning equipment.

L_{50} represents a long-term statistical median noise level over the measurement period and does reveal the long-term influence of local traffic.

L_{10} describes typical levels or average for the maximum noise levels occurring, for example, during nearby pass-bys of trucks, buses and automobiles, when there is relatively steady traffic. Thus, while L_{10} does not necessarily describe the typical maximum noise levels observed at a point, it is strongly influenced by the momentary maximum noise level occurring during vehicle pass-bys at most locations.

L_1, the noise level exceeded for 1% of the time is representative of the occasional, isolated maximum or peak level which occurs in an area. L_1 is usually strongly influenced by the maximum short-duration noise level events which occur during the measurement time period and are often determined by aircraft or large vehicle passbys.

Chapter 3

NOISE AND VIBRATION DESIGN CRITERIA FOR THE METRO RAIL PROJECT

This section is Section 7 of the Design Criteria for the Metro Rail Project, and is included in this report as Chapter 3.

3. NOISE AND VIBRATION

3.1 GENERAL INTRODUCTION

This document is intended to provide design criteria for all noise and vibration control problems relating to the construction and operation of the Southern California Rapid Transit District (SCRTD) Metro Rail System, excluding the transit vehicle noise and vibration specifications.

The basic goals of these design criteria are to:

- Provide transit system patrons with an acoustically comfortable environment by maintaining noise and vibration levels in vehicles along the way and in stations within acceptable limits.
- Minimize the adverse impact of system operation and construction on the community by controlling transmission of noise and vibration to adjacent properties.
- Provide noise and vibration control consistent with economic constraints and appropriate technology.

Community acceptance of a rail rapid transit system requires control of airborne noise and vibration from transit train operations, and from transit ancillary areas and facilities such as yard operations, vent and fan shafts of the ventilation system, electrical substations, emergency service buildings, and air conditioning chiller plants. The design should also provide for any required control of ground-borne noise and vibration from the transit vehicle operations.

Community acceptance of construction noise and vibration requires that the contractors use machinery and equipment with efficient noise and vibration suppression devices and that other noise and vibration abatement measures be employed for protection of both employees and the public.

Providing a satisfactory and comfortable acoustical environment for patrons in station areas requires use of sound absorption materials on underplatform areas, platform level walls and ceilings, and the ceilings and walls of concourse areas for control of noise and reverberation in the station. Similarly, enclosed areas of above-grade stations should have ceiling and, possibly, wall-mounted absorption materials. Overall control of station noise also requires inclusion of maximum noise limits in equipment specifications.

The criteria presented in this document is based upon scales that most closely correlate with subjective evaluation of noise. For most typical noise sources, it has been found that the A-weighted sound level gives good correlation with subjective evaluation of response to noise. Thus, the A-weighted sound level, which can be read directly from a sound level meter, is best for evaluating the response of people to the noise created by transit system operation and construction.

3.2 MEASUREMENT PROCEDURES AND ASSUMPTIONS

3.2.1 General

Unless otherwise indicated, all noise levels or measurements refer to the use of A-weighting and "slow" response of an instrument complying with the Type 2 requirements of the latest revision of American National Standard (ANSI) S1.4-1971, "Specification for Sound Level Meters" (Ref. 1).

All noise levels are expressed in decibels referenced to 20×10^{-6}Pa (0.0002 microbar) as measured with the A-weighting network of a standard sound level meter, abbreviated dBA.

3.2.2 Transit System Wayside Noise and Vibration Measurements

Transit wayside noise guidelines are based on measurements taken at appropriate distances and performed in essentially a free-field or open space environment away from reflective or shielding surfaces. Unless otherwise indicated, vibration guidelines are based on measurements of vibration in the vertical direction on the ground surface or on building floors.

3.2.3 Construction Noise and Vibration Measurements

A. Measure construction noise in accordance with Section 3.2.1. In addition, all impulsive or impact noise levels or measurements refer to use of an impulsive sound level meter complying with the criteria of IEC 179 (Ref. 2) for impulse sound level meters. As an alternative procedure, a Type 2 General Purpose sound level meter on C-weighting and "fast" response may be used to estimate peak values of impulsive or impact noises.

B. Noise levels at buildings affected acoustically by the Contractor's operations refer to measurements at points between 3 feet and 6 feet from building facades or building setback lines or a distance of 200 feet from the Construction Limits, whichever is closer.

C. Vibration levels at buildings affected by construction operations refer to vertical direction vibration on the ground surface or building floor, or 200 ft from the Construction Limits, whichever is closer.

D. Vibration levels at buildings affected by blasting operations refer to the 3-axis vector sum of vibration velocity on the ground surface or building floor, or 200 ft from the Construction Limits, whichever is closer.

3.3 COMMUNITY CATEGORIES AND RELATION TO CRITERIA FOR WAYSIDE NOISE AND VIBRATION

A wayside community noise impact criterion provides a basis from which to determine the type and extent of noise reduction measures necessary to avoid annoyance in the community. The wayside noise criteria must be related to the type of activity taking place in the building or community and the ambient noise levels in the absence of transit system noise. Obviously, a passby noise level of a given magnitude is more objectionable in a quiet residential area at night than in a busy commercial area during the day.

The typical existing ambient or background noise and vibration levels vary significantly from one type of community to the next. Therefore, it is necessary to make a judgment as to the nature of the community in which the transit system is to be located before determining the appropriate criterion for permissible noise or vibration levels from the transit system in that community.

Table 3.3.1 indicates the five generalized categories of wayside areas into which the communities along the transit corridors can be categorized for the purpose of assigning appropriate noise and vibration criteria. The table indicates the description of the areas and the normal expected range of ambient noise levels. These categories and noise levels are based in part, on the information developed from several studies of rail transit corridor environments along with data presented in the 1974 U.S. Environmental Protection Agency (EPA) document, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety", usually referred to as the "Levels Document" (Ref.3), and other field data obtained in many community areas in the U.S.A. and Canada.

TABLE 3.3.1 GENERAL CATEGORIES OF COMMUNITIES ALONG METRO RAIL SYSTEM CORRIDORS

Area Category	Area Description	Typical (Average or L_{50}*) Ambient Noise Level-dBA	Typical Day/Night Exposure Levels-L_{dn}
I	Low Density urban residential, open space park, suburban residential or quiet recreational area. No nearby highways or boulevards.	40-50 - day 35-45 - night	Below 50
II	Average urban residential, quiet apartments and hotels, open space, suburban residential, or occupied outdoor areas near busy streets.	45-55 - day 40-50 - night	50-60
III	High Density urban residential, average semi-residential/ commercial areas, parks, museum, and non-commercial public building areas.	50-60 - day 45-55 - night	55-65
IV	Commercial areas with office buildings, retail stores, etc., primarily daytime occupancy. Central Business Districts.	60-70	Over 60
V	Industrial areas or Freeway and Highway Corridors.	Over 60	Over 65

*L_{50} is the long-term statistical median noise level.

The categories defined in Table 3.3.1 are used in determining appropriate design criteria for the Metro Rail System noise and vibration. The land use or area categories presented above are similar to those used for other transit properties and presented in the APTA Publication, "Guidelines for Design of Rapid Transit Facilities" (Ref. 4). In most cases, experience with the new systems now in operation has indicated that these categories and the associated criteria provide for adequate results and most of the neighbors of the transit facility find the noise and vibration acceptable.

3.4 WAYSIDE NOISE AND VIBRATION DUE TO TRANSIT OPERATIONS

3.4.1 Airborne Noise from Above-Ground Train Operations

Table 3.4.1 presents design criteria for single-event maximum noise levels for airborne noise from transit trains for various types of buildings in each of the land use or area categories listed in Table 3.3.1. These criteria are generally applied to nighttime operations because the sensitivity to noise is greater at night than during daytime. The maximum levels are based on the maximum level that will not cause significant intrusion or alteration of the pre-existing noise environment and represent noise levels which are considered acceptable for the type of land use in each area. The criteria presented in Table 3.4.1 are generally applicable at the nearside of the nearest dwelling or occupied building under consideration or at 50 ft from the track centerline, whichever is closer.

TABLE 3.4.1 CRITERIA FOR MAXIMUM AIRBORNE NOISE FROM METRO TRAIN OPERATIONS

Community Area Category	Maximum Single Event Noise Level Single Family Dwellings	 Multi-Family Dwellings	 Commercial Buildings
I Low Density Residential	70 dBA	75 dBA	80 dBA
II Average Residential	75	75	80
III High Density Residential	75	80	85
IV Commercial	80	80	85
V Industrial/Highway	80	85	85

For some types of buildings or occupancies maximum noise level limits should be applied regardless of the community area category. The design should reflect careful consideration of noise control when the transit line is near auditoriums, TV studios, schools, theatres, amphitheatres, and churches. Table 3.4.2 lists design goals for maximum airborne noise from transit operations in these areas.

TABLE 3.4.2 CRITERIA FOR MAXIMUM AIRBORNE NOISE FROM METRO TRAIN OPERATIONS NEAR SPECIFIC TYPES OF BUILDINGS

Building or Occupancy Type	Maximum Single Event Noise Level
Amphitheatres	65 dBA
"Quiet" Outdoor Recreation Areas	70 dBA
Concert Halls, Radio and TV Studios	70 dBA
Churches, Theatres, Schools, Hospitals, Museums, Libraries	75 dBA

3.4.2 Ground-borne Noise from Train Operations

Table 3.4.3 presents the pertinent criteria for maximum ground-borne noise due to transit train operations for various types of residential communities. It is noted that ground-borne noise and ground-borne vibration are exactly the same phenomenon up to the point of perception at the dwelling. Ground-borne vibration describes waves in the ground which can be measured using vibration pickups mounted on sidewalks, foundations, basement walls, or stakes in the ground and which can be perceived as mechanical motion. Ground-borne noise describes sound generated when the same waves in the ground reach room surfaces in buildings, causing them to vibrate and radiate sound waves into the room and thus can only be perceived inside buildings.

Wayside impact due to transit train vibration is normally described in terms of ground-borne noise because in most situations the noise produced by the vibration of room surfaces is audible at ground-borne vibration levels below those which are perceptible to tactile senses. Thus, in most, but not every case, a criterion limiting audible noise levels will provide adequate protection against tactile ground-borne vibration levels.

In most cases for surface or aerial transit operations the airborne noise is significantly louder than the ground-borne noise and the ground-borne noise is not perceived separately from the airborne noise. Thus, assessment of the acoustic noise levels due to vibration instead of ground vibration levels facilitates comparison with expected interior airborne noise.

TABLE 3.4.3 CRITERIA FOR MAXIMUM GROUND-BORNE NOISE FROM METRO TRAIN OPERATIONS

Community Area Category	Maximum Single Event Noise Level		
	Single Family Dwellings	Multi-Family Dwellings	Hotel/ Motel Buildings
I Low Density Residential	30 dBA	35 dBA	40 dBA
II Average Residential	35	40	45
III High Density Residential	35	40	45
IV Commercial	40	45	50
V Industrial/Highway	40	45	50

As with airborne noise, there are some types of buildings for which specific design criteria should be applied, regardless of area category. Table 3.4.4 presents design criteria for generally acceptable levels of transient ground-borne noise levels in occupied spaces of various types of buildings and occupancies. This table is not intended to be all inclusive but may be a convenient general guide to the designer.

TABLE 3.4.4 CRITERIA FOR MAXIMUM GROUND-BORNE NOISE FROM METRO TRAIN OPERATIONS NEAR SPECIFIC TYPES OF BUILDINGS

Type of Building or Room	Maximum Single Event Noise Level
Concert Halls and TV Studios	25 dBA
Auditoriums and Music Rooms	30 dBA
Churches and Theatres	35 dBA
Hospital Sleeping Rooms	35-40 dBA
Courtrooms	35 dBA
Schools and Libraries	40 dBA
University Buildings	35-40 dBA
Offices	35-45 dBA
Commercial Buildings	45-55 dBA

Ground-borne noise which meets the design criteria listed above will not be inaudible in all cases, however, the level will be sufficiently low that no significant intrusion or annoyance should occur. In most cases, there will be noise from street traffic, other occupants of a building, or other sources, which will create intrusion that is equivalent or greater in level than the noise from transit trains passing by.

A range for the maximum ground-borne noise limit is given in some cases to permit the designer to adjust the design criterion to be suitable for the environment and location of the building. For example, at offices in a quiet, landscaped industrial park area the limit should be at the low end of the range, 35 dBA, whereas for offices located at a busy intersection or in a noisy central business district the limit can be at the upper end of the range, 45 dBA.

3.4.3 Ground-Borne Vibration from Train Operations

Table 3.4.5 presents the appropriate criteria for maximum ground-borne vibration for various types of residential buildings. The criteria apply to measurements of vertical vibration of floor surfaces within the buildings.

TABLE 3.4.5 CRITERIA FOR MAXIMUM GROUND-BORNE VIBRATION FROM METRO TRAIN OPERATIONS

	Maximum Single Event Ground-borne Vibration Velocity Level (dB re 10^{-6} in/sec)		
Community Area Category	Single Family Dwellings	Multi-Family Dwellings	Hotel/ Motel Buildings
I Low Density Residential	70	70	70
II Average Residential	70	70	70
III High Density Residential	70	70	75
IV Commercial	70	75	75
V Industrial/Highway	75	75	75

As with ground-borne noise, there are some types of buildings for which specific design criteria for ground-borne vibration should be applied, regardless of area category. Table 3.4.6 presents design goals or generally acceptable levels of transient ground-borne vibration levels in occupied spaces of various types of buildings and occupancies. This table is not intended to be all inclusive.

TABLE 3.4.6 CRITERIA FOR MAXIMUM GROUND-BORNE VIBRATION FROM TRAIN OPERATIONS

Type of Building or Room	Maximum Single Event Vibration Velocity Level (dB re 10^{-6} in/sec)
Concert Halls and TV Studios	65
Auditoriums and Music Rooms	70
Churches and Theatres	70-75
Hospital Sleeping Rooms	70-75
Courtrooms	75
Schools and Libraries	75
University Buildings	75-80
Offices	75-80
Commercial & Industrial Buildings	75-85
Vibration Sensitive Industrial or Research Laboratory	60-70

Ground-borne vibration which meets the design criteria listed above will not be imperceptible in all cases; however, the level will be sufficiently low so that no significant intrusion or annoyance should occur. In most cases, there will be vibration from street traffic, other occupants of a building, or other sources, which will create intrusion that is equivalent or greater in level than the vibration from the metro trains.

A range for the maximum ground-borne vibration limit is given in some cases to permit the designer to adjust the design criterion to be suitable for the environment and location of the building. For example, at offices in a quiet, landscaped industrial park area the limit should be at the low end of the range, 75 dB, whereas for offices located at a busy intersection or in a noisy central business district the limit can be near the upper end of the range, 80 dB.

3.5 NOISE AND REVERBERATION CONTROL IN STATIONS

3.5.1 Purpose

The purpose is to define criteria and acoustical treatment which will result in a desirable acoustical environment at and around stations throughout the Metro Rail system. The use of sound absorption material installed on the ceilings and walls of enclosed areas is necessary for control of noise and reverberation in the stations. Where appropriate and applicable, noise control can also be achieved through limitations on permissible noise from equipment. These design features are required because it is essential that acoustical control be included in the design of modern transit system facilities in order to provide a satisfactory and attractive environment for transit system patrons and to minimize impact on the neighboring community.

The inclusion of acoustical treatment in the design of transit system stations accomplishes four major purposes:

- Control and reduction of noise from transit vehicle operations.
- Provision for good intelligibility of announcements from the public address system.
- Control of noise in enclosed areas generated by patrons and or noise from exterior sources.
- Assistance in the control of noise from station air handling equipment, vertical circulation equipment and any other station mechanical equipment.

Acoustical treatment of the stations accomplishes these objectives by the absorption of sound energy as it impinges on the interior surfaces of the station thus preventing multiple reflections and the build-up of reflected or reverberant sound energy. The amount of control of reverberation and the consequent reduction of noise obtained is dependent upon the area of the acoustical treatment, the absorption coefficient, and the placement of the treatment. The four basic goals which are to be accomplished with the treatment have been used to derive a set of criteria for determining the appropriate areas, absorption coefficients, and placements of the acoustical material to obtain the most economical and appropriate design for the station acoustical treatment.

The criteria were developed to be consistent with the design goal maximum noise levels presented in Table 3.5.1 The noise levels inside stations are dependent on the design of the transit cars and station mechanical equipment and on the acoustical treatment in stations.

The criteria and designs for the acoustical treatment take into account the general architectural characteristics expected of the Metro Rail stations and the expected noise to be radiated by the transit cars and other noise sources.

TABLE 3.5.1 MAXIMUM NOISE LEVELS IN UNDERGROUND STATIONS

On platform, trains entering and leaving	80 dBA
On platform, trains passing through	85 dBA
On platform, trains stationary	68 dBA
On platform or in mezzanine areas with only station ventilation system & auxiliaries operating	55 dBA
On platforms or other public areas with tunnel ventilation system and/or underplatform exhaust operating at any normal level	55 dBA
On platforms or other public areas with tunnel ventilation system operating in emergency status	70 dBA
In station attendants' booths or offices	50 dBA

Table 3.5.2 summarizes the criteria for reverberation time and acoustic treatment of the various areas of underground stations. Compliance with the criteria for acoustic treatment assures that the reverberation time criteria and the associated noise control will be achieved.

TABLE 3.5.2 SUMMARY OF STATION ACOUSTIC DESIGN CRITERIA

	Areas Exposed to Street Traffic	Enclosed Concourse Areas	Train Rooms
Maximum Reverberation Time (500 Hz).	1.2 to 1.4 sec.	1.2 sec.	1.5 sec.
Maximum Mechanical Equipment Noise	---	55 dBA	55 dBA[1]
Treatment:			
Minimum wall/ceiling area	20-25%	35%[2]	35%[3]
Minimum ceiling only. . .	70-100%	---	---
Treatment Properties:			
Minimum 500 Hz absorption coefficient	0.6	0.6	0.6[3]
Minimum NRC	0.6	0.6	0.5[3]

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[1] 50 dBA maximum in station attendants' booths.

[2] Including at least 50% of ceiling area.

[3] Underplatform treatment also required--minimum absorption coefficient at 250 Hz - 0.4, at 500 Hz - 0.65 (3" to 4" thick material).

3.5.2 Station Acoustical Design

A. Scope: This section presents guidelines to be used in designing appropriate acoustic treatment for the various enclosed areas of the Metro Rail system stations. The design of absorption treatment for enclosed areas consists of four basic steps:

- Determine required reverberation times and quantities of absorption.
- Determine locations that will provide maximum control of noise.
- Select appropriate absorption coefficients for the treatment materials.
- Select acoustical materials and design material installations.

B. Reverberation Time and Absorption Quantity

1. General: As summarized in Table 3.5.2 the acoustical criteria for stations includes maximum reverberation time at 500 Hz, minimum areas for treatment, and minimum absorption properties. Following these criteria will result in sufficient absorption to control reverberant noise levels and to provide good speech intelligibility for the PA systems.

2. Trainrooms: Analysis of underground train rooms indicates that optimum treatment is obtained with a reverberation time of about 1.3 seconds. This reverberation time will provide for good speech intelligibility while acting to efficiently control noise.

The design goal for reverberation time in the trainrooms should be 1.2 to 1.5 seconds, a sufficient range to allow flexibility in the architectural design of the stations.

The acoustical treatment should be continuous and uniform for the entire length of the enclosed space. When the trainrooms have a relatively constant cross-section, it is most appropriate to define the quantity of treatment in terms of treatment per lineal foot of station platform. From this, it is a simple matter to determine the width of treatment that is required as a function of the absorption coefficient of the material. Table 3.5.3 indicates the treatment widths that are required to attain the recommended reverberation time on a typical station platform of 28 ft width.

The values given in Table 3.5.3 are based on consideration of the volumes, the surface areas, and the natural absorption of the finish surfaces of the stations. Because transit stations have relatively uniform cross-sections, the figures for treatment per lineal foot in Table 3.5.3 are sufficient to describe the criterion to be used in designing the acoustical treatment for the full length of the platforms.

TABLE 3.5.3 ACOUSTICAL TREATMENT CRITERIA FOR SUBWAY STATIONS

		Acoustical Treatment per foot of Station Structure	
Station Type	Location	Typical Available Area (sq ft)	Design Criterion Area (sq ft)
Cut and Cover	Total	149	33
	Underplatform	8	8
	Ceiling and Walls	72	25

3. Mezzanines and Passageways: For enclosed concourse areas such as mezzanine, fare collection areas, and corridors, for appropriate noise control the reverberation time should not exceed 1.2 seconds. The appropriate reverberation time for these areas is lower than for the trainrooms because the enclosed volume of these spaces is significantly less than for the trainrooms.

4. Station Areas At- or Above-Grade: In station areas directly connected to the street level and exposed to street traffic, noise control is less critical because of the presence of street noise and the short periods of time patrons normally spend in these areas. As a result, less noise reduction is needed and the design goal for the reverberation time in areas exposed to street noise can be increased to the range of 1.2 to 1.4 seconds at 500 Hz.

5. Ancillary Areas: Ancillary areas include service rooms, toilets, mechanical and electrical equipment rooms and train control and communications equipment rooms. Such spaces used for fans and other potentially noisy equipment shall be separated from public areas as much as possible. Access to such noisy spaces should be through double doors or sound-treated doors. All such spaces either used by the public or adjacent to public spaces should have acoustical treatment applied which is appropriate to the noise levels and occupancy of the space.

6. Location of Absorption Material

a. General: The location of the sound control material is an important consideration in the architectural design of the stations.

The preferred locations for acoustical treatment in the stations are listed in Table 3.5.4 in the order of priority. As indicated above, continuous treatment of the underplatform surfaces is essential for effective control of train noise. It is also very effective to treat the side walls opposite the platform, however, as long as the underplatform areas have continuous treatment, the side wall treatment is not required to obtain good results.

The basic design criteria call for coverage of 35% of the wall and total projected ceiling area with acoustical treatment in addition to the underplatform treatment. For the station type proposed for the Metro Rail System it is possible to suitably control reverberation characteristics and noise without placing acoustical treatment on the side walls.

TABLE 3.5.4 PREFERRED LOCATIONS FOR SOUND CONTROL TREATMENT

Platform Areas - Enclosed Station Trainrooms

1. Underplatform overhang surfaces
2. Trainroom ceilings
3. Side walls

Mezzanine and Corridor Areas

1. Ceilings - between structural members or directly on the ceiling surface for flat ceilings.
2. Walls - using appropriate panel assemblies or direct wall mounted materials

b. Concourse, Mezzanines and Passageways: All enclosed public areas of the station shall receive acoustical treatment equal to a minimum of 35% of the projected wall and ceiling area. Acoustical material in public areas shall be placed out of reach of patrons, a minimum of 9 feet from floor surfaces.

c. Entrances: Entrance enclosures shall have acoustical treatment on a minimum of 25% of the wall and ceiling area.

d. Openings: Large openings in enclosed spaces may be considered as acoustical treatment for the purpose of calculation.

7. Acoustical Materials and Installations

a. General: This section covers the criteria for selection and application of acoustical materials appropriate for station facilities. Acoustical treatment for transit system stations consists basically of three elements:

- The sound absorption media or material
- A protective covering
- An architectural or trim facing.

b. Flammability: All acoustical materials shall be non-combustible.

c. Materials: Absorption panels for wall and ceiling treatment shall be:

- Cellular glass blocks behind perforated sheet metal facings or slit-and-slat system facing. The material should be of 2" or 4" thickness in platform areas, 2" thickness in mezzanine areas and 1" to 1-1/2" thickness at other locations. This material is to be used because of the non-flammability and lack of need for protective covering film or cloth or for mechanical protection in most applications.

- Glass fiber blankets that are wrapped in close weave glass cloth or other non-flammable sheeting not to exceed 4 mils thickness. This material should be of 2 to 6 lb/cu ft density and of 2" to 4" thickness in platform areas, 2" thickness in mezzanine areas and 1" thickness at other locations. Mechanical protection facings of hardware cloth or expanded metal or architectural facings or perforated metal or slit-and-slat panels shall be used with this material. For design purposes, the expected sound absorption coefficients for glass fiber treatments are given in Table 3.5.5.

TABLE 3.5.5 TYPICAL SOUND ABSORPTION COEFFICIENTS TO BE EXPECTED FROM GLASS FIBER SOUND CONTROL MATERIALS MOUNTED DIRECTLY AGAINST A CONCRETE SURFACE

	Sound Absorption Coefficients				
Frequencies in Hz	125	250	500	1000	2000
1" thick Glass Fiber	.08	.30	.65	.80	.85
2" thick Glass Fiber	.20	.55	.80	.95	.90
3" thick Glass Fiber	.45	.80	.90	.95	.90

d. Under Platform Treatment: The horizontal and vertical surfaces other than exhaust fan inlets under the platform edge shall be completely covered with 4" cellular glass blocks, or 3" to 4" thick glass fiber panels.

e. Trainroom Treatment: Ceilings shall be covered with 2" or 4" thick cellular glass blocks, or 2" to 3" thick glass fiber boards to achieve a 60% to 70% coverage.

f. Mezzanine and Passageways: 70% to 100% of the ceiling area shall be covered with acoustical treatment. For exposed, concrete ceilings greater than 11 feet in height, 2" cellular glass blocks shall be used. Behind suspended metal ceilings, 2" glass fiber blankets or 2" cellular glass blocks shall be used.

g. Concourse Areas: Similar to previous section. Glass fiber treatment shall be 1" to 2" thick.

h. Installation: For the underplatform treatment, if glass fiber wrapped in glass cloth is used, the panels shall be retained in place using either an expanded metal facing, hardware cloth facing or perforated metal facing. For center platform stations the use of expanded metal or hardware cloth is the most economical and is satisfactory since the material is not visible to patrons. For a side platform station where the material is visible to patrons on the opposite platform, a perforated metal facing shall be used.

Wherever perforated metal or slit-and-slat facings are used, the open area shall be at least 30% of the total area. With the use of either expanded metal or perforated metal facing the attachment to the underplatform surfaces can be through the use of simple metal brackets. Air space should be provided around the edges to allow free circulation of air to prevent loading of the acoustical material panels due to air pressure transients created by the train movements. Panels with perforated metal or slit-and-slat facings -- either for underplatform or ceiling and wall installations -- shall have a dimpled screen placed between the metal facing and the face of the acoustic blanket to establish an air space of about 1/2" thickness between the perforated facing and the blanket or glass cloth bag.

If a continuous panel system or a suspended acoustical tile ceiling type of system is used, it is essential that gaps or openings be provided to permit free air flow between the acoustical treatment panels and the concrete surface behind in order to prevent loading of the acoustical panel by the air pressure transients created by train piston action or the air due to train movements. All acoustic systems shall have positive anchorage designed to resist the shock of transient air pressure produced by the movement of the train through the station at maximum design speed.

i. Ancillary Room Treatment: For any ancillary spaces either of two basic types of materials shall be used. For spaces with equipment which radiates relatively low noise levels or in which the noise is intermittent, such as in switchgear rooms or shops, the acoustical treatment shall be a 1" thick glass fiber application. An alternate could be the use of 3/4"- or 1"-thick acoustical tile, acoustical ceiling board or painted duct liner board for the absorption material. In spaces with noisy equipment such as fans and pumps, the acoustical treatment materials shall be 2" minimum thickness. In such spaces the material need not have an architectural trim facing. Application of 2"-thick (two layers of 1" thickness) duct liner blanket to the walls and ceiling, perhaps with hardware cloth facing for mechanical protection, provides appropriate sound absorption characteristics. In the ancillary spaces with the higher noise level equipment the treatment area shall be 30% of the wall and 50% of the ceiling area and the sound absorption material must be distributed reasonably uniformly over the ceiling in panels or patches and the wall material must be distributed over at least two adjacent walls. That is, the material should not be concentrated on one part of the ceiling or concentrated on two opposite walls but rather must be distributed between the ceiling and walls and with the wall treatment located to give approximately equal division of area on walls located at right angles to each other.

3.5.3 Transit Station Areas Related to Street Traffic Noise

A. Scope:

- Entrance areas
- Stairs from street level
- Elevators from street level
- Escalators from street level
- Vent shafts from street level

B. General Considerations:

- Where feasible and practical, these areas should be shielded from street and railroad vehicle noise.

- Open areas, particularly platforms, should have sound barrier walls blocking the line-of-sight between significant noise sources and the patron areas.

- The reverberation time of enclosed areas should be in the range of 1.2 to 1.4 seconds at 500 Hz when area is unoccupied.

C. Acoustical Treatment

Width of treatment equivalent to 20% to 25% of the cross-section perimeter or 70% to 100% of the ceiling is required. The treatment can consist of an absorptive wall panel system, an acoustical panel, or other acoustical absorption assembly applied to the ceiling or a combination of these. The acoustical treatment should have a Noise Reduction Coefficient, NRC, of at least 0.60 and a minimum sound absorption coefficient of 0.60 at 500 Hz.

3.5.4 Enclosed Concourse Areas

A. Scope:

- Fare collection areas
- Stairs
- Escalators
- Corridors

B. General Considerations:

- The maximum noise level from mechanical and electrical equipment shall not exceed 55 dBA in the absence of occupants.

- The reverberation time of the areas shall not exceed 1.2 seconds at 500 Hz when area is unoccupied.

C. Acoustical Treatment

The acoustical treatment shall cover not less than 35% of the combined surface area of ceiling and walls, or the equivalent, including coverage of at least 50% of the ceiling area where possible. The acoustical treatment shall have an NRC of at least 0.60 and a minimum sound absorption coefficient of 0.60 at 500 Hz.

3.5.5 Trainrooms

A. General Considerations:

- Maximum noise level on platform due to station ventilation system and other operating auxiliaries shall not exceed 55 dBA.

- Maximum noise level on platform due to normal operation of tunnel ventilation system or underplatform exhaust fans shall not exceed 55 dBA.

- Maximum noise level on platform due to emergency operation of ventilation systems shall not exceed 70 dBA.

- The reverberation time of the platform area shall not exceed 1.5 seconds at 500 Hz when the area is unoccupied.

B. Acoustical Treatment

Acoustical treatment with a minimum NRC of 0.60 and minimum 500 Hz sound absorption coefficient of 0.60 shall cover not less than 35% of the combined surface area of ceiling and walls, or the equivalent. The underside of the platform overhang and the wall of the underplatform overhang space shall be covered with acoustical material having a minimum absorption coefficient of 0.40 at 250 Hz and 0.65 at 500 Hz (3 to 4 inch thick material).

3.5.6 Ancillary Areas

A. Scope:

- Toilets and service rooms
- Electrical equipment rooms
- Train control and communications equipment rooms
- Mechanical equipment rooms
- Traction power equipment rooms

B. General Considerations:

Spaces for noisy ancillary equipment shall be located away from public spaces if possible. Noisy ancillary spaces opening directly to public spaces shall have sound rated or double entrance doors. Acoustical treatment for each space or type of space depends on location, type of noise and occupancy.

C. Acoustical Treatment

Toilet, locker and service rooms shall have acoustical treatment applied to 60% to 100% of the ceilings for control of reverberation and noise. The acoustical absorption material shall have an NRC of at least 0.55. Electrical equipment rooms, train control equipment rooms and traction power equipment rooms with noise generating equipment shall have acoustical treatment covering at least 40% to 50% of the ceiling area. The acoustical material shall be an equipment room type of ceiling/wall treatment, such as 1 inch thick glass fiber boards, and shall have an NRC of at least 0.65. Mechanical equipment rooms housing fans, pumps and other equipment which generate high sound levels shall have sound absorption treatment equivalent to 2 inch thick glass fiber board or blanket (minimum NRC of 0.75) applied to cover 30% of the total wall area and 50% of the ceiling area in the rooms. In other spaces with equipment which generates only low or moderate noise the acoustical treatment shall be as indicated above for electrical equipment rooms.

3.5.7 Vertical Circulation Equipment

A. Scope:

- Escalators
- Elevators

B. General Considerations

For equipment located in public areas and for all normal operating conditions, the noise level at 3 ft from the equipment shall not exceed 55 dBA for steady-state noise, and transient noise shall not exceed 60 dBA measured using the fast meter response.

C. Escalator Noise

Noise produced by escalators operating individually in either direction under no load and under maximum load in the station environment shall not exceed 55 dBA 5 ft above the tread at the entrance combs at both ends of the escalator.

D. Elevator Noise

Steady-state noise produced by elevators or associated equipment shall not exceed 55 dBA (Slow) in public spaces 3 ft or more from the elevator or associated equipment or within the elevator cab at any location 5 ft above the floor and 1 foot or more from any wall. Transient noise produced by elevators or associated equipment, not including entrance door operations, shall not exceed 60 dBA (Fast) in public spaces 3 ft or more from the elevator or associated equipment or within the elevator cab at any location 5 ft above the floor and 1 foot or more from any wall. Transient noise produced by operation of the elevator door shall not exceed 65 dBA (Fast) 3 ft or more from the elevator door inside or outside of the elevator cab.

3.5.8 Ventilating Equipment

A. Scope:

- Fan and Equipment Rooms
- Fan Equipment
- Vibration isolation
- Seismic considerations

B. Fan and Equipment Rooms

Spaces for fans and other potentially noisy equipment shall be separated from public areas insofar as possible. If direct access into such rooms from public areas cannot be avoided, provide doors having a suitable sound rating. Control sound transmission through other openings by appropriate means such as acoustically lined ducts or shafts.

C. Fan Equipment

The noise levels from fan shafts and other stationary equipment are dependent on the sound level radiated by the machinery. For station ventilation fans and subway emergency ventilation fans the sound power level should not exceed the values given in Table 3.5.6.

TABLE 3.5.6 VENTILATION FAN SOUND POWER LEVEL LIMITS

Octave Band Center Frequency (Hz)	Sound Power Level (dB) Subway Emergency Ventilation Fans	Sound Power Level (dB) Underplatform Heat Removal Fans
63	87	104
125	96	107
250	98	109
500	99	110
1000	99	107
2000	94	104
4000	91	100
8000	90	96

Fans shall have certified sound power levels not to exceed the above decibel ratings (re 10^{-12} watts) when operating under specified load conditions and measured at the fan in accordance with the AMCA test code (Ref. 5). Emergency ventilation fans shall be operated in both directions with inlet bell and outlet cone for sound power verification tests.

D. Vibration Isolation:

Because of the nature of subway station and other transit facility structures, it is generally not necessary to provide spring type vibration isolators for fans and other equipment, in the same manner as is provided in office or other general purpose buildings. Subway station structures are of heavy concrete construction and the fans and equipment are generally separated from public areas. Therefore, spring type vibration isolators are not required and simple rubber support pads between the concrete mounting surface and the machine or device are sufficient.

In subway structures, substation structures and in any separate mechanical eqiupment or plant structures, except as noted below, vibration isolation consisting only of standard ribbed rubber pads or 1/2" thick neoprene pads should be provided between the mounting feet or bracket and the support surface for the following items:

- fans
- pumps
- emergency generators
- elevator motors, motor generators, d.c. power convertors and hydraulic power units
- electrical equipment containing reactors or choppers

Flexible connectors should be provided in pipes and ducts only as necessary to prevent stress or load concentration or to provide for alignment tolerance, except for hydraulic elevator power units. Each hydraulic elevator power unit output line should have a muffler in the line and two flexible connectors located at right angles to each other and separated by at least 4 ft of line. The connectors can be located on each side of the muffler or both on the same side of the muffler, but in any case should be in close proximity to the hydraulic power unit.

In any location where fans are placed in a room which is located directly above a public area, spring isolators shall be provided for support of the fan and flexible connectors shall be used for connection of the fan to duct work. The static deflection for such spring isolators should be a minimum of 1". Rubber pads of 1/2" thickness shall be provided between the spring foot and the support surface.

In all cases where anchor bolts pass through the rubber support pads, a neoprene sleeve and washer shall be used to separate the anchor bolt shank and head (or nut) from the machine support foot or bracket.

E. Seismic Considerations:

Since most equipment installed in transit facilities is rigidly fixed and not vibration isolated, seismic restraints are not necessary. For any equipment which is vibration isolated because of close proximity to public spaces, seismic restraints should be included and should be designed to limit motion to 3/4 inch in any direction and to accept a force in any direction corresponding to at least 1.0 g acceleration.

3.6 NOISE IN ABOVE-GROUND STATIONS [For future alignment extensions]

3.6.1 General Considerations

In above-ground stations noise levels will be governed by train operations. For ballast and tie tracks the maximum noise level should not exceed 80 dBA on the train platform as trains leave and enter the platform. For concrete trackbed the appropriate limit is 80 to 85 dBA.

Station location is a potential problem, particularly when train platforms are located in a highway median, adjacent to a street with a high volume of traffic traveling at high speeds, or adjacent to a railroad right-of-way. An appropriate acoustical design with shielding can relieve patrons on platforms from an otherwise serious noise problem created by traffic or other noise sources. Design goals for maximum noise levels should be similar to those for the transit trains.

The maximum noise level design goal on the station platforms is 55 dBA for any ancillary mechanical or vertical circulation equipment. Ventilation system noise in station attendants' booths should not exceed 50 dBA.

3.6.2 Acoustical Design Criteria

Train noise levels are somewhat dependent on vehicle design. However, in enclosed or partially enclosed platform areas, train noise can be reduced by application of underplatform overhang treatments as for subway stations; see section 3.5.5.

In fully or partially enclosed station platforms the reverberation time of the platform area should be between 1.2 to 1.5 seconds at 500 Hz when the area is unoccupied; a sufficient range to allow flexibility in the architectural design of the stations. This reverberation time will minimize reflection effects and provide good speech intelligibility while acting to efficiently control noise from trains, street traffic or people.

3.7 AIRBORNE NOISE FROM TRANSIT ANCILLARY FACILITIES

3.7.1 General Introduction

There are sources of community noise in a subway or above-grade transit system other than trains. The two basic types of airborne noise from ancillary facilities are transient and continuous. For example, transient noise is transmitted from vent shaft openings during train passbys. Power sub-stations, chiller plants and fan noise may be characterized as continuous ancillary equipment noise. These noises can be obtrusive due to their tonal and continuous nature. The appropriate noise level design goal limit depends on the activities of occupants as well as background noise in the area. The acceptable levels of transient and continuous noises are different. Transient noises are acceptable at higher levels than continuous noises, particularly continuous noises containing pure tones.

Table 3.7.1 presents the design goals for the transit system ancillary facility noises in each of the community area categories listed in Table 3.3.1. This should result in general community acceptance.

TABLE 3.7.1 DESIGN CRITERIA FOR NOISE FROM TRANSIT SYSTEM ANCILLARY FACILITIES

Community Area Category	Maximum Noise Level, dBA Transient	Maximum Noise Level, dBA Continuous
I Low Density Residential	50	40
II Average Residential	55	45
III High Density Residential	60	50
IV Commercial	65	55
V Industrial/Highway	75	65

The criteria in Table 3.7.1 shall be applied at a distance of 50 ft from the shaft outlet or other ancillary facility or shall be applied at the setback line of the nearest building or occupied area, whichever is closer.

As stated previously, transient noise design goals apply to short time duration events such as train passby noise transmitted from vent shaft openings. Continuous noise design goals apply to noises such as fans, cooling towers or other long duration noises except electrical transformer hum. The design goals for transformer noise, or other sources with tonal components, should be 5 dBA less than given in the Table 3.7.1. Sound attenuation is not required on the outlet of emergency exhaust fans except in cases where the emergency exhaust fans are used as part of a station ventilation system.

3.7.2 Fan and Vent Shafts

For fan and vent shafts with surface gratings or openings the noise shall be limited in accordance with the criteria for exterior noise from ancillary facilities, Table 3.7.1.

Vent shaft noise reduction shall be achieved by absorption treatment in the shafts - applied to the walls and ceilings. Fan shaft noise reduction shall be achieved by use of standard duct attenuators in shafts where the fans are near the surface gratings. For shafts with fans located remotely from the grating the noise reduction shall be achieved by the use of standard attenuators and sound absorption treatment applied to the fan room and shaft walls and ceilings with the combination to achieve the total attenuation required. Sound absorption treatment shall consist of 2 to 4 inch thick mechanically attached panels, e.g. expanded cellular glass foam blocks.

3.7.3 Substations and Emergency Power Generation

Substation and emergency power generation equipment noise shall be limited to 5 dBA less sound level than listed for continuous noise in Table 3.7.1. Reduction of noise from these sources shall be achieved by barriers, enclosures, sound absorption materials and mufflers - as applicable to the individual facility or unit design.

3.7.4 Chiller Plant Noise

Chiller plant noise levels shall comply with design criteria listed for continuous noise in Table 3.7.1. Reduction of noise from chiller plants shall be achieved by barriers, enclosures and sound absorption materials, as applicable to the individual facility or unit design.

3.8 NOISE IN SUBWAY TUNNELS

High speed train operations in tunnels can generate excessive noise levels and noise abatement techniques shall be used to reduce the noise to an acceptable level. The maximum interior car noise at maximum tunnel operating speeds shall not exceed 80 dBA. An acoustical absorption system may be employed in the tunnel or additional sound insulation may be provided on the cars to meet this design goal. Tunnel sound absorption treatment can, for instance, provide 5 dBA or more reduction of noise levels inside the car. Reducing tunnel noise by a sound absorption system improves the acoustical environment for system employees and aids in complying with the statutory noise limits set by the Occupational Safety and Health Administration.

3.9 SHOP EQUIPMENT NOISE

To avoid excessive noise exposure for employees and to comply with existing and proposed standards and requirements of the Occupational Safety and Health Administration, shop equipment noise should not exceed 85 dBA at operator stations and should not exceed 90 dBA at any point 3 ft from the equipment.

3.10 VIBRATION ISOLATION OF SUBWAY STRUCTURES

3.10.1 Scope

Vibration isolation shall be provided at any point where the subway structure is in very close proximity or directly against a building structure or building foundation elements.

3.10.2 General Considerations

Vibration isolation in the form of a resilient element shall be provided between the subway structure elements and building structure elements to prevent direct transmission of noise and vibration to buildings.

3.10.3 Isolation Elements

- The resilient element between the two structures shall consist of intervening soil of at least 2 feet thickness or depth, or there shall be an elastomer pad between the subway structure and building.

- The elastomer pad shall be a 1 or 2 inch thickness closed-cell expanded neoprene, selected to give proper support of hydraulic or structural loads with deflection of the elastomer pad not exceeding 10% to 20% of pad thickness.

3.11 CONSTRUCTION NOISE AND VIBRATION CONTROL

3.11.1 General

Perform construction operations in a manner to minimize noise and vibration. Provide working machinery and equipment with efficient noise suppression devices and employ other noise and vibration abatement measures necessary for protection of both employees and the public. In addition, restrict working hours and schedule operations in a manner that will minimize to the greatest extent feasible the disturbance to the public in areas adjacent to the work and to occupants of buildings in the vicinity of the work. Protect employees and the public against noise exposure in accordance with the requirements of the Occupational Safety and Health Act of 1970 and the current statutory noise limits set by the California Occupational Safety and Health Administration (Ref. 6). Compliance with the requirements of this Section will not relieve the Contractor from responsibility for compliance with state and local ordinances, regulations, and other Sections of this criteria document.

3.11.2 Special Requirements

Compliance with the requirements of this Section will require the use of machines with effective mufflers or enclosures and selection of quieter alternative procedures. Compliance may also require the use of completely closed enclosures (tongue and groove plywood or sheathing) around work sites or a combination of closed boarding and effective mufflers or enclosures. It will also be necessary to arrange haul routes to minimize noise and vibration at residential sites and it may be necessary to place operating limitations on machines and trucks. Shop drawings of work sites and haul routes showing provisions for control of construction noise shall be submitted to the Engineer for approval.

3.11.3 Monitoring

Monitor noise and vibration levels of work operations to assure compliance with the noise and vibration limitations contained herein and retain records of noise and vibration measurements for inspection by the Engineer. Promptly inform the Engineer of any complaints received from the public regarding noise and vibration. Describe the action proposed and the schedule for implementation and subsequently inform the Engineer of the results of the action.

3.11.4 Definitions

A. Daytime refers to the period from 7:00 a.m. to 8:00 p.m. local time daily except Sundays and legal holidays. Nighttime, refers to all other times including all day Sunday and legal holidays.

B. Construction Limits are defined for the purpose of these noise and vibration control requirements as the Right-of-Way lines, Construction Easement Boundary or property lines as indicated on the drawings.

C. Special Zones or Special Construction Sites, outside of Construction limits, may be designated by the agency having jurisdiction to be considered as being within the Construction Limits.

3.11.5 Noise Level Restrictions

A. Noise Level Restrictions in All Areas

In no case expose the public to construction noise levels exceeding 90 dBA (slow) or to impulsive noise levels with a peak sound pressure level exceeding 140 dB as measured on an impulse sound level meter or 125 dBC maximum transient level as measured on a general purpose sound level meter on "fast" meter response.

B. Noise Level Restrictions at Affected Structures

Conduct construction activities in such a manner that the noise levels 200 feet from the Construction Limits or at the nearest affected building, whichever is closer, do not exceed the levels listed in the following schedules:

1. Continuous Noise: Prevent noises from stationary sources, parked mobile sources or any source or combination of sources producing repetitive or long-term noise lasting more than a few hours from exceeding the limits of Table 3.11.1.

TABLE 3.11.1 LIMITS FOR CONTINUOUS CONSTRUCTION NOISE

Affected Structure or Area	Maximum Allowable Continuous Noise Level, dBA	
Residential	Daytime	Nighttime
single family residence	60	50
along an arterial or in multi-family residential areas, including hospitals	65	55
in semi-residential/commercial areas, including hotels	70	60

Commercial	At All Times
in semi-residential/commercial areas, including schools	70
in commercial areas with no nighttime residency	75
Industrial	
all locations	80

2. Intermittent Noise: Prevent noises from non-stationary mobile equipment operated by a driver or from any source of non-scheduled, intermittent, non-repetitive, short-term noises not lasting more than a few hours from exceeding the limits of Table 3.11.2.

TABLE 3.11.2 LIMITS FOR INTERMITTENT CONSTRUCTION NOISE

Affected Structure or Area	Maximum Allowable Intermittent Noise Level, dBA	
Residential	Daytime	Nighttime
Single family residence areas	75	60
along an arterial or in multi-family residential areas, including hospitals	80	65
in semi-residential/commercial areas, including hotels	85	70

Commercial	At All Times
in semi-residential/commercial areas, including schools	85
in commercial areas with no nighttime residency	85
Industrial	
all locations	90

C. Special Zone or Special Construction Site

In areas outside of Construction Limits but for which the Contractor has obtained designation as a Special Zone or Special Construction Site from the agency having jurisdiction, the noise limitations for buildings in industrial areas apply.

In zones designated by the local agency having jurisdiction as a special zone or special premise or special facilities, such as hospital zones, the noise level and working time restrictions imposed by the agency shall apply. These zones and work hour restrictions shall be obtained by the Contractor from the local agency.

D. More Than One Limit Applicable

Where more than one noise limit is applicable, use the more restrictive requirement for determining compliance.

3.11.6 Noise Emission Restrictions

Use only equipment meeting the noise emission limits listed in Table 3.11.3, as measured at a distance of 50 feet from the equipment in substantial conformity with the provisions of the latest revisions of SAE J366b, SAE J88, and SAE J952b (Refs. 7, 8, 9) or in accordance with the measurement procedures specified herein.

TABLE 3.11.3 NOISE EMISSION LIMITS ON CONSTRUCTION NOISE

TYPE OF EQUIPMENT	MAXIMUM NOISE LIMIT	
	Date Equipment Acquired	
	Before 1-1-1982	On or After 1-1-1982
All equipment other than highway trucks; including hand tools and heavy equipment	90 dBA	85 dBA
	Date Equipment Acquired	
	Before 1-1-1982	On or After 1-1-1982
Highway trucks in any operating mode or location	83 dBA	80 dBA

Peak levels due to impact pile drivers may exceed the above noise emission limits by 10 dBA.

3.11.7 Vibration Level Restrictions

A. Vibration Limits in All Areas: Conduct construction activities in such a manner that vibration levels at a distance of 200 ft from the Construction Limits or at the nearest affected building, whichever is closer, do not exceed root-mean-square (rms) vibration velocity levels of 0.01 inches per second in any direction over the frequency range of 1 to 100 Hz.

B. Special Zones: In zones designated by the local agency having jurisdiction as a special zone or special premise or special facilities, the vibration level and working time restrictions imposed by the agency shall apply. These zones and work hour restrictions shall be obtained by the Contractor from the local agency.

3.11.8 Noise and Vibration Control Requirements

Notwithstanding the specific noise and vibration level limitations specified herein, utilize the noise and vibration control measures listed below to minimize to the greatest extent feasible the noise and vibration levels in all areas outside the Construction Limits.

- Utilize shields, impervious fences or other physical sound barriers to inhibit transmission of noise.

- Utilize sound retardent housings or enclosures around noise producing equipment.

- Utilize effective intake and exhaust mufflers on internal combustion engines and compressors.

- Line or cover hoppers, storage bins and chutes with sound deadening material.

- Do not use air or gasoline driven saws.

- Conduct truck loading, unloading and hauling operations so that noise and vibration is kept to a minimum.

- Route construction equipment and vehicles carrying spoil, concrete or other materials over streets and routes that will cause the least disturbance to residents in the vicinity of the work. Advise the Engineer in writing of the proposed haul routes prior to securing a permit from the local government.

- Site stationary equipment to minimize noise and vibration impact on the community, subject to approval of the Engineer.

- Use vibratory pile drivers or augering for setting piles in lieu of impact pile drivers. If impact pile drivers must be used, their use is restricted to the hours from 8:00 a.m. to 5:00 p.m. weekdays in residential and in semi-residential/commercial areas.

3.12 BLASTING NOISE AND VIBRATION CONTROL

3.12.1 General

Perform blasting operations in a manner to minimize noise and vibration. Use blasting procedures and covers providing effective suppression of noise and vibration and employ other abatement measures necessary for protection of both employees and the public. In addition, restrict working hours and schedule operations in a manner that will minimize to the greatest extent feasible the disturbance to the public in areas adjacent to the work and to occupants of buildings in the vicinity of the work. Compliance with the requirements of this Section will not relieve the Contractor from responsibility for compliance with state and local ordinances, regulations, and other Sections of this Criteria document.

3.12.2 Monitoring

Monitor noise and vibration levels of work operations to assure compliance with the limitations contained herein and retain records of measurements for inspection by the Engineer. Promptly inform the Engineer of any complaints received from the public regarding noise or vibration. Describe the action proposed and the schedule for implementation and subsequently inform the Engineer of the results of the action.

3.12.3 Time of Blasting

A. General: Restrict blasting to daytime hours, 7:00 a.m. to 8:00 p.m. daily except Sundays and legal holidays.

B. Emergency: In the event that safety or emergency considerations require blasting during nighttime hours, 8:00 p.m. to 7:00 a.m. and Sundays and legal holidays, blasts may be fired at such times subject to prior notice to and approval by the Engineer and subject to the restrictions of Section 3.12.4.B.

C. Special Considerations: In addition to the restrictions of Section 3.12.3.A. if situations and circumstances require, restrict blasting to within reasonably safe distances of noise and vibration sensitive premises or facilities to specific daytime periods determined by the Engineer and schedule and coordinate each shot with the Engineer.

3.12.4 Ground Vibration Due to Blasting

A. General: Conduct blasting operations to avoid damage to structures or buildings and to prevent peak particle velocity of blast induced motion from exceeding 2.0 inches per second on or in the nearest structure or on the ground at the nearest structure or 200 feet from the Construction Limits, whichever is closer.

Peak particle velocity is defined as the instantaneous maximum vector sum of the velocity vectors in three mutually perpendicular directions at the point of interest.

B. Emergency Blasting: Emergency blasting required to protect the safety of the project during the nighttime period will be controlled to prevent peak particle velocity of ground vibration at the nearest building having nighttime occupancy or 200 feet from the Construction Limits, whichever is closer, from exceeding 0.2 inches per second. Notwithstanding the above, if the emergency arises from inability of contractor to fire loaded holes within the daytime period solely due to unavoidable conditions, peak particle velocity of ground vibration may exceed 0.2 inches per second but will not exceed 2.0 inches per second.

C. New Concrete: Conduct blasting operations to prevent peak particle velocity of ground vibration from exceeding 1.0 inch per second at concrete less than 3 days old or 2.0 inches per second at concrete less than 7 days old. Do not blast within 25 feet of concrete less than 7 days old unless a satisfactory plan has been submitted in writing and accepted by the Engineer.

3.12.5 Noise (Overpressure) Due to Blasting

A. General: Conduct daytime blasting in such a manner as to limit instantaneous peak overpressure to 0.01 psi at the nearest building or 200 feet from the Construction Limits, whichever is closer. All instrumentation must be linear in response with a range of at least 5 Hz to 200 Hz.

B. Emergency: Conduct nighttime blasting in such a manner as to limit instantaneous peak overpressure to 0.0004 psi at the nearest building or 200 feet from the Construction Limits, whichever is closer.

C. Overpressure Control Measures: Notwithstanding the specific limitations specified herein, utilize control measures such as listed below to minimize to the greatest extent feasible the blasting overpressure in all areas outside the Construction Limits.

- Utilize weighted covers on vertical and inclined shafts to contain blasting overpressure.
- Utilize blasting mats at the excavation where feasible.
- Minimize charge per delay.
- Arrange covers and excavation to maximize underground volume exposed to blast pressure.

3.12.6 Test Blasts

Perform at least one small charge test blast at each new drill and blast excavation site prior to commencement of production blasting. The purpose is to establish local ground-borne vibration and airborne overpressure propagation characteristics and anomalies to aid in determination of efficient charges that will not cause the ground-borne vibration and airborne overpressure limits to be exceeded. Coordinate scheduling of each test blast with the Engineer.

3.12.7 General Precautions in Blasting Operations

- Notify all parties owning or operating subsurface utilities 72 hours before commencing blasting operations.

- Coordinate and obtain the Engineer's approval for the daily blasting schedule.

- Use controlled blasting techniques to minimize fracturing the rock outside the neat lines of the excavation.

- Use such sizes and arrangement of explosive charges and such methods of detonation that will reduce the magnitude of vibration resulting from the explosion to the limits specified in previous Sections to prevent damage to the constructed works as well as to services, buildings or property in the neighborhood; and to minimize nuisance to nearby residents.

- Employ all necessary and satisfactory means of protection such as temporary bridges, staging, chains, rope-nets, mats, timber and the like, to prevent any stones and fragments of rock or other materials from being shot or thrown out of any excavation.

- As the excavation proceeds and immediately after each blast, test the roof and walls and scale loose and shattered rock which is liable to fall. Carry out similar checks on previously excavated sections at least every 48 hours.

- Do not blast in ground which, in the opinion of the Engineer, is loose or liable to slips. Wedging and barring only shall be allowed in such ground.

- Before blasting within 15 feet of an existing line of water, gas or sewer pipes or within 50 feet of any completed part of the Works, submit and obtain approval of a plan showing the relative positons of the existing service, or completed part of the Works and the area to be blasted and the blasting technique to be employed.

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Chapter 4

NOISE AND VIBRATION CONTROL MEASURES

4. NOISE AND VIBRATION CONTROL MEASURES

4.1 Rail Fixation

In the past 10 to 15 years there have been many track fastening and support systems developed to reduce the noise and vibration generated by transit train operations and to improve the stability and maintainability of the track system.

Some of the designs have been built and tested on an experimental basis; however, a number have also been installed and used under service conditions. For subway applications, direct fixation resilient rail fasteners with rubber pads of various configurations, resiliently supported concrete ties, and floating slab trackbeds have been shown to provide improved performance with regard to ground-borne noise and vibration. These systems can, and usually do, produce better rail fixation stability and generally require less maintenance than ballast and tie installations.

Wilson, Ihrig & Associates has been engaged in a continuing study and review of track fixation systems and the acoustical and vibration performance achieved by the various designs. The following discussion presents a review of the designs and the performance with evaluation and recommendations relative to the Metro Rail System.

There are four basic concepts of rail fixation which are being considered for the Metro Rail System:

1. Ballast and ties

2. Direct fixation resilient fastener on concrete invert

3. Resiliently supported ties on concrete invert

4. Floating slab trackbed

The following discussions outline the features of the basic concepts for rail fixation indicating the factors significant in noise and vibration performance.

4.1.1 Ballast and Tie

In general terms, ballast and tie track installations in subways result in the lowest airborne noise in the subway, i.e., the lowest noise exposure for patrons in the trains, because of the airborne sound absorption of the ballast. However, there are numerous instances where ballast and tie track installations in subways result in high levels of ground-borne vibration and noise causing excessive noise exposure in buildings near or adjacent to the subways. The high levels of ground-borne vibration and noise result from the vibration produced at the wheel/rail interface being transmitted to the subway structure, and then to the adjacent ground, by the relatively stiff ballast supporting the ties. Ground-borne noise and vibration will be higher for thin layers of ballast relative to thick layers of ballast.

In order to have adequate resilience of the ballast, and to avoid crushing of the ballast stones due to load concentration, it is necessary to use a ballast layer at least 18" thick, in a subway installation. Even with a deep ballast layer, it is possible for excessive crushing and compaction to occur because of the rigid invert support (in contrast to the resilient earth support for surface ballast and tie installations). The depth of the ballast required results in greater depth of subway structure than for any of the other designs. Further, the compaction and crushing of the ballast which can occur with use causes progressively increasing stiffness and higher levels of transmitted vibration and noise.

The degree of effectiveness of any of the three alternate types of support will vary with design details, but all can be more effective in reducing ground-borne vibration than ballast and tie. While the degree of effectiveness in reducing ground-borne vibration is different for each rail fixation and support design, they all produce slightly higher airborne noise levels in the subway tunnel.

It is possible through the installation of sound absorbent material on the interior surfaces of the tunnel to effectively reduce the airborne noise to be the same or comparable to that obtained with a ballast and tie installation. Rail weight, fastener stiffness and absorptive treatment all affect the airborne noise. However, it is possible with concrete invert and a resilient track support system to have airborne noise in a tunnel comparable to the quietest system, and at the same time achieve reduced ground-borne vibration and noise transmitted to adjacent buildings. Using concrete invert with an appropriately designed resilient support system for the track can give the best overall performance in terms of both patron noise exposure and the noise and vibration produced in adjacent buildings by operations of the transit trains. Other advantages achieved through the use of a resilient support system for the track with a concrete invert include improved stability and maintainability of track alignment with less track maintenance required, improved electrical isolation of the track, improved conditions for cleaning, and probably longer life for the track and support components.

One method for reducing rail forces from ballast and tie installations, and thus ground-borne vibration to buildings adjacent to the subway, is the use of a ballast mat. Ballast mats are usually thick, resilient layers of elastomer, cork, fiberglas, or rock wool, placed under the ballast. Although widely tested and installed in Europe and Japan, they have received only limited attention in the United States. Installations are often designed to improve electrical isolation, water drainage or reduce ballast pulverization, with the resulting vibration reduction as an additional benefit.

Vibration measurements at the invert indicate that ballast mats can be quite effective in the frequency range above 30 to 40 Hz. However more research and development is needed before ballast mats can be used primarily for vibration reduction, to determine that the ballast mat will significantly reduce the transit train vibration in the frequency range of interest, and will have suitable life expectancy.

4.1.2 Direct Fixation

A wide variety of designs for resilient direct fixation rail fasteners have been tried both in service and test installations. This type of rail fixation uses one or two elastomer pads of various thicknesses, depending on the design details, and obtains the vibration isolation or reduction of vibration and noise transmitted to the subway structure (therefore reducing the vibration transmitted via the ground to adjacent buildings) by interposing the elastomeric pad or pads between the rail and the invert. Most designs can be characterized by two basic types. First is the unbonded type such as the TTC fastener, and second the fastener with bonded elastomer pad, such as the BART fastener. These are shown in Figures 4.1 and 4.2, respectively.

The typical direct fixation fastener design consists essentially of a flat steel plate for anchoring the rail and a flat elastomer pad located between the plate and the concrete invert. In some of the unbonded fastener designs elastomer pads are placed both between the rail and the plate, and between the plate and the invert. Many designs of both the bonded and unbonded variety of resilient direct fixation fasteners have been devised and tried but they are all in effect a variation of the basic designs as represented by the TTC and BART fasteners. This type of fastener can be used to provide electrical isolation, to reduce the overall height required in subways, and to reduce ground-borne and structure vibration levels. They have been found to be technically and economically feasible, providing satisfactory and proven performance.

Tests of the acoustical performance of the various resilient direct fixation fasteners indicate that there are measureable but small differences in ground-borne noise and vibration performance for widely different fastener configurations. This is probably because there is little difference in the net spring rate for the various fasteners. The fasteners are all required to limit lateral and longitudinal deflections of the rail and this places limitations on the degree of resilience that can be obtained. The designers for each type of rail fastening do attempt to design for minimum vertical spring rate to reduce vibration transmission but the limitations on lateral and longitudinal stiffness result in a relatively narrow range of vertical stiffnesses.

Although resilient direct fixation, D.F., fasteners are generally more effective at reducing ground-borne vibration than ballast and tie track, the amount of ground-borne vibration reduction which can be achieved is limited by the requirements for stability of the rail. Experience has shown that the reduction of ground-borne vibration provided by the D.F. fastener is adequate in many instances, particularly in locations where there are no buildings in very close proximity to the subway.

For a resilient D.F. fastener with a resilient pad which is sufficiently stiff to properly support the rail, particularly for lateral deflections, the stiffness is such that the amount of vibration transmitted to the invert is still excessive for many applications and excessive low-frequency noise and vibration can result in buildings near or adjacent to the subway. Those designs with the softest elastomer pads, providing the most resilient support and the best low-frequency vibration reduction, can allow excessive rail vibration amplitude and result in increased airborne noise due to the rail vibration. Consequently, the softer direct fixation fasteners - giving better reduction of ground-borne vibration - can result in increased patron noise exposure due to higher undercar noise levels. This effect can be compensated for by the use of sound absorption material on the tunnel interior surfaces.

A variation of the common D.F. configuration has been developed by Clouth Gummiwerke in Germany. This fastener uses elastomer-in-shear as the resilient element of a bonded, resilient direct fixation rail fastener. Commonly known as the "Cologne Egg", the resilient element of this fastener consists of an oval ring, whose major axis is transverse to the rail. This fastener is designed to achieve low vertical stiffness without sacrificing lateral stability. Figure 4.3 illustrates this design. The fastener has been used for several installations in Europe and short sections have been installed at MBTA and WMATA in the United States.

Preliminary results from tests to determine the vibration reduction of the Cologne Egg fastener with respect to a resilient D.F. fastener at WMATA indicate that the vibration reduction averages approximately 5 dB in the range of 50 to 300 Hz. Tests of the vibration transmission properties of the soil at several points along the proposed Metro Rail Alignment indicate that the most significant frequency components of ground-borne vibration are in the range of 15 to 40 Hz. Based on the test data obtained at WMATA and the soil damping and transmission characteristics along the proposed Metro Rail Alignment, the Cologne Egg fastener would not provide effective ground-borne vibration reduction over a standard resilient D.F. fastener.

4.1.3 Resiliently Supported Tie on Concrete Invert

In this category only the RS-STEDEF system developed in France has been installed and extensively tested. Figures 4.4 and 4.5 show the configuration and details. This design uses two block ties of the RS type similar to those used for ballast and tie installations. The ties are supported in pockets in a concrete invert with a neoprene rubber boot and an expanded neoprene support pad between the tie and the invert for vibration reduction. The rail is fixed to the tie blocks with an electrical insulating clip utilizing a 3/16" rubber pad between the rail and tie so that the rail fixation to the tie is relatively rigid. This rail clip and close coupling to the tie blocks result in a low level of rail vibration for audible noise frequencies and hence low noise radiation from the rail.

This design has been tested extensively by the Paris Metro [RATP] and is being used extensively in their new installations in place of the standard ballast-and-tie used in their earlier double-track tunnel installations. The RS-STEDEF design has also been installed at a number of locations for the Baltimore Region Rapid Transit System subway and at a subway location on the MARTA system in Atlanta. One of the main reasons for adoption of the RS-STEDEF resiliently supported tie by these systems is the reduced ground-borne vibration and noise which is achieved by the design.

4.1.4 Floating Slab Trackbed

A number of varieties of floating slab trackbed have been designed and installed. One of the early concepts involving the use of massive floating slab sections, actually floating bridge sections, was used in London for the subway structure beneath the Barbican residential development. A similar system has been installed by London Transport on the London-Heathrow Line for reduction of ground-borne vibration and noise.

Systems requiring less space in the subway and which are significantly less expensive, include the insulated track slab design for the Lime Street Station of the Mersey Railway Extensions by British Railways, and the floating slab trackbed designed for the Washington, D.C. Metropolitan Area Transit Authority Metro System.

The continuous floating slab consists of a continuous concrete slab trackbed supported on resilient pads of rubber or load bearing fiberglass. The vibration isolation is provided by the concrete floating slab acting as an inertia mass and the support pads acting as soft support springs. The rail is fixed to the slab by a relatively stiff direct fixation fastener. The system is very effective in reducing ground-borne vibration from transit train operations. Compared with resilient direct fixation fasteners on rigid invert, concrete floating slabs of approximately 12" thickness have been found to reduce ground-borne vibration by 15 to 18 decibels over the low frequency range which is most important in producing noise in nearby buildings.

The disadvantages of the continuous floating slab system include the cost of construction, the difficulty of forming and pouring the concrete slab in place in the subway structure, the difficulty replacing resilient elements, and the higher in-tunnel noise levels. The vibration of the slab transmitted away from the train (due to the fact that the slab is continuous) generates marginally higher in-tunnel noise levels at low frequencies than other types of resilient track support systems.

More recently, the discontinuous floating slab or "double tie" has been developed which combines the best features of the resiliently supported tie and the continuous floating slab trackbed. This system provides equivalent or even superior performance over that achieved with the continuous floating slab trackbed. The discontinuous floating slab consists of concrete blocks supported by resilient pads. The rail is attached to the slabs using procedures similar to those used for continuous floating slabs. Figure 4.6 shows this discontinuous floating slab as used at the Toronto Transit Commission (TTC).

The advantages of the discontinuous floating slab is that the system can be constructed using pre-cast rather than cast-in-place concrete inertia masses, the resilient elements can be easily replaced, and standard rail fixation hardware can be used. The discontinuous floating slab has been used at TTC (Toronto), MARTA (Atlanta), MURLA (Melborne), NFTA (Buffalo) and MTRC (Hong Kong). These installations have all been quite successful.

Audible noise perceived inside buildings adjacent to the subway is usually the primary form of intrusion from transit train operations in subway. Most floating slab designs focus on controlling ground-borne noise in the audible frequency range. However, recent experience at WMATA, MARTA and NYCTA indicates that ground-borne vibration of a perceptible level can be a significant problem. This phenomenon seems to be a particular problem in situations where the transit vehicle's primary suspension has a high vertical stiffness. This is further aggravated by the fact that many wood frame structures have fundamental resonances which are also in the same range as the floating slab resonance. It is important that the slab resonance frequency or car primary suspension resonance frequency be low enough to avoid coincident amplification of ground-borne vibration.

To optimize performance, the vertical motion resonance frequency of the floating slab must be lower than the dominant frequency of the ground-borne vibration. This frequency is a function of the truck design, the subway construction, and the soil parameters. Most of the lightweight floating slabs such as those used in Toronto, Washington and Atlanta have been designed to have a vertical motion natural frequency of the slab-support system lower than 15 Hz when loaded with the weight of the transit car body and truck.

The lower the vertical natural frequency, the more effective the vibration isolation. Increasing the mass of the floating slab lowers its frequency, however, cost and space considerations often limit the amount of mass that can be used on the floating slab. Soft supports would also provide a low natural frequency, however limitations on allowable rail deflection preclude the use of very soft supports. Thus the floating slab system for the Metro Rail System must be designed with a compromise between the rail deflections, produced by the static load of the trains, and the floating slab mass achievable in the space available in the subway structure. These factors can be determined during final design once the final tunnel and vehicle configurations are determined.

4.1.5 General Discussion

Table 4.1 indicates, in general terms, the relative acoustical performance of the rail fixation systems discussed. Although Table 4.1 qualitatively indicates the car interior noise levels expected for operation on various types of track, the actual level inside the cars is highly dependent on the car design. Different types of cars will have different levels of interior noise, depending on the degree of sound insulation provided by the car body walls, ceiling and floor. The lowest levels of interior noise are for operation on ballast and tie track. With proper design to meet the vehicle noise specifications, (see Chapter 8) the interior noise experienced by patrons should be generally acceptable on all types of track.

With the addition of sound absorption material to the side walls of the subway structure, for track support systems which utilize concrete invert, the in-tunnel noise level is reduced to be comparable to that for operation on ballast and tie track. Note that very little additional sound reduction would be obtained through the addition of sound absorption with ballasted track.

In estimating and evaluating the effectiveness of various rail fixation types, it is also necessary to consider the rail weight and fastener spacing because these factors affect the overall performance. In order to gain maximum acoustical performance with any of the resilient support systems for the track it is necessary to use rail of at least 115 lb/yd weight and fastener spacing of at least 30" center-to-center. Even better optimization of the acoustical performance would be achieved if a rail weight in the range of 120 to 130 lbs/yd and a fastener spacing of 36" could be used.

The wider fastener spacing results in an effectively lower rail support modulus, giving a more flexible system in terms of transmission of vibration to the subway structure, all other conditions being equal. The heavier rail weight results in lower vibration amplitudes of the rail, reducing airborne noise radiated by the rail, and distributes the loading of the rail over more rail fasteners which results in lessened vibration forces transmitted to the subway structure, thereby helping to minimize the ground-borne noise from the transit train operations.

For the type of occupancies and building usage along the Metro Rail alignment the ground-borne noise and vibration due to transit train operations with the use of resilient direct fixation fasteners will be satisfactory in most of the nearby buildings. There are also significant portions of the alignment where ballast and tie track would be a suitable track fixation with respect to the generation of ground-borne noise and vibration. However, we would not recommend that ballast and tie be the basic rail fixation system without further investigation of the feasibility and practicality of using ballast mats to further reduce ground-borne noise and vibration.

For the Metro Rail System it is recommended that the basic rail fixation system for the subway structure be a resilient direct fixation fastener as previously discussed. The fasteners should be installed with a minimum of 30" center-to-center spacing and the rail should be 115 lbs/yd minimum weight. This system will provide adequate reduction of ground-borne noise and vibration to give satisfactory results along most of the Metro Rail Alignment. For some sections along the alignment near buildings which have spaces which have activities which are more sensitive to noise and vibration, the resiliently supported tie or a floating slab trackbed should be installed to reduce the levels of ground-borne noise and vibration.

Those locations where special measures to control ground-borne noise and vibration are indicated in Chapter 5. At these locations either the resiliently supported tie or discontinuous floating slab could be used in most instances. At some locations it is anticipated that the discontinuous floating slab should be used rather than the resiliently supported tie in order to further reduce the ground-borne noise and vibration to meet the required criteria since the floating slab trackbed is somewhat more effective at reducing low frequency noise and vibration.

TABLE 4.1 COMPARISON OF ACOUSTICAL PERFORMANCE OF THE BASIC RAIL FIXATION SYSTEMS

FIXATION TYPE	AIRBORNE NOISE IN SUBWAY	GROUND-BORNE NOISE
Ballast & Tie	Quiet due to absorption of ballast	Noisy due to stiffness of support, worsening with age. Intermediate to noisy with the use of ballast mats.
Resilient Direct Fixation	Intermediate to noisy due to rail vibration and reflective concrete invert	Intermediate to noisy due stiffness required for rail stability
Resiliently Supported Tie of RS-STEDEF Design	Intermediate to noisy due to rail vibration and reflective concrete invert	Intermediate to quiet depending on thickness of resilient pads, weight of ties and tie-spacing
Continuous Floating Slab Trackbed	Intermediate to noisy due to reflective concrete invert and because floating slab vibration generates noise	Quiet because of vibration isolation provided by mass and support pads
Discontinuous Floating Slab Trackbed	Intermediate to noisy due to reflective invert but has relatively good control of rail and slab radiation	Quiet because of vibration isolation provided by mass and support pads

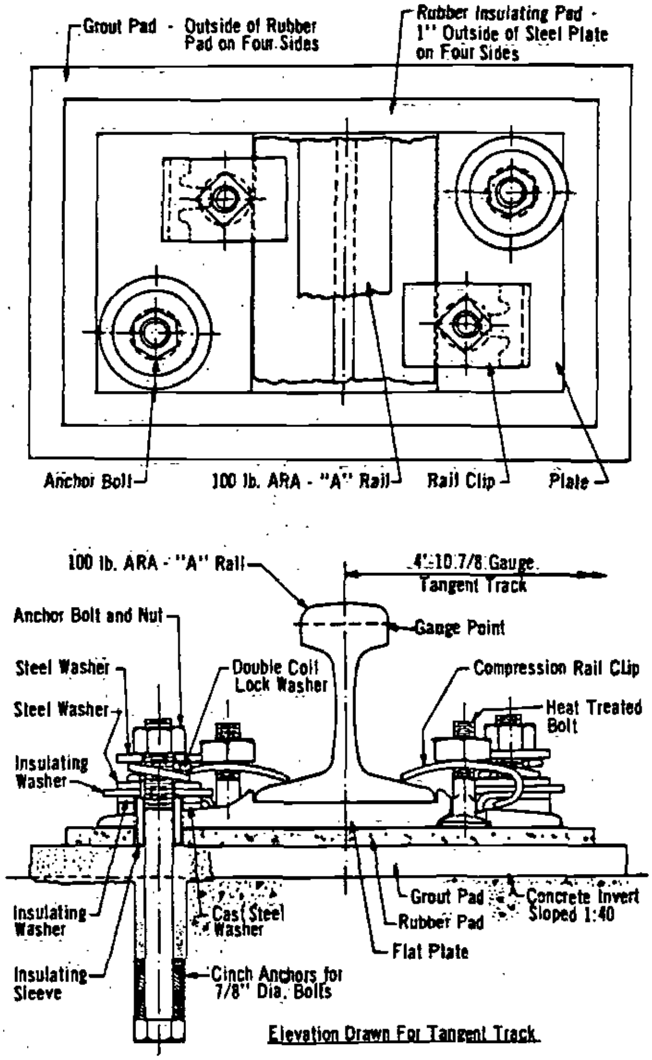

FIGURE 4.1 TORONTO TRANSIT COMMISSION DIRECT FIXATION RESILIENT RAIL FASTENER WITH UNBONDED NEOPRENE PAD

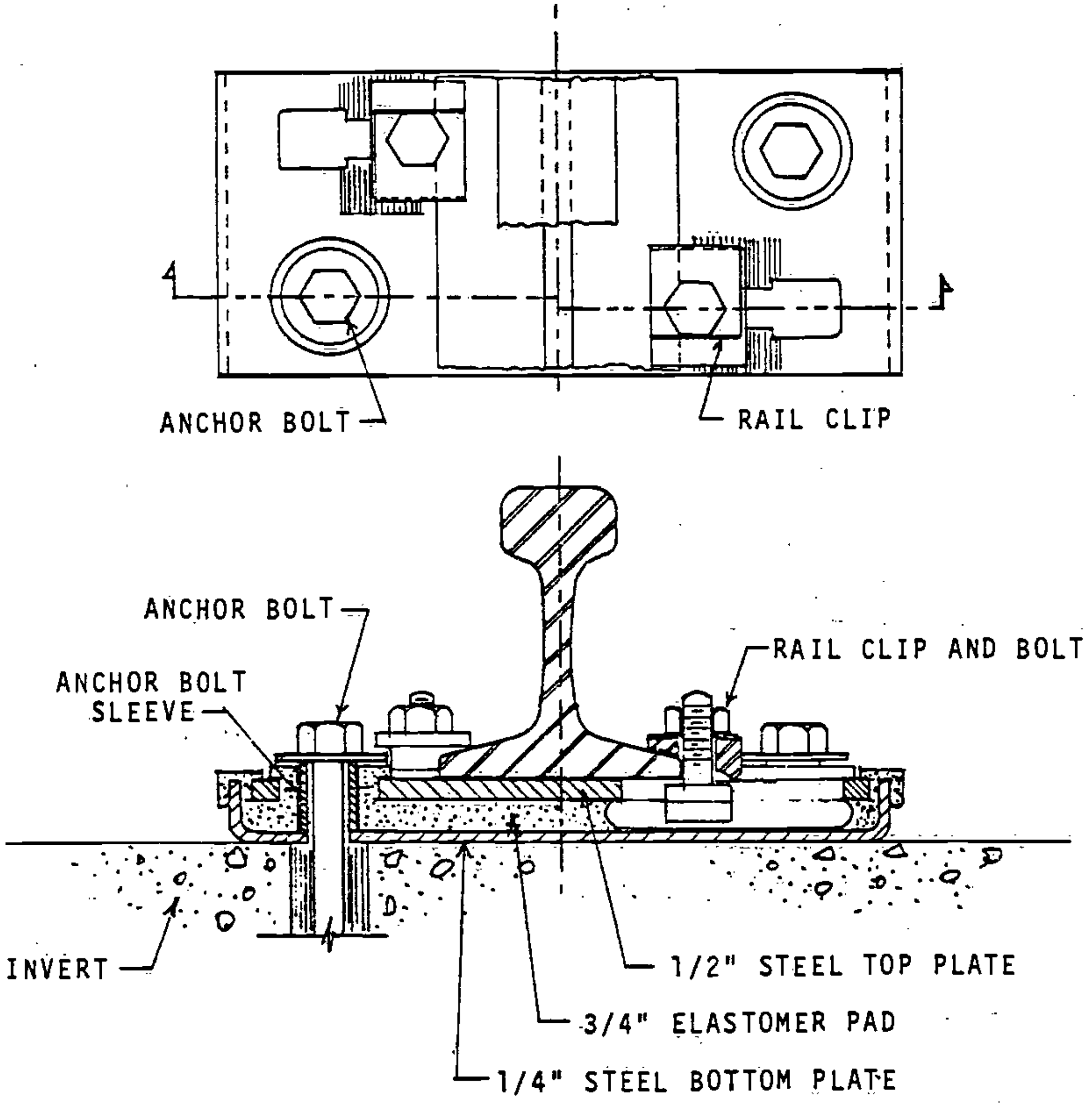

FIGURE 4.2 BART DIRECT FIXATION RESILIENT RAIL FASTENER WITH BONDED ELASTOMER PAD

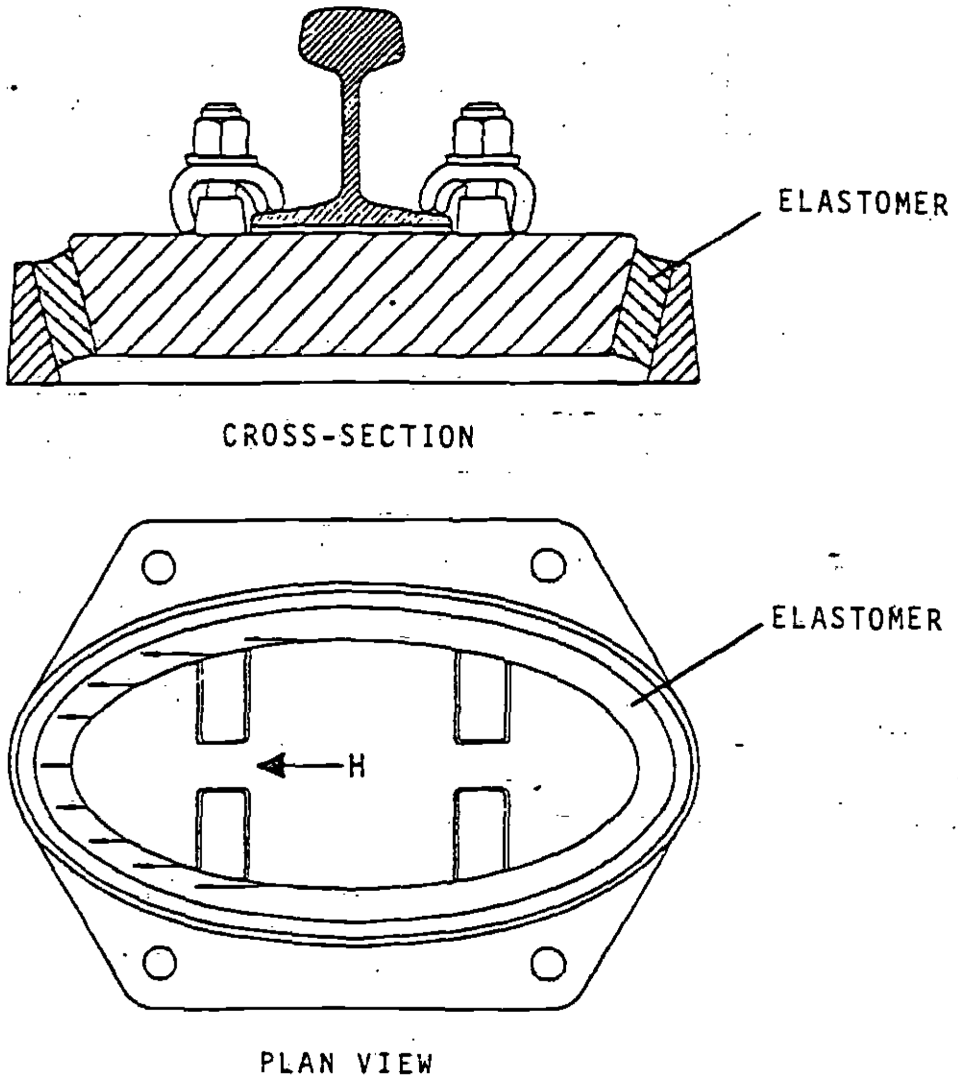

FIGURE 4.3 CLOUTH 1403/c ("COLOGNE EGG") RAIL FASTENER

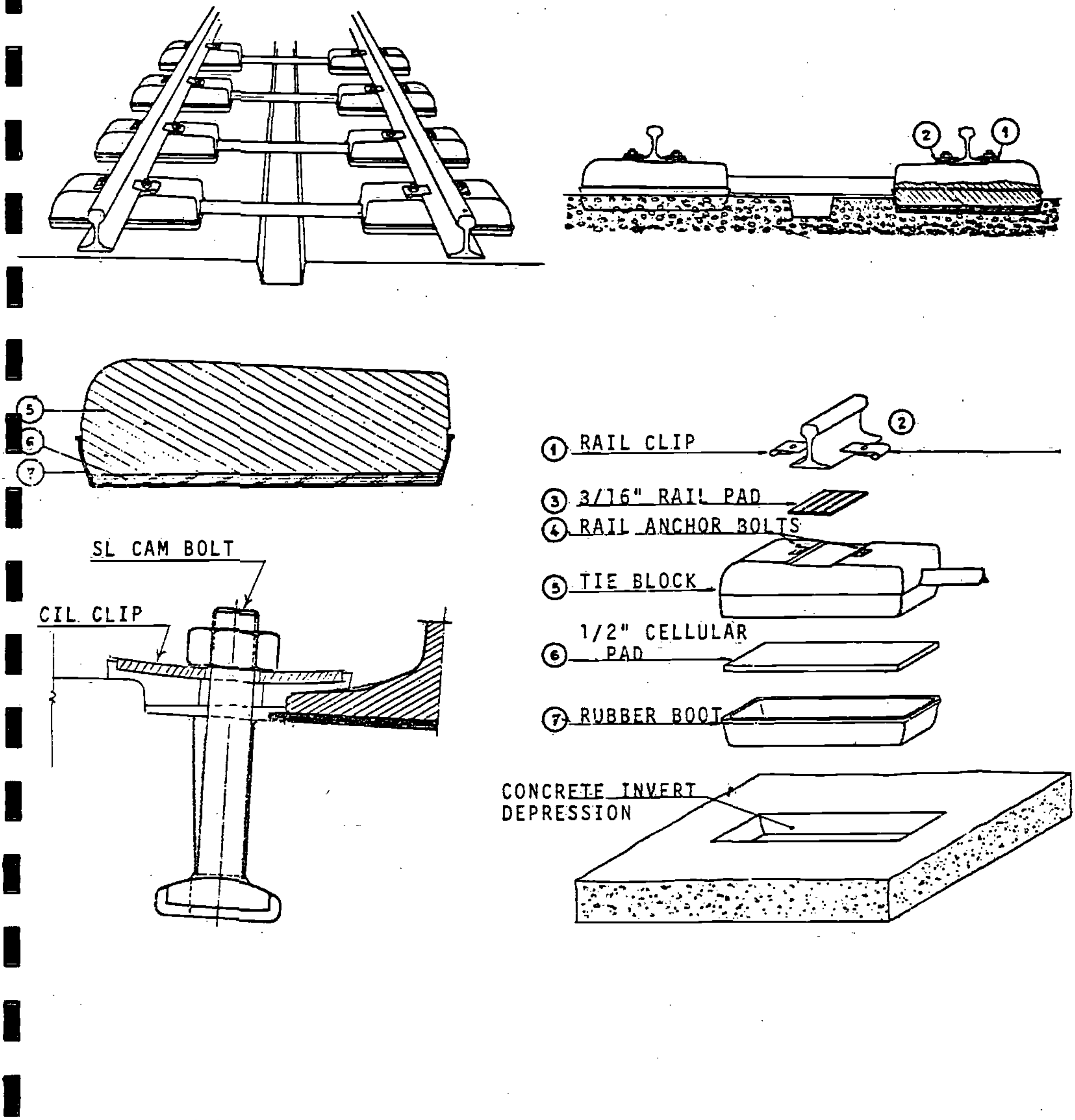

FIGURE 4.4 COMPONENTS OF THE RS-STEDEF RESILIENTLY SUPPORTED TIE RAIL FIXATION DESIGN

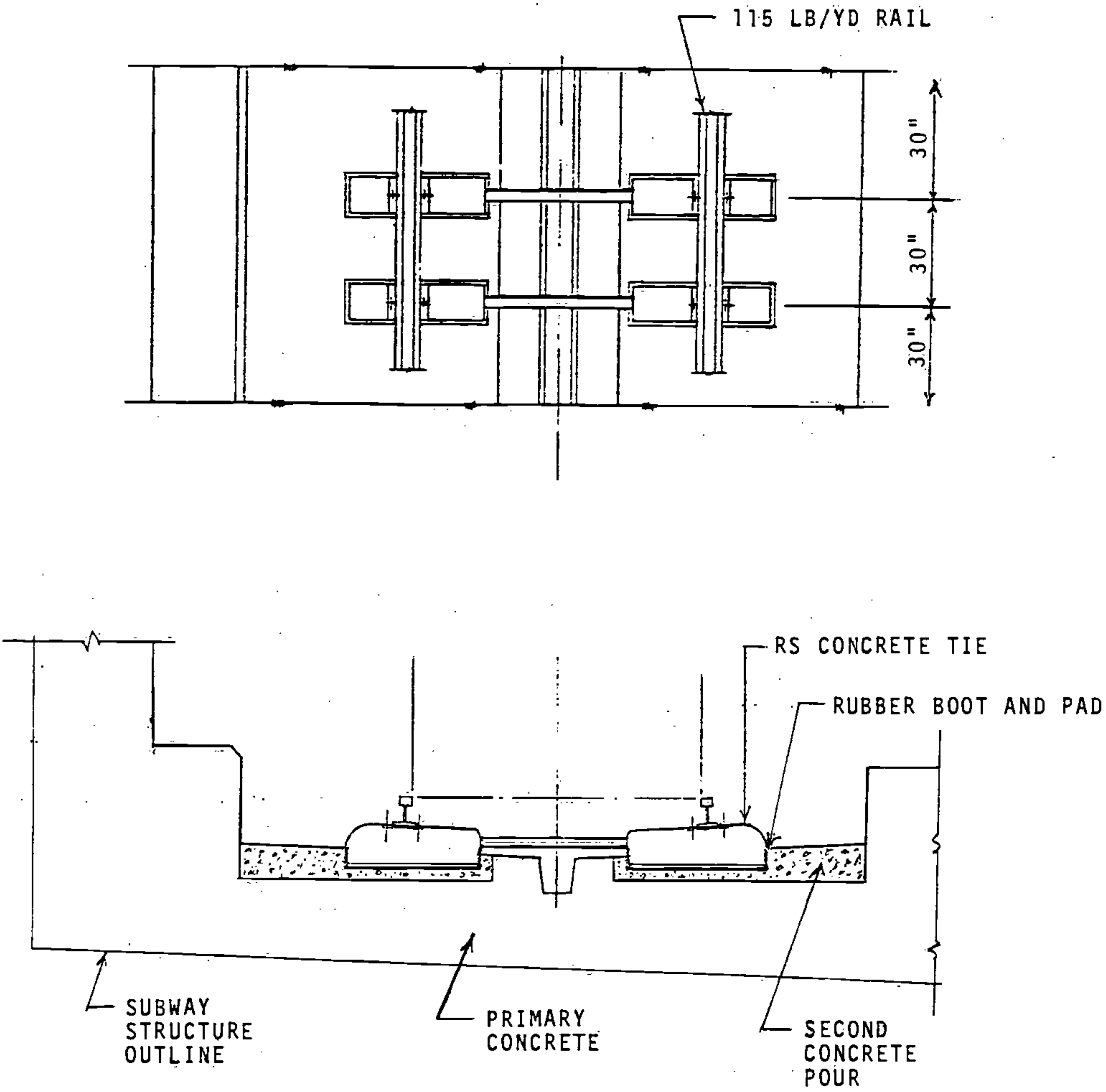

FIGURE 4.5 PLAN AND SECTION VIEW OF THE RS-STEDEF RESILIENTLY SUPPORTED TIE IN A BOX SECTION SUBWAY

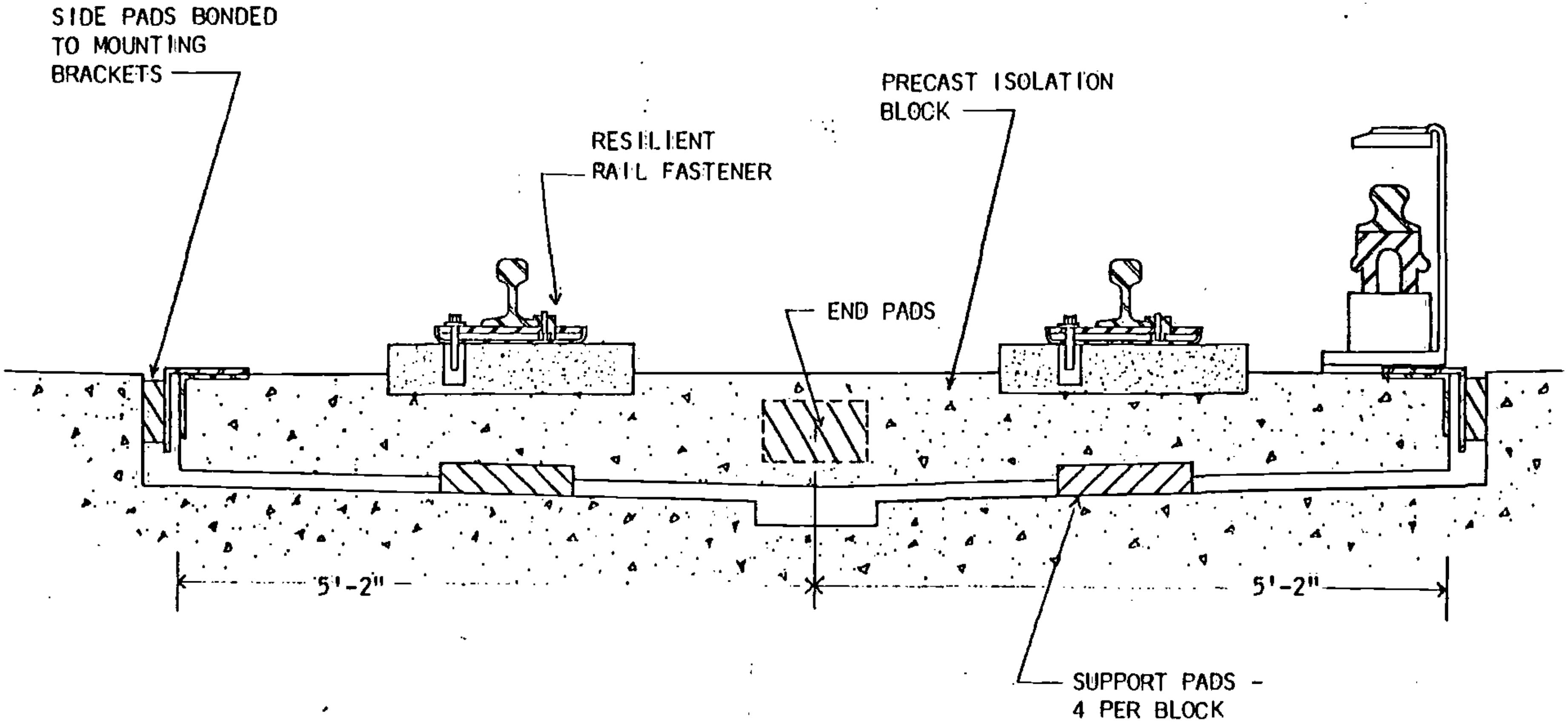

FIGURE 4.6 CROSS-SECTION OF THE DISCONTINUOUS FLOATING SLAB TRACK SUPPORT SYSTEM USED AT THE MARTA SYSTEM

4.2 VIBRATION ISOLATION OF SUBWAY STRUCTURES

At certain locations along the Metro Rail Alignment there are buildings in such close proximity to the subway structure that it will be necessary to consider the use of vibration isolation materials between the subway structure and the building structures in order to prevent direct transmission of noise and vibration from the subway structure to the buildings.

The main factor that must be kept in mind is that in the construction of the subway it is essential that there be no solid or direct transmission path for structure-borne vibration between the subway structure and the building structure. A vibration isolation pad or insert should be placed between the subway structure and the building structure elements in order to break the transmission path for structure-borne vibration and noise.

There are a number of paths by which vibration and noise can be transmitted from a subway structure to a building. These paths include:

1. ground-borne transmission from the subway structure to the piles or platform footings or below the grade sections of the building structure via the earth between the two structures
2. structure-borne transmission from the side walls of the subway to the walls and floors of a building which are directly adjacent to the subway via soldier piles, jack piles or other structural elements placed during construction for support of the excavation or underpinning of the adjacent buildings
3. structure-borne transmission of vibration by connection between building structural elements and the subway structure or any subway appendages such as ventilation shafts, stairways, entrances, etc.
4. transmission of vibration by coupling between building support piles or spread footings and the soldier piles of other piling used for subway construction which are attached to or part of the subway structure and which may be near or in contact with building structural or foundation elements

Providing isolation between the subway structure elements and the building to prevent direct transmission of the noise and vibration requires a resilient element between the two structures either in the form of intervening soil of at least 2 ft thickness or depth, or the provision of an elastomer pad between the subway structure and the building structure.

Review of the feasibility and effectiveness of vibration attenuation through the use of vibration isolation elements or resilient elements between subway structures and building structures indicates that it is not feasible or effective to use large areas of resilient materials between the subway structure and the surrounding earth. However, effective vibration reduction can be obtained through the use of relatively thin, 1" or 2" thick, layers or pads of resilient material placed directly between the subway structure and building support or building structure elements at points where the two are in close proximity or would otherwise be in direct contact. This procedure provides the maximum possible amount of vibration reduction through reducing the vibration that would be transmitted by direct contact or connection.

The amount of vibration reduction that can be achieved by external vibration reduction elements is limited by the levels of ground-borne vibration that are transmitted to the buildings via the soil between other parts of the subway and building structures. It is unnecessary and impractical to consider further vibration reduction features between the subway and building.

The vibration isolation pads need only be capable of achieving similar vibration reduction (at a point that would otherwise be a direct or stiff connection) to that achieved by the other transmission paths such as the soil supporting both structures. Any further vibration and noise reduction must be accomplished by the rail fixation and support system.

In locating vibration reduction elements to be used externally on subway structures, the general criterion which should be used by designers is that the vibration reduction pads are only necessary when the subway structure and any portion of the building are in very close proximity or directly adjacent. In such cases, the design criteria should indicate that the details be arranged to prevent direct or rigid contact between any portion of the subway structure, including piling left in place, and any portion of the building supporting structure.

At any point where vertical building elements or surfaces would otherwise be in contact with the vertical or near vertical wall of the subway structure or soldier piles, a 1" thick resilient pad should be placed between the subway structure and the building elements. At any point where a horizontal or near horizontal element of the building would otherwise be in direct contact with a horizontal or near horizontal portion of the subway structure, a 2" thick resilient pad should be placed between the two structures.

The width or area of the resilient pad should be larger than the building element dimensions along the subway structure in order to provide some overlap for prevention of bridging between the building structure and the subway structure by any rigid material. The resilient material should be a closed-cell expanded neoprene with specific limitations on the dynamic spring rate in shear and in compression to be sure of adequate vibration isolation from use of the material. The static spring rate in compression must, of course, be adequate to support the loadings encountered and the thickness limited to limit the deflection under load to permissible values. Calculations indicate that 1"and 2" thickness of appropriate expanded neoprene give proper support and deflection.

Recommendations on specific locations and configurations of isolation pads (if needed) can be determined once the final design details have been determined.

In handling the closed-cell neoprene, no sharp tools or nails should be used, to avoid penetrations of the expanded neoprene which could cause short-circuiting of the vibration isolation which the material is suppose to provide. A puncture of the material caused by a sharp tool in handling could result in a path for wet concrete to flow into the expanded neoprene and, therefore, make a stiff bridge between the concrete subway structure and a pile. This will completely eliminate the vibration isolation effectiveness of the pad.

Similarly, if the neoprene pads were to be attached to timber lagging or structural members by means of nails there would be a direct rigid contact between the lagging or building structure element and the concrete subway structure. The nail heads would be in contact with the subway structure concrete and the nail shafts would conduct vibration to the lagging and piles and, therefore, to the building. It is, therefore, essential that the neoprene sheets or pads be attached with adhesive and that no mechanical fasteners of any type be used.

4.3 SOUND ABSORPTION TREATMENT IN TUNNELS

The basic design of a subway structure is favorable for the development of high noise levels and transmitting these noise levels from one area to another, such as from tunnels to stations, and from subway to surface via vent shafts. Because surfaces on the interior of the subway are all hard concrete or steel reflecting surfaces, the enclosed space is highly reverberant causing a buildup of sound level. When a ballast and tie trackbed is used this effect is considerably diminished due to the acoustical absorption produced by the ballast layer, however, for the basic type of track fixation recommended herein the trackbed is a hard reflective surface thus eliminating the one source of natural sound absorption in the subway structure.

Because of the desire to minimize patron noise exposure, it is recommended that sound absorption treatment for any subway running tunnels with slab tracks be considered. Sound absorption treatment on tunnel walls can typically result in reduction of car interior noise noise levels by 3 to 5 dBA, a substantial noise reduction which is quite noticeable to system patrons. Investigation of the types of materials which can be applied leads to the conclusion that there are practical absorption materials available which can be installed easily and economically and which will have adequate durability to withstand the subway environment.

An appropriate sound absorption system can provide for reduction of noise heard by patrons in transit vehicles traveling in subway, can provide for reduction of noise caused by transit vehicles as heard by patrons in the stations, and can reduce the noise transmitted from transit vehicles to vent shafts. Thus, the application of sound absorbing materials in the subway structures can result both in improving the environment presented to system patrons, as with sound absorbing materials added to station interiors, and in reduction of one of the forms of noise transmitted to the community areas near the transit system facilities.

The three basic factors to be considered in the design of a subway sound absorption system are (1) the location for placement of the material, (2) the type of material to be used and (3) the extent or area of coverage at each location.

In subway structures the best location for the sound absorbing material is on the trackbed or the lower portions of the side wall surfaces. Application of sound absorbing material at these locations can accomplish both the reduction of reverberation in the subway and, because most noise sources on a transit vehicle are in the space beneath the car, such locations for the sound absorption minimize the reflection of sound and, therefore, optimize the efficiency of the sound absorption material in reducing noise. Placing the sound absorbing material on the trackbed presents problems of maintenance and durability and, therefore, the recommended location for the sound absorbing material is the sidewalls - concentrating on the lower side walls.

The requirements on fire resistance, mechanical durability and cleanability for the sound absorption materials to be used in subways place considerable limitations on the choice of materials, however, there are a number of spray-on mineral fiber materials which have satisfactory properties. The recommended absorption material for use in the subway is spray-on mineral fiber applied at a thickness of 3/4" to 1". This form of material has been demonstrated to give adequate durability and cleanability in existing subway installations and the sound absorption data and calculations indicate that substantial noise reduction can be obtained.

The extent of coverage of the sound absorbing material depends on the degree of noise reduction desired. There are some practical limitations on the maximum amount of noise reduction which can be obtained by the use of sound absorption treatment. Estimates of the noise reduction as a function of total area of coverage indicate that there are some optimum ranges of coverage extent which give the maximum return in terms of noise reduction per sq ft of material installed. There are two general ways in which the materials can be installed:

1. Application of sound absorbing material to the entire length of subway structures which would reduce the car interior noise, the noise on station platforms, and the noise transmitted to vent shafts.

2. If economic considerations prohibit continuous treatment, then relatively short sections of structure at the ends of stations could be treated - an arrangement which will not reduce the in-car noise experienced by patrons but which can provide for maximum noise reduction on station platforms and to vent shafts located near the ends of station platforms.

For a running tunnel the most practical treatment is a spray-on material. There are many types of spray-on materials which are marketed as sound absorption materials. Some of the products are effective as sound absorbing materials and some are not very effective. The special requirements of the subway installation for reasonable mechanical durability, fire resistance, and the ability to withstand waterspray for cleaning, limits the selection of materials even further. None of the materials described as "acoustic plaster" provide satisfactory sound absorption or mechanical properties and, therefore, should not be considered. Some of the materials are mineral fiber and some are cellulose fiber. Because the cellulose fiber materials do not retain the fireproofing chemical treatment they should not be considered.

The mineral fiber materials, Pyrok, Sound Shield "85" and Kilnoise have all been found by the TTC (Toronto Transit Commission) to be acceptable under the requirements of their specifications. The TTC specifications require a Noise Reduction Coefficient, NRC, of 0.50 minimum and indicate that sound absorption material installed on the side walls is to be subjected to semi-annual washing. The washing consists of two passes of a wall washing machine first with a spray of mild detergent and second with rinse spray. The water pressure at the pump is 500 lbs/sq in, the spray nozzle capacity is .94 gpm, and the nozzle is 10" from the material with a spray angle of 57°. The nozzle apparently produces a relatively fine spray so that there is not a great deal of force applied to the sound absorption material.

The area of treatment in the subways depends upon the sound absorption coefficient of the treatment, which is a function of the thickness for a spray-on mineral fiber material. The absorption coefficients achievable with spray-on mineral fiber acoustical materials indicate that for achieving the maximum reasonable noise reduction the use of a 1/2" to 5/8" thick spray-on treatment will require covering the full height of the side walls on both sides of the track. The specifications for any material selected for application should include a minimum sound absorption coefficient at 250, 500 and 1000 Hz in order to ensure the expected results. The application of sound absorption material should be a continuous application along the side walls of the subway structure and should extend from the invert upward. The treatment on the side walls should extend from the invert to a height approximately equivalent to the top of the cars.

The sound absorption treatment in station areas or areas with long continuous platforms should be different than recommended for the running tunnels. Refer to Section 4.6 of this report on station acoustic treatment for information on recommended station acoustic treatment.

If it is decided for economic or other reasons that the running tunnels should not be lined for noise control, then short sections of the tunnels or box structures near the ends of station platforms should be lined in order to reduce the noise transmitted from the untreated tunnels to the station platforms. Calculations of the noise transmission in subways indicate than an application on both sides of the tunnel or box-section for a distance of at least 200 ft (starting at the station platform and extending away from the station 200 ft into each tunnel) is sufficient to prevent transmission of high noise levels to the ends of the station platforms. If there are vent shaft transition sections at the end of the platform, which are directly exposed to the subway, then the walls of the vent shaft transition sections should be included in the acoustic treatment area.

4.4 Fan and Vent Shaft Noise Levels

Transit system facilities or operations which can create noise intrusion or annoyance include fan and vent shafts. At ventilation shafts the train noise transmitted to the surface gratings and then to the surrounding community areas depend on the speed of the transit trains and the presence or absence of sound absorption material in the shafts and in the tunnels near the vent shaft. At fan shafts the main noise is from the fans, but the noise from the transit trains can also transmit through the shafts. It has been found that the attenuation required for the fan noise provides more than adequate attenuation for the transit train noise.

In general, the noise from the fan shafts is dependent upon the number of fans required in the shaft, i.e., the total volume of air to be handled by the shaft. The noise from the subway ventilation fan units is limited by a specification requiring certified maximum sound power levels which is included in the contract documents. This specification of maximum sound power level from the fans determines the maximum noise level which can be expected from operation of fans at each fan shaft in the absence of any attenuation treatment.

In the absence of acoustical treatment in the shafts, both measurements and calculations of the sound transmission through the various configurations of fan and vent shaft show that there will be very little attenuation of the transit train noise or the fan noise as it is transmitted through the ducts to the surface. This is because the shafts are of concrete, which has a negligible sound absorption coefficient, and because the shafts are of large cross-sectional area.

Reduction of the noise from the transit trains and from the ventilation fans can be achieved through: (1) the use of sound absorption treatment applied to the wall and ceiling surfaces of the shafts, and (2) the use of sound attenuators on the ventilation fans. In general, the sound absorption treatment applied to vent shaft walls and ceilings is a 2" to 4" nominal thickness panel material of expanded cellular glass or mineral fiber. The sound absorption coefficient must be at least 0.75 in the middle frequency range (the range included in the 500 Hz and 1000 Hz octaves) where the maximum reduction of noise is needed to control the noise in accordance with the requirements of the design criteria.

At this time the final locations and exact configurations of the fan and vent shafts have not been determined, thus a general discussion follows which indicates the design criteria which will be applied to achieve noise levels which are comparable to or less than the existing typical ambient noise levels and, therefore, will not contribute significantly to the noise environment.

The design criteria for fan and vent shafts is given in Table 7.7.1 of the Design Criteria document and is repeated here for convenience as Table 4.4-1. As with other aspects of the design criteria, the appropriate noise level design goal limit depends on the activities of occupants as well as the background noise in the area. The acceptable levels of noise from vent shafts and fan shafts are different. This is because the noise from a vent shaft is transient in nature while that from a fan shaft is continuous. Transient noises are acceptable at higher levels than continuous noises. Thus the transient noise design goals apply to the train passby noise transmitted from vent shaft openings and the continuous noise design goals apply to the fan noise from fan shaft openings.

TABLE 4.4-1 DESIGN CRITERIA FOR NOISE FROM TRANSIT SYSTEM FAN AND VENT SHAFTS

Community Area Category	Maximum Noise Level, dBA Vent Shaft	 Fan Shaft
I Low Density Residential	50	40
II Average Residential	55	45
III High Density Residential	60	50
IV Commercial	65	55
V Industrial/Highway	75	65

The criteria shall be applied at a distance of 50 ft from the shaft outlet or shall be applied at the setback line of the nearest building or occupied area, whichever is closer.

4.5 Ancillary Facility Noise

As with the location of fan and vent shafts, the final location of ancillary facilities has not been defined at the time of this study, however a general discussion of the noise from ancillary facilities follows. As with the noise from fan and vent shaft openings, the noise from ancillary facilities is subject to the Metro Rail design criteria for maximum permissible noise levels.

Ancillary facilities include such items as power sub-stations, emergency power generation equipment and chiller plants. The criteria for noise from these ancillary facilities is essentially the same as that shown for fan shafts in Table 4.4-1, except that sub-station and emergency power generation noise shall be limited to 5 dBA less sound level than given in Table 4.4-1. This is due to the fact that transformers generate a continuous noise with tonal components which is more obtrusive than sound without a tonal nature.

The specification of a maximum permissible noise level from ancillary facilities is intended to control the level of sound to minimize or eliminate annoyance due to noise from the facilities. The design of each facility is required to incorporate noise reduction features sufficient to achieve the appropriate noise level for the site.

The noise reduction features of typical facilities include sound barrier walls surrounding the noise sources; complete enclosures around the noise sources; sound attenuators on fans, blowers or cooling towers; and the use of sound absorption material, both inside enclosures and on the noise source side of sound barriers.

The net effect of the provisions in the Metro Rail design procedures for reducing noise generated by these facilities is that, regardless of the final location chosen for the ancillary facilities, the noise generated will be compatible with the ambient noise of the surrounding area. In most cases the noise will be comparable to the pre-existing background noise. In some cases the noise will be audible but will not be intrusive nor will it be of a higher level than is appropriate for the nearby land use. The criteria is generally a more severe requirement than is placed on typical residential air conditioning systems and other mechanical equipment found in residential and semi-residential/commercial areas.

4.6 Acoustical Treatment For Sound Control in Stations

4.6.1 Introduction

Rapid transit system stations are often highly reverberant, noisy spaces where patrons are exposed to high levels of train noise. There is a tradition of using acoustically reflective materials, such as concrete or ceramic tile, on all surfaces of train platform areas for durability, abuse resistance, and ease of cleaning. This practice contributes to the high noise level on subway platforms of many existing systems since sound energy from train operations is not dissipated but instead is reflected back into the room each time it impinges on a room boundary.

The primary means of controlling train noise in transit stations is to provide sufficient acoustical absorption treatment on the wall and ceiling surfaces to prevent excessive build-up of reverberant sound energy. The application of acoustical absorption material on the interior surfaces of transit stations and the underplatform areas adjacent to the transit cars substantially reduces noise from transit train operations. In addition, the treatment acts to reduce noise from all other noise sources in stations, such as crowd noise and mechanical equipment noise, and the acoustic treatment results in greatly improved intelligibility of public address system announcements.

All of the recently constructed rail transit subway stations in the United States have incorporated, or will incorporate, sound absorbing material on the station interior surfaces. This includes stations at BART, WMATA Metro, MARTA, Baltimore Region Rapid Transit, NFTA (Buffalo) and new stations added to the TTC facilities. This design results in a much better overall acoustical environment and much lower noise levels from train operations than is found in older systems which have untreated, highly reverberant stations.

For the Metro Rail subway stations the acoustical design criteria require that sound absorbing materials be installed in underplatform areas, train room walls and ceilings, and in enclosed concourse areas such as fare collection areas, stairs, escalators and corridors. Inclusion of these design features in the Metro Rail stations will create an attractive acoustic environment for the transit patrons.

The inclusion of acoustical treatment in enclosed spaces of the stations will accomplish four major purposes.

A. Reduction of noise from transit train operations.

B. Control of general crowd noise.

C. Assistance in the control of noise from station air conditioning equipment and other mechanical equipment.

D. Provision for intelligibility of announcements from the public address systems.

These four basic goals can be used to derive the criteria for the amount, location, and properties for the acoustical treatment. The Noise and Vibration Design Criteria presents criteria for noise levels and amounts of acoustical treatment which will result in a desirable acoustical environment at and around the Metro Rail System. The purpose of this section is to provide a discussion of the acoustical treatment criteria, with specific recommendations on materials and arrangement and placements of acoustical treatment to be considered for accomplishing the design objectives.

4.6.2 Criteria

The Noise and Vibration Design Criteria document presents all of the basic criteria and specifications for the acoustic properties of the Metro Rail stations. This section briefly summarizes the criteria.

The criteria were developed to be consistent with the design goal maximum noise levels presented in Table 4.6.1. The noise levels inside stations are dependent on the design of the transit cars and station mechanical equipment and on the acoustic treatment in stations. The criteria and designs for the acoustic treatment take into account the general architectural characteristics of the Metro Rail stations and the expected noise to be radiated by the transit cars and other noise sources.

Table 4.6.2 summarizes the criteria for reverberation time and acoustic treatment of the various areas of subway stations. Compliance with the criteria for acoustic treatment assures that the reverberation time criteria and the associated noise control will be achieved.

TABLE 4.6.1 DESIGN GOAL MAXIMUM NOISE LEVELS

	Level - dBA
On platform, trains entering and leaving	80
On platform, trains passing through	85
On platform, trains stationary	68

On platform or in mezzanine areas with only station ventilation system and other auxiliaries operating	55
On platforms or other public areas with tunnel ventilation system and/or underplatform exhaust operating at any normal level	55
On platforms or other public areas with tunnel ventilation system operating in emergency status	70
In station attendants' booths or offices	50

TABLE 4.6.2 SUMMARY OF STATION ACOUSTIC CRITERIA

	Areas Exposed to Street Traffic	Enclosed Concourse Areas	Train Rooms
Maximum Reverberation Time (500 Hz)	1.2 to 1.4 sec.	1.2 sec.	1.5 sec.
Maximum Mechanical Equipment Noise	--	55 dBA	55 dBA[1]
Treatment:			
Minimum wall/ceiling area	20-25%	35%[2]	35%[3]
Minimum ceiling only	70-100%	--	--
Treatment Properties:			
Minimum 500 Hz absorption coefficient	0.6	0.6	0.6[3]
Minimum NRC	0.6	0.6	0.6[3]

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[1] 50 dBA maximum in station attendants' booths

[2] Including at least 50% of ceiling area

[3] Underplatform treatment also required - minimum absorption coefficient at 250 Hz = 0.4, at 500 Hz = 0.65 (3" to 4" thick material)

4.6.3 Absorption Treatments for Sound Control - General Discussion

The basic designs of subway stations are very conducive to the development of high noise levels and the efficient transmission of noise from one area to another, for example, along platforms or from platforms to mezzanine areas. This is because interior surfaces of subway structures are generally concrete, steel or other hard surfaces with little ability to absorb sound energy. Without sound absorption treatment the result is high noise levels due to reverberant build-up of sound energy, efficient transmission of sound energy over long distances in the enclosed space and poor speech intelligibility for public address system announcements.

In subway stations, train noise can be controlled with appropriate placement of sound absorbing material. The noise sources on a transit car are primarily located in the confined space beneath the transit cars. Hence, sound absorbing materials on the walls near the undercar space are very effective at absorbing the sound energy and reducing the levels of train noise on the station platform. In effect, such treatment reduces the reverberant build-up of sound energy.

Obtaining maximum benefit from acoustic treatment requires that the material be installed in the proper locations. With appropriate design of the sound absorption treatment, the same material will substantially reduce noise from trains, patrons (crowd noise) and station mechanical equipment along with controlling reverberation time which provides for good speech intelligibility of public address system announcements. However, it is possible through inappropriate placement of treatment to control reverberation without obtaining satisfactory or efficient reduction of train noise.

Figures 4.6.1 and 4.6.2 present examples of the effects of sound absorbing material in subway stations. Figure 4.6.1 shows typical noise levels measured in two TTC subway stations, the first station with sound absorption treatment on the underplatform surfaces only (an insufficient amount to control reverberation), and the second station with sound absorption treatment on the entire ceiling along with the underplatform area. The sound absorption at the ceiling is provided by a suspended acoustical tile ceiling, an arrangement that gives nearly uniform absorption and noise reduction across the frequency range. The range of levels shown in Figure 4.6.1 are the typical maximum levels that occur as trains arrive and depart.

As shown in Figure 4.6.1, the absorption treatment is very effective. the average difference between stations with little absorption and stations with a large amount of absorption is 13 dBA - a sufficient reduction to create a dramatic subjective difference.

Figure 4.6.2 illustrates the effectiveness of underplatform treatment on reducing train noise. Two BART stations are compared; both have ceiling sound absorption treatment and about the same reverberation time, but only one has significant underplatform treatment. The underplatform treatment at the Lake Merritt Station is a complete, continuous layer of 4" thick glasswool covered with sheet plastic. At the time these measurements were taken, the 19th Street Station had almost no acoustical treatment under the platform, only one row of acoustical tile units placed about 2 ft on center. In both stations the acoustical treatment is sufficient to reduce reverberation time to about 1.2 seconds.

Figure 4.6.2 shows that the continuous underplatform treatment in the Lake Merritt Station additionally reduces train noise by 4-5 dBA with an even larger reduction, 5-8 dB, in the middle and low frequencies. This result points out the importance of proper placement of sound absorbing material. Because the train noise largely originates from under the train and is partially confined to the underplatform area, underplatform acoustical treatment is very effective at reducing levels of train noise. In fact, without underplatform treatment it is impossible to obtain the full potential for limiting train noise on the platform. The noise reductions that have been obtained at BART, WMATA Metro and TTC stations are dependent on the use of continuous acoustical treatment in the underplatform areas.

One important point that should be made regarding use of sound absorbing material is the "law of diminishing returns". Intuitively, it is logical to think that if some acoustical absorption material provides good results, more treatment will provide even better results. However, only a limited amount of noise control can be achieved with the application of absorption treatment, and beyond a certain point it becomes very uneconomical to use more absorption material to achieve a given amount of noise control. Beyond that point other noise control procedures must be used. The recommendations in this report and the guidelines in the Criteria Document are designed for efficient use of materials and account for the diminishing returns of excessive sound absorption treatment. The recommended amount of treatment will control reverberation and maximum levels of train noise to the optimum extent achievable with appropriate use of sound absorption material. Further, noise and reverberation control could be achieved by using greater amounts of treatment. However, to obtain significantly or even noticeably greater effect the added treatment required would be substantially greater - more than double the recommended amounts. The small improvement in noise reduction which would be achieved would have only a small effect on the acoustical environment and certainly would not justify the added cost.

Figure 4.6.3 presents comparative noise levels for similar train operations in stations without acoustic treatment and in stations with acoustic treatment comparable to the arrangements recommended herein. Note the large reduction in platform noise levels with the acoustic treatment. Also note the similarity of levels in two acoustically treated stations of very different overall design, BART and WMATA Metro, but with similar acoustical design parameters. Wayside noise tests for identical operating conditions indicate that the BART, WMATA Metro and CTA cars, used in the test of Figure 4.6.3, all produce about the same noise power (source levels) so that the differences on Figure 4.6.3 are primarily due to differences in station acoustics.

4.6.4 Metro Rail Station Acoustical Treatment

This section presents specific guidelines that can be used to design appropriate acoustical treatment for the various enclosed areas of the Metro Rail stations. The Noise and Vibration Design Criteria includes criteria for reverberation time, percent coverage of surfaces by acoustical treatment, and minimum absorption properties of the treatment. The purpose of this section is to relate the Noise and Vibration Design Criteria to the station designs.

The design of absorption treatment for enclosed areas consists of four basic steps:

A. Determine required reverberation times and quantities of absorption

B. Determine locations that will provide maximum control of noise

C. Select appropriate absorption coefficients for the treatment materials

D. Select acoustical materials and design material installations

This section discusses these four steps as they apply to the enclosed areas of the Metro Rail stations.

4.6.4.1 <u>Reverberation Time and Absorption Quantity:</u> As summarized in Table 4.6.2, the acoustical criteria for stations includes maximum reverberation time at 500 Hz, minimum areas for treatment, and minimum absorption properties. Following these general guidelines will result in sufficient absorption to control reverberant noise levels and to provide good speech intelligibility for the PA systems.

Analysis of the underground train rooms indicate that optimum treatment is obtained with a reverberation time of about 1.3 seconds. This reverberation time will provide good speech intelligibility while acting to efficiently control noise. Use of more absorption material to further reduce the noise levels would require large additional amounts of absorption material. The amounts of treatment to reduce reverberation time to 1.3 seconds will reduce the noise by about 9 dB compared to the untreated space. Increasing the amount of acoustical treatment material by 50% (that is, increasing the absorption by 1.5 times) will reduce reverberation time to less than 1 second but will give only about 1.5 dB additional noise level attenuation - clearly an ineffective and uneconomical use of material.

The design goal for reverberation time in the train rooms should be 1.2 to 1.5 seconds, a sufficient range to allow flexibility in the architectural design of the stations.

For enclosed concourse areas such as mezzanine, fare collection areas, and corridors, for appropriate noise control the reverberation time should not exceed 1.2 seconds. The appropriate reverberation time for these areas is lower than for the train rooms because the enclosed volume of these spaces is significantly less than for the train rooms.

In station areas directly connected to the street level and exposed to street traffic, noise control is less critical because of the presence of street noise and the short periods of time patrons normally spend in these areas. As a result, less noise reduction is needed and the design goal for the reverberation time in areas exposed to street noise can be increased to 1.2 to 1.4 seconds.

In the station platform areas the acoustical treatment should be continuous and uniform for the entire length of the enclosed space. Since the train rooms have a relatively constant cross-section, it is most appropriate to define the quantity of treatment in terms of treatment per lineal foot of station platform. From this, it is a simple matter to determine the width of treatment that is required as a function of the absorption coefficient of the material.

The following is an example of this approach which is based on consideration of the volumes, the surface areas and the natural absorption of the finish surfaces of a typical subway station. If the added absorption needed at 500 Hz is 23 units (in sabins (sq ft units) per foot of structure) then the equivalent width of continuous treatment would be:

35 ft for material with an absorption coefficient of 0.65 (at 500 Hz),

29 ft for material with an absorption coefficient of 0.80, and

26 ft for material with an absorption coefficient of 0.90.

This same approach can be used with a combination of materials that have different absorption coefficients.

4.6.4.2 Location of Absorption Material: The location of the sound control material is an important consideration in the architectural design of the stations. The appropriate locations for acoustical treatment in typical subway stations are indicated by Figures 4.6.4 and 4.6.5. The preferred locations for the acoustical treatment are listed in Table 4.6.3, in the order of priority. As indicated above, continuous treatment of the underplatform surfaces is essential for effective control of train noise. It is also very effective to treat the side walls opposite the platform, however except for very large stations, as long as the underplatform areas have continuous treatment, the side wall treatment is not required to obtain good results. Experience with other transit systems has shown that except for very large stations, omitting the side wall treatment has economic and architectural advantages and only minor acoustical disadvantage. Thus, for most stations, satisfactory acoustical results can be achieved without the side wall treatment.

Figures 4.6.4 and 4.6.5 show typical cross-sections of the two general types of subway stations along with recommended locations for acoustical absorption material. The amount of treatment recommended for each typical station type is summarized in Table 4.6.4.

The criteria call for coverage of 35% of the wall and total projected ceiling area with acoustical treatment in addition to the underplatform treatment. For the two typical station types shown it is possible to suitably control reverberation characteristics and noise without placing acoustical treatment on the side walls. For the side platform type station, if the side walls are not treated it will be necessary to include acoustical absorption panels in all of the ceiling coffers. This arrangement will comply with the acoustical design criteria with a small margin of safety. If more than 10% of the coffers are used for light fixtures, the coffer absorption should be supplemented by absorption placed on the sides or lower edges of the coffers or on the side walls. In this analysis it has been assumed that the platform overhang will be 3 ft or more so that treatment can be placed under the overhang providing a total underplatform area of 8 sq ft per foot of station for treatment. If only a small platform overhang is utilized, then the underplatform acoustic treatment can only be applied to the underplatform vertical wall.

TABLE 4.6.3 PRIORITIES FOR LOCATIONS OF SOUND CONTROL TREATMENT

A. Platform Areas - Subway Stations

1. Underplatform overhang surfaces
2. Trainroom ceilings
3. Side walls

B. Mezzanine and Corridor Areas

1. Ceilings - between structural members or directly on the ceiling surface for flat ceilings
2. Walls - using appropriate panel assemblies or direct wall mounted materials

TABLE 4.6.4 ACOUSTICAL TREATMENT FOR TYPICAL SUBWAY STATIONS

Station Type	Location	Acoustical Treatment per ft of Station Structure Available Area*	Required Area*
Center Platform Station	Total	140	35.0
	Underplatform	5	5.0
	Ceiling and Walls	80	30.0
Side Platform Station	Total	160	35.0
	Underplatform	8	8.0
	Ceiling - Coffers	27	27.0
	Coffer bottoms (beams)	12	--
	Walls	22	--

*Since the station cross-sections are relatively uniform, the area for treatment is effectively in terms of the perimeter of the typical cross-sections as shown on Figures 4.6.4 and 4.6.5.

The typical side platform station has a mezzanine level overpass. In the region of the overpass the train room ceiling height increases from approximately 11 ft to 21 ft above platform level. With this increase in cross-sectional area the treatment in the ceiling coffers over the platform and trainway area should be supplemented by sound absorption treatment on other surfaces, either other ceilings or on wall surfaces. The additional treatment could be accomplished by adding acoustical panels to the sloping ceiling sections at the sides, where the ceiling is of greater width and by providing sound absorption panels on the bottom surfaces of the mezzanine and overpass areas to the side of above the platform. Figure 4.6.6 indicates some possible locations for the additional treatment. For optimum control of the train noise in this central area of the side platform station at least 50% of the underside of the overpass and mezzanine floors (exposed to the platform area) should be covered with sound absorption treatment or panels.

In addition to the subway station platforms, acoustical absorption material will be required in all other enclosed spaces that will be occupied by patrons or employees. This includes (but is not limited to) corridors, escalators, mezzanines, entrance areas, and fare collection areas. No acoustical treatment is required in areas with open roofs or walls. The general guidelines are that enclosed areas should have a minimum of 35% of the wall and ceiling projected area covered with acoustical treatment. At least 50% of all ceiling areas should be covered. Entrance areas should have acoustical treatment on a minimum of 25% of the wall and ceiling area. When the enclosed areas have large openings for corridors, escalators, etc., the area of these openings can be counted as treated area.

In enclosed areas of small cross-section, it is best if the acoustical treatment is applied to both the walls and the ceilings. When the sound absorption is located primarily on the horizontal or vertical surfaces, the effectiveness of the absorption material is reduced by the reflections between the untreated parallel surfaces. For example, in rectangular spaces application of absorption material on the ceiling only can sometimes result in noise and reverberation reductions of only 20% to 30% of the expected reduction. This is because full efficiency of the absorption material depends upon good diffusion and uniform distribution of the sound energy. However, generally most of the enclosed spaces in subway stations have a number of openings and obstructions at elevators, escalators, and stairways, which should provide sufficient sound diffusion to compensate for placing all of the material on one surface. If material is to be put on one surface only, it is preferable to place the material on the ceilings, except in the train rooms. The ceiling treatment can be 3/4" to 1" thick sound absorbing material such as acoustical tile, acoustical ceiling board, or other acoustical absorption assembly.

4.6.4.3 Selection of Acoustical Material: Acoustical treatment for transit system stations consist basically of three elements:

1. The sound absorption media or material,
2. a protective covering, and
3. an architectural or trim facing.

For some treatments each of these elements is an individual material and for others the functions are combined. For example, glasswool blankets encased in plastic bags with a perforated or expanded metal covering is one type of treatment with individual materials for each function. Acoustical tile with painted or vinyl facing is an example of treatment with combined functions. Another element which must be considered in the overall design is the fastening or mounting procedure since each type of treatment requires a different fastening system. Finally, the acoustic treatment should be of non-flammable materials to comply with safety criteria.

It should be noted that certain flammable materials are effective for sound absorption, however, other non-flammable materials are available and every effort should be made to use non-flammable materials for the station acoustic treatment. The following discussion includes comments on both flammable materials and non-flammable materials and their effectiveness in order to provide designers with sufficient information to make effective material selections.

For a number of reasons it is advisable that sound absorption treatments with low frequency absorption coefficients of high value be used in transit system station platform and mezzanine areas. This requires that the absorbing media or material be relatively thick, however, it also minimizes the total area of treatment required.

One of the most economical materials for sound absorption treatment is glasswool or glass fiber boards or blankets. Unfortunately, many of these materials are flammable because of the binder used. However, there are varieties of glasswool available that are non-flammable, usually because no binder material at all is used in the specific product. Glass fiber is available in a number of different forms including flexible, semi-rigid and rigid boards (ordinary duct liner for example). Table 4.6.5 indicates the sound absorption coefficients that can be expected for various thicknesses of glass fiber. For acoustical treatment, the recommended density for glass fiber is 2 to 6 lb/cu ft. This density range is assumed in Table 4.6.5. It is often most economical to use multiple layers of 1" thick material for the thicker treatments since 1" thickness is a high volume product, more readily available than single layers of greater thicknesses.

A disadvantage of glass fiber materials, particularly the non-flammable products, is that a protective or retaining covering and facing are generally required. Some other non-flammable materials - such as cellular glass blocks - can be used for some applications with no protective covering or facing.

TABLE 4.6.5 TYPICAL SOUND ABSORPTION COEFFICIENTS TO BE EXPECTED FROM GLASS FIBER SOUND CONTROL MATERIALS MOUNTED DIRECTLY AGAINST A CONCRETE SURFACE

MATERIAL	Sound Absorption Coefficients Frequencies in Hz 125	 250	 500	 1000	 2000
1" thick Glass Fiber	.08	.30	.65	.80	.85
2" thick Glass Fiber	.20	.55	.80	.95	.90
3" thick Glass Fiber	.45	.80	.90	.90	.90

Most transit system structures are all-concrete with the result that they are highly reflective at low frequencies. For this reason it is important that the sound absorption treatment have substantial low frequency absorption. As summarized in Table 4.6.2, the Noise and Vibration Design Criteria Document specifies the minimum sound absorption properties of the acoustical treatment that will be used in the Metro Rail stations. Although 1" thick glass fiber meets these criteria, to insure that there is sufficient low frequency absorption in the station areas it is recommended that the treatment in the subway station platform areas be made up of 2" to 4" thick absorption material. For platform ceilings and mezzanine areas 2" thickness is adequate. Treatment 1" thick will be sufficient in other areas of the stations such as entrances, corridors, etc. For the subway station applications it is necessary to provide a facing and to enclose glass fiber absorption material in a film or wrapping to prevent accumulation of dust and to permit washing of the facing. This type of covering slightly decreases the high frequency absorption and slightly increases the mid and low frequency absorption. The net effect is a slight improvement, compared to the bare material, in reducing the overall levels of train noise.

Since there are fire resistance requirements for the acoustical treatment material, the use of both plastic film for protective covering and glass fiber materials with a resin binder may be prohibited for specific applications. Alternate materials are available. An alternate for plastic film covering which gives good performance against water and dust is close weave glass fiber cloth. Because of surface tension a water spray will generally not penetrate the glass fiber cloth. The Owens-Corning Fiberglas Company provides a fireproof glass fiber material denoted TIW, Thermal Insulating Wool, which has no binder. This is a multi-purpose material for industrial applications at temperatures up to 1000°F and is also denoted M-1000 Insulation for marine application. Since this material does not have a binder, its use requires mechanical retention, for example, a fiberglass cloth bag and metal screen.

For underplatform overhang treatments a recommended material assembly is a 3" to 4" thickness of non-flammable glasswool with an appropriate non-flammable plastic film cover of not more than 4 mils thickness or a glass cloth covering and a facing of expanded metal or hardware cloth. For platform areas and mezzanine ceilings the recommended design is 2" glasswool with appropriate covering and either perforated sheet metal or slit-and-slat configuration facings. Such treatment can be arranged in panels of appropriate size and shape to fit the architectural requirements.

An alternate recommended material for underplatform overhang treatment - a material which does not require a protective covering or facing and which is non-flammable - is the cellular glass block material made by Pittsburgh Corning Company; Geocoustic Blocks. These blocks are an incombustible, low density, cellular glass that is rigid and self-supporting, requiring only a mechanical fastening. The faces of the blocks are slotted to increase the absorption. The 4" thick blocks have good sound absorption characteristics and transit system experience indicates that they require little maintenance when used in areas not accessible to the public. This material generally should not be used in thicknesses less than 2" and should not be used in any location subject to mechanical abuse. The best applications are underplatform overhangs, fan and vent shafts and behind architectural facings.

For areas other than platforms and mezzanines, ordinary acoustical tile or panels of 3/4" or 1" thickness are appropriate. These materials - which may be of compressed glasswool or other appropriate fire resistant cellular material - can be of the type with painted or vinyl facing. Also, as for mezzanine areas, panels of glasswool blankets with perforated metal facing can be used.

4.6.4.4 Recommended Installation Procedures: The recommended acoustical treatment material for the subway station ceilings and walls is the cellular glass block material, such as the Pittsburgh Corning Company Geocoustic Blocks. The material should be of 2" or 4" thickness in platform areas, 2" thickness in mezzanine areas and at other locations. This material is recommended because of the non-flammability and lack of need for a protective film or cloth covering or for mechanical protection in many applications. For economy and acoustical efficiency, the alternate material recommended is glasswool without binder using a glass cloth covering or bag. This material should be of 2 to 6 lb/cu ft density and of 2"to 4" thickness in platform areas, 2" thickness in mezzanine areas and 1" thickness at other locations. Mechanical protection facings of hardware cloth or expanded metal or architectural facings of perforated metal or slit-and-slat panels should be used with this material.

The expected sound absorption coefficients for glass fiber treatments have been given in Table 4.6.5. The numbers given in this table are, in many instances, somewhat less than will be found in the literature. For these materials, the absorption coefficients given in the table are the maximum that can be expected in a normal, practical installation. The absorption coefficients given for laboratory tests are often obtained under very special conditions designed to maximize the absorption coefficient and do not always represent realistic values.

For the underplatform treatment the recommended arrangement is the use of either 3" to 4" thick mechanically retained glass fiber material of 2 to 6 lb/ cu ft density wrapped with close weave glass cloth or 4" thick slotted Geocoustic Blocks. The material should be mounted to give maximum coverage of the underplatform area. At stations with a significant platform overhang, absorption material should be placed on the underside of the overhang surface as well as the vertical wall. The minimum treatment for the underplatform area is a 2.5 ft width of continuous treatment on the vertical wall.

For the underplatform treatment, if glass fiber wrapped in glass cloth is used, the panels should be retained in place using either an expanded metal facing, hardware cloth facing or perforated metal facing For center platform stations the use of expanded metal or hardware cloth is the most economical and is satisfactory since the material is not visible to patrons. For a side platform station where the material is visible to patrons on the opposite platform a better appearance can be obtained through the use of a perforated metal facing.

Wherever perforated metal or slit-and-slat facings are used, the open area should be at least 30% of the total area. With the use of either expanded metal or perforated metal facing the attachment to the underplatform surfaces can be through the use of simple metal brackets. Air space should be provided around the edges to allow free circulation of air to prevent loading of the acoustical material panels due to air pressure transients created by the train movements. Panels with perforated metal or slit-and-slat facings, either for underplatform or ceiling and wall installations, should have a dimpled screen placed between the metal facing and the face of the acoustic blanket to establish an air space of about 1/2" thickness between the perforated facing and the blanket or glass cloth bag. This air space serves two purposes: (1) It allows the sound waves to diffuse over the entire face of the acoustical material, thereby assuring full efficiency as a sound absorber and (2) the air space allows free air flow for pressure equalization to help prevent loading of the facing by air pressure transients, especially if high flow resistance material is used as a cover for the glasswool.

For the ceilings and walls of the train rooms there are a number of treatment configurations available. Table 4.6.6 indicates some of the basic materials. Materials equivalent to the glass fiber products in Table 4.6.6 are marketed by other companies such as the Manville Corporation and Pittsburgh Plate Glass Company and should be given equal consideration. The list is only intended to be representative.

For treatment on flat, continuous surfaces and for platform or mezzanine ceiling areas the use of sectioned or continuous panels consisting of a metal or plastic slit-and-slat system or a perforated metal facing with fiberglass or cellular glass blocks between the facing and the concrete surface is appropriate. However, it should be remembered if a continuous panel system or a suspended acoustical tile ceiling type of system is used, that it is essential that gaps or openings be provided to permit free air flow between the acoustical treatment panels and the concrete surface behind in order to prevent loading of the acoustical panels by the air pressure transient created by train movements. If pressure equalization provisions are not provided, it has been found that in some instances the loading due to the air pressure transients does eventually cause fatigue failure of the fastenings, allowing the panels to come loose from the mounting surface and fall.

TABLE 4.6.6 SOUND ABSORPTION MATERIALS RECOMMENDED FOR CONSIDERATION AS ACOUSTICAL ABSORPTION TREATMENT IN METRO RAIL STATIONS

Material	Approximate Sound Absorption Coefficients with Rigid Backing	
	250 Hz	500 Hz
4" Thick Geocoustic Blocks, 12" x 18" - Slotted:		
Unspaced	1.0	1.06
Spaced 2" in both directions	0.90	1.06
Spaced 6" in both directions	0.60	0.66

4" Thick Geocoustic Blocks, 12" X 18" - Perforated:		
Unspaced	0.79	0.84
Spaced 2" in both directions	0.82	0.94
Spaced 6" in both directions	0.53	0.59
2" Thick Geocoustic Blocks, 12" x18" - Perforated:		
Unspaced	0.79	0.73
Spaced 2" in both directions	0.74	0.71
Spaced 4" in both directions	0.42	0.60
2" Thick Plain Glasswool of 2 to 6 lb/cu ft density wrapped with glass cloth	0.60	0.80
2" Thick Owens-Corning Aeroflex Duct Liner (3 lb/cu ft density) or Type 702 Blanket faced with a vinyl or neoprene coating	0.55	0.80
2" Thick Owens-Corning Glass Cloth Faced Boards backed with Type 703, 704, or 705 Board	0.55	0.85

The last two materials listed in Table 4.6.6 are recommended only for applications where flammable materials are acceptable. Note that several combinations of spaced and unspaced Geocoustic Blocks are listed. The absorption coefficients for the spaced configurations are based on the gross area of the treatment, i.e., the block area plus the area of the spaces between blocks. Use of spaced configurations can result in material economy, however, to avoid loss of low frequency absorption the 4" thick units should be spaced not more than 6" and the 2" thick units not more than 4" apart. For lowest cost and for non-flammability, Geocoustic Blocks should be specified to be unpainted and without surface coating or wrapping.

Some materials, such as vinyl or neoprene coated or glass cloth faced glasswool board, can be painted or are available with appropriate surfaces so that no further facing is required, particularly for a ceiling application. However, the flammability of the material must be considered for each type of application. As discussed above, an alternate arrangement is the use of plain glass fiber boards or blankets wrapped in a close weave glass fiber cloth and faced with a perforated sheet metal, slit-and-slat system, or other facing. With this latter arrangement the facing material must have at least 30% open area to avoid degradation of the sound absorption coefficient.

The recommended covering for any side wall treatment is perforated sheet metal with at least 30% open area. Perforation patterns such as 1/16" diameter holes staggered at 7/64" center, 1/8" diameter holes at 3/16" centers, and 3/16" diameter holes at 5/16" centers provide adequate open area. There are, of course, other combinations of equivalent performance.

The acoustical material applied to the coffer areas could be of a pre-formed perforated metal panel with glass fiber behind. The material can be applied directly against the face of the concrete ceiling. This is similar to the design used for the WMATA Metro system stations and does provide a durable installation with excellent sound absorption characteristics. The minimum thickness of the glass fiber material should be 2".

A basic panel system for ceilings and, possibly, walls, for the mezzanine and corridor areas can be arranged to provide the acoustical absorption very simply. The panel may be of perforated metal, and slit-and-slat configuration of boards or metal or some form of architectural trim which has at least 30% open area and no bars or sections that are greater than 2" width between openings. Such an arrangement will provide for a completely transparent acoustical face. Acoustical material can then be located at 1/2" to 6" distance behind the face and could be cellular glass blocks or non-flammable glasswool of 2" thickness.

For corridors and entrances the sound absorption treatment can consist of wall or ceiling treatment as described above for platforms and mezzanines, or the absorption could be an application of 3/4" to 1" thick acoustical tile, acoustical ceiling board, cellular glass blocks, or sound absorption assembly such as perforated sheet metal with fiberglass blankets behind the sheet metal facing. The absorption coefficient should be at least the value listed in the Noise and Vibration Design Criteria for each type of space, considering the type of mounting used.

For any ancillary spaces two basic types of materials are recommended. For spaces with equipment which radiates relatively low noise levels or in which the noise is intermittent, such as in switchgear rooms or shops, the recommended acoustical treatment is a 1" thick glass fiber application. An alternate could be the use of 3/4" or 1" thick acoustical tile, acoustical ceiling board or painted duct liner board for the absorption material. In spaces with noisy equipment such as fans, pumps and chillers, the acoustical treatment material should be of 2" minimum thickness.

In such spaces the material need not have an architectural trim facing. Application of 2" thick (two layers of 1" thickness) duct liner blanket to the walls and ceiling, perhaps with hardware cloth facing for mechanical protection, gives an economical sound absorption treatment that has appropriate absorption characteristics.

In the ancillary spaces with the higher noise level equipment the treatment area required is 30% of the wall and 50% of the ceiling area and the sound absorption material must be distributed reasonably uniformly over the ceiling in panels or patches and the wall material must be distributed over at least two adjacent walls. That is, the material should *not* be concentrated on one part of the ceiling or concentrated on two opposite walls but rather must be distributed between the ceiling and walls with the wall treatment located to give approximately equal division of area on walls located at right angles to each other.

4.6.5 Summary

The recommendations for the acoustical treatment of stations can be summarized as follows:

A. Sound absorption treatment is required in the underground station platform areas, and in the mezzanine, corridor, and entrance areas for control of reverberation and noise from transit train operations and other noise sources.

B. The sound absorption treatment in the underground platform areas should consist of:

   1. Complete coverage of the underplatform edge horizontal and vertical surfaces with either low density cellular glass blocks of 4" thickness or 3" to 4" thick glasswool panels.

   2. 30% to 40% coverage of the ceiling and side walls of the platform area with 2" thick cellular glass blocks or 2" thick glasswool with glass fiber boards or blankets with appropriate architectural facing. If the treatment is placed on the ceilings only, 60% to 70% of the ceiling should be covered.

C. If glass fiber is used in the underplatform areas, it should be wrapped in close weave glass cloth and should be mechanically retained with hardware cloth or expanded metal facing for protection.

D. Absorption panels for wall and ceiling treatment should be:

   1. Cellular glass blocks behind perforated sheet metal facings or slit-and-slat system facing.

2. Glass fiber blankets that are wrapped in close weave glass cloth or other non-flammable sheeting not to exceed 4 mils thickness and placed behind perforated sheet metal facings or slit-and-slat system facing.

3. For areas where non-flammability is not required, the materials could be either duct liner material sprayed with vinyl or neoprene surfaces and protected with perforated metal or other architectural facing that is acoustically transparent, or a painted, vinyl or glass cloth faced material without other facing.

   The use of ordinary acoustical tile, ceramic tile, or other materials of this nature is not recommended in platform or mezzanine areas because of the lack of low frequency absorption characteristics of these materials.

E. Typical mezzanine, corridors, and other enclosed spaces should have a minimum of 30% coverage of the total wall and ceiling areas. The treatment should be divided between the walls and ceilings such that there is approximately 50% coverage of the ceiling area and no directly opposing set of walls without treatment on at least one of the walls. In areas where it is architecturally necessary and in narrow corridors the treatment can be concentrated on the ceiling covering 70% to 100% of the ceiling.

4.7 Noise Control at Yards and Shops

The activities in a storage and maintenance yard result in noise due to a number of sources, as given in the following listing of the major sources.

Wheel squeal on curves,

Clicks and pings as wheels pass over rail joints and through switches

Train rolling noise,

Transit car auxiliary equipment operation,

Coupling and decoupling of cars,

Train horns,

Workmen shouting, and

Telephone or warning buzzers or horns, announcement or call loudspeakers and noise created by maintenance work.

There are two additional sources of noise that have been encountered in yard operations but that are not included in the above list and they will not occur with the Metro Rail Cars: The sound of brakes squealing and the sound of air release frequently encountered with air brakes or dumping cycles of air compressor and air brake systems. Both of these sources of noise are not present as significant noise sources on modern transit vehicles because of the use of quiet operating brakes and the use of systems which do not require dumping of air in the operating cycle, thus eliminating the characteristic air release sound.

The principal noises which have been found to create annoyance in residential areas near transit system yards are the noise from the transit cars:

(1) The noise from auxiliary equipment on the cars,

(2) The noise from car propulsion systems and the wheel and rail interaction when the cars are moving on the track,

(3) The pings, clicks and bangs which occur as wheels pass through switches and over frogs and joints in the special trackwork included in the yard and,

(4) The wheel squeal which results when the cars move on short radius tracks entering the yard or on the turnaround track.

These sources produce randomly occurring noises which are of considerably different character than typical community background noise and, therefore, if of sufficient level they can be noticeable and intrusive. Most of the noise produced by the transit vehicles themselves is controlled (due to the specification requirements for in-car noise and subway station platform noise) to a level that will avoid impact on adjacent areas unless the separation distance from the yard and the residential or other noise critical area is very small.

All auxiliary equipment on modern transit cars is required to meet a specification of 68 dBA at 15 ft from each individual item. With all equipment operating the maximum allowable noise level is 60 dBA 50 ft from the center of the vehicle. With older vehicles it has been found that air compressors and other items which operate either constantly or cyclicly can typically produced noise levels as high as 75 to 80 dBA at 15 ft from the car. With some vehicles the air release noise has been even greater. The noise limit specifications on auxiliary equipment for the Metro Rail transit vehicles will eliminate these noises as sources of impact in the community near the system yards.

Train speeds in yards are generally limited to the range of 15 to 20 mph maximum so that noise from the trains rolling is generally a maximum of 70 dBA at 50 ft and usually is considerably less - in the range of 60 to 65 dBA at 50 ft. Because of the noise limit specifications on vehicle auxiliary and propulsion equipment and because of low speeds of operation in yards, the general rolling noise due to train operations does not result in any impact in adjacent communities and is comparable with and compatible with typical community background noise.

For this first phase of the Metro Rail Project, there will be only the main yard and shops near the Union Station, with only minor storage facilities near the North Hollywood Station at the other end of the line. The main yard and shops will be located in an industrial area near the Santa Ana Freeway and Santa Fe Railroad freight yard. Thus there is already a high ambient noise level existing in the area with no nearby residential or critical noise receptors. For these reasons no special noise control features will be necessary to reduce the noise levels from yard activities.

In order to create a pleasant working environment for yard personnel and ensure that the California Standards for Occupational Noise Exposure are not violated under the worst conditions, it is recommended that sound absorbing materials be added to the ceiling and wall areas of the main work areas, including he heavy repair shop, service and inspection shop, wheel shop, general repair area and automotive repair area.

Location of an efficient sound absorbing material on the walls and ceiling will help control the reverberant build-up of sound within the space and will help minimize the direct reflections of noise produced by the various activities in the shops. Between 50% and 75% of the ceiling area and 50% of the wall area should be treated with a material having a minimum NRC (Noise Reduction Coefficient) of 0.95. Specific materials can be determine during final design once the final configuration of the main yard and shops have been determined.

Chapter 5

ESTIMATE OF NOISE AND VIBRATION LEVELS FROM TRANSIT TRAIN OPERATIONS

5. ESTIMATE OF NOISE AND VIBRATION LEVELS FROM TRANSIT TRAIN OPERATIONS

5.1 Introduction

Underground operations of rail rapid transit systems do result in ground-borne vibration and noise which is transmitted from the subway structure to adjacent buildings via the intervening geologic strata. The ground-borne vibration originates at the wheel/rail interface and is due to vibration and noise generated by the wheels rolling on the rails. The level of this vibration at the source is influenced by the degree of roughness or smoothness of the wheels and rails, the speed of the train, and by the type of subway structure and geologic strata in which the structure is founded.

The vibration which can be perceived from the operation of transit trains in subway is generally perceived as a low pitched rumbling noise radiated inside nearby buildings due to the vibration of the building structure induced by the ground-borne vibration and noise. The vibration may also be perceptible as mechanical motion, although the usual sensation, if perceived, is that of a low frequency rumbling noise.

It should be noted that the vibration is of such a low level that there is no possibility or potential for structural damage due to the ground-borne vibration transmitted to buildings near the subways. It should also be noted that trains operating on aerial structure if an aerial structure alignment is ever implemented in the future will produce vibration levels which will be low enough in level that they will not be felt by nearby occupants of buildings. This is due primarily to the fact that the airborne noise from trains traveling on aerial structure generally overpowers the perception of ground-borne noise and vibration if there is a perception of the train passby.

The transmission of the ground-borne vibration and noise to buildings near the subway structure is affected by a number of factors, primarily the type of intervening strata between the subway and building, i.e., rock or soil, and by the type of building and building foundations. In general it has been found that the various factors can be generalized to reduce the number of variables sufficiently to define classes of situations where the noise can be predicted with a reasonable degree of confidence.

For the distances over which ground-borne vibration from transit trains is of concern, the small variations in soil or rock strata (which can have an influence in vibration transmitted over long distances) are insignificant. Therefore, the only significant factor with regard to the strata, as far as transit system ground-borne vibration is concerned, is whether the founding and intervening media are rock or earth. Buildings near a subway structure can be classified either as small, lightweight buildings - such as one- or two-story brick or frame single family dwellings or small commercial buildings and large, masonry buildings - such as multi-story office, commercial, hotel or apartment buildings. There is a gray area between the two categories, however, most buildings can be assumed to be within one of the two categories. Using these simplifications and the considerable amount of data from the TTC facilities and some data from the BART, WMATA Metro and MARTA facilities, as well as some limited propagation data obtained near the proposed Metro Rail alignment, it is possible to derive expected ground-borne vibration levels in the occupied spaces of buildings near the subway structures.

There is a considerable amount of background information available which permits prediction of the noise levels to be expected from ground-borne vibration due to transit trains. The measurements which have been accomplished at TTC, BART, WMATA Metro and MARTA facilities provide a relatively well founded empirical basis for determining the expected noise levels. The measurements have included evaluations with different types of subway structures and with different types of founding and intervening geologic strata, including rock and soil. Data for both types of configurations have been obtained at the TTC and WMATA Metro facilities. The data provide a basis for evaluation and verification of theoretical estimates of the difference between ground-borne vibration from earth founded and rock founded subways.

The evaluations of subway operations have also included the determination of the effects of resilient rail fasteners, resiliently supported ties and floating slab trackbeds for reduction of ground-borne vibration as discussed in detail in Chapter 4. These evaluations have shown that resiliently supported ties generally reduce the ground-borne noise and vibration by 6 to 10 dB, while floating slab trackbeds can reduce the ground-borne noise and vibration by as much as 15 to 20 dB. These reductions are relative to the ground-borne noise and vibration that transit trains produce when operating on direct fixation resilient rail fasteners which already reduce the ground-borne noise and vibration a significant amount over the direct fastening systems which have been used on older systems. The reduction of ground-borne noise and vibration attributable to these special design features occurs in the frequency range where rumbling noise is most predominant and audible in the buildings near the subway structure.

5.2 Expected Noise and Vibration Levels

As previously indicated the Metro Rail System has adopted strict design criteria for ground-borne noise and vibration (Section 7.4.2 and 7.4.3 of the "Noise and Vibration Design Criteria for the Metro Rail Project" included as Chapter 3 of this report). Estimates of the expected ground-borne noise levels from the operations of Metro Rail trains were included in our report, "Noise and Vibration Study - Alternative Route Alignments for the Metro Rail Project," dated November 1982. This analysis indicated the estimated ground-borne noise levels in all of the nearby structures and showed a comparison of the expected performance for three methods of track fixation (resilient direct fixation fasteners, resiliently supported ties and floating slab trackbeds) with the appropriate criterion. These comparisons provide a means for determining those areas where special design features (i.e. resiliently supported ties and floating slab trackbeds) are needed to reduce the noise and vibration to levels below those for the standard design facilities.

Since those ground-borne noise predictions were made, a final route has been adopted. Although many of the ground-borne predictions made at that time are still accurate, some may no longer be accurate due to even a slight change in the alignment plan, profile, vehicle speed or vehicle type. The final configuration of these parameters will be developed during final design at which time new ground-borne noise predictions will be made in order to determine the exact location and extent of each track fixation type.

Review of the expected levels calculated during our earlier analysis indicates that resiliently supported ties or floating slab trackbeds should be used to reduce the levels of ground-borne noise in buildings adjacent to the subway alignment along significant portions of the route. In addition that analysis indicated that there are several locations where the use of resiliently supported ties or floating slab trackbeds will not reduce the ground-borne noise from transit train operations to acceptable levels when compared with the appropriate criterion for the particular building use. The somewhat higher noise levels expected in these buildings are due primarily to a very shallow tunnel (depth to top-of-rail of 30 to 40 ft) and/or to the presence of a crossover in the tunnel which raises the expected noise level on the order of 10 decibels. These locations will be reanalyzed during final design to determine specific measures which will further reduce the ground-borne noise. These include such measures as minor alignment relocation, crossover relocation, subway structure modification, train speed modification and non-standard (heavier weight) floating slabs.

During final design all residential buildings adjacent to the alignment will be re-examined in detail to determine what, if any, mitigation measures will be needed to ensure that the ground-borne noise from transit train operations will not exceed the limits set by the appropriate criterion. In addition Table 5.1 indicates particular buildings among others which will be re-examined during final design in the same manner as the residential buildings.

TABLE 5.1 PARTICULAR BUILDINGS TO BE RE-EXAMINED DURING FINAL DESIGN - WITH GENERAL LOCATION BETWEEN TRANSIT STATIONS

Transit Station	Building
Union	
Civic Center	County Court House Law Library
5th/Hill	Pershing Square Theater Building Clark Hotel Wilshire Grand Building Parson's Building Hyatt Regency Hotel Central Bank Building
7th/Flower	Roosevelt Building Barker Brothers Building Global Marine Building Hilton Hotel Travelodge Motel Mid-Wilshire Convalescent Hospital
Wilshire/Alvarado	Otis/Parsons Art Gallery Sheraton West Hotel
Wilshire/Vermont	Southland University Building Gaylord Hotel IBM Building Atlantic Richfield Building Wilshire Christian Church
Wilshire/Normandie	Wilshire-Hyatt Hotel St. Basil Roman Catholic Church Wilshire Boulevard Temple Ahmanson Center
Wilshire/Western	McKinley Building Wiltern Theatre Union Bank Building Pierce National Life Insurance Building Christ Church Wilshire Professional Building St. James Episcopal Church & School Theatre of Arts

TABLE 5.1 (continued)

Transit Station	Building
Wilshire/Crenshaw	Swett & Crawford Group Building Wilshire Dunes Motel Scottish Rite Temple Wilshire United Methodist Church Farmers Insurance Building Leona School Burroughs Jr. High School
Wilshire/La Brea	Mutual of Omaha Building El Rey Theater Museum Square Buildings
Wilshire/Fairfax	Los Angeles County Art Museum Guardian Convalescent Hospital Hancock Park School Farmer's Daughter Motel
Fairfax/Beverly Station	CBS Television City Great Western Savings Fairfax High School King Solomon Home for the Elderly Country Villa Convalescent Hospital Garden of Palms Rest Home
Fairfax/Santa Monica	Fairfax Tower Elderly Housing St. Ambrose School Motel
La Brea/Sunset	KRLA Television Building Motel Hollywood High School Blessed Sacrament School
Hollywood/Cahuenga Hollywood Bowl	Hollywood Pacific Theater
Universal City	Campo de Cahuenga Recording Studios on Lankershim St. Charles Borromeo Church Guild Theatre El Portal Theater
North Hollywood	

Chapter 6

CONSTRUCTION NOISE AND VIBRATION

6. CONSTRUCTION NOISE AND VIBRATION

6.1 INTRODUCTION

One of the impacts associated with a rail rapid transit system project is the short-term noise and vibration impact of construction activities. As with any large project, the construction of a rapid transit system involves the use of machines and procedures which, in the past, have resulted in intense noise levels and, occasionally, high vibration levels in and around the construction site. The Metro Rail system way structures will be primarily subway. Construction activities will include demolition, clearing, grading, excavating, pile driving, drilling, materials handling and placement, erection and finish work, and will involve the use of all of the various kinds of machines and procedures which are associated with these activities. It is also possible that blasting will be used for excavation and tunneling in rock.

In recent years considerable progress has been made in the reduction and control of construction noise through modifications of the equipment to reduce noise generated at the source, through modifications of construction procedures and by selection of those construction procedure alternates which are less noisy. Also, in many areas and for many types of construction projects there have been noise limits or noise standards included in the construction contracts or applied by governmental agencies in order to limit the noise impact from the construction. These efforts at reducing construction noise have produced considerable success. With new construction projects the work can be and is accomplished with considerably less noise impact than is traditionally expected.

For subway construction the acoustical impacts can be of two different characters. In the areas where tunneling is used the only impact due to the construction activities (except at access shafts) will be the ground-borne vibration due to the excavation process, either the tunnel boring machine or blasting. Also, there may be some ground-borne vibration due to the vehicles used to remove material. For cut-and-cover subway and station construction there will be impacts due to ground clearing, excavation, erection and finishing activities.

6.2 Construction Equipment Noise Levels

There is considerable information available on the typical noise levels created by modern construction equipment and there is a growing body of information on lower noise levels which can be achieved with modified equipment or equipment which is designed with noise reduction and control as one of the design parameters.

Measurements made at transit system construction project sites provide the best information relative to expected noise levels from the type of construction activities which are associated with the Metro Rail system. Table 6-1 presents a series of noise levels observed for various types of machines and activities associated with the WMATA Metro and MARTA construction projects. These data are for construction activities using standard present day equipment with little or no noise control or noise reduction modifications to the equipment. The WMATA Metro data were obtained before noise restrictions and limits had been applied to the construction activities on the Metro project.

Typical noise levels at construction sites, as indicated by Table 6-1, do result in substantial acoustic impact on neighboring communities and in new and future projects most of these noise levels are considered unacceptable. There are many techniques available for reducing the noise, some of which involve little or no cost and some of which involve considerable cost. In some instances modifications of procedures or use of different procedures and equipment can result in much lower noise levels and impact. For the Metro Rail project, a very effective procedure will be to include noise limit specifications in the construction contracts in order to reduce or limit acoustic impact due to construction activities.

6.3 Ground-Borne Noise and Vibration from Construction

Because of the nature of some construction activities, high amplitudes of ground-borne vibration may result in some impact in neighboring community areas. Blasting and impact pile driving are two types of activities traditionally associated with high levels of ground-borne vibration. It is also possible that some types of heavy vehicles and excavation activities can generate sufficient ground-borne vibration levels to be perceptible or noticeable in nearby buildings.

The vibration levels created by the normal movement of vehicles including graders, loaders, dozers, scrapers and trucks generally are of the same order of magnitude as the ground-borne vibration created by heavy vehicles running on streets and highways. Large trucks and buses operating on city streets and on highways generate ground-borne vibration due to wheel/roadway interaction and particularly high vibration levels can be associated with truck and bus operations on rough or pock-marked streets. In general, the ground-borne vibration from vehicle operations on streets, even very rough streets, is not sufficient to create noticeable impact on adjacent community areas. This vibration is of a level that is generally imperceptible or barely perceptible and is considered acceptable, producing little or no impact. Thus, it can be expected that the normal vehicle activities at the construction sites will not generate sufficient ground-borne vibration to result in significant impact.

Blasting, drilling and excavation procedures for the short segments of cut-and-cover subway and stations can result in ground-borne vibration levels which are perceptible or noticeable in adjacent community areas. The amplitudes of vibration from such activities are limited for safety reasons by procedural techniques. For example, through the use of time delay charges in blasting the maximum amplitude of the ground-borne vibration is limited to a level well below the criteria for structural damage to adjacent facilities. Impact pile drivers, which create considerable noise and vibration, also produce vibration levels which are well below the intensity required for structural damage to adjacent buildings and other facilities.

In conjunction with rock blasting, rock drilling is the standard method of inserting the blast charge. Drilling can also be a technique which can be used during excavation of small areas of hard rock. The projected vibration levels from rock drilling are shown in Figure 6-1 along with some additional structural and human response criteria.

The possibility of noise intrusion from rock drilling would be to people inside nearby buildings, similar to the possible noise intrusion from operations of transit trains in subway. During drilling it is likely that the ground-borne noise may be audible and may be noticeable to people in buildings with a low level of background noise.

The relative noise and vibration impact or intrusion during drilling should be minor at most since the time of drilling in close proximity to any single building will be very short, a few days at most.

Pertinent criteria for maximum noise and vibration due to blasting has been developed and are contained in Sections 7.12.4 and 7.12.5 of the Noise and Vibration Design Criteria Document and are based on the results of measurements and subjective evaluations at construction sites around the world. Noise and vibration levels from blasting are dependent on the charge size and location. Thus the noise and vibration levels can cover a wide range depending on the procedures of the contractor.

The contractor must locate the charges and gauge the size of the charge in order to meet the criteria. Figure 6-1 indicates the typical vertical velocity level expected at approximately 200 ft from a blast if the vibration and noise criteria are not exceeded.

The possibility of noise and vibration intrusion during blasting will be minimized if the criteria are not exceeded and because the proximity of blasting near any single building will be very short and only during the blast itself.

Tunnel boring machines also create ground-borne vibration and noise, however, experience to date indicates that the vibration from the use of such machines is considerably less in intensity than that from blasting or pile driving and that it is not significantly greater than the vibration created by heavy trucks traveling on city streets.

The probable method of excavation for most of the subway will be with the use of a tunnel boring machine (TBM). As indicated above, with the use of a TBM the potential noise and vibration impact is considerably lower than if traditional blasting techniques are used. As for transit trains operating in subway, the possibility of noise and vibration impact from the operation of a TBM is to occupants inside buildings adjacent to the new subway alignment. Outside of a building, there is no possibility of noise or vibration impact from TBM operation.

Use of a TBM will create vibration levels which are generally imperceptible at distances greater than 75 to 100 ft from the operating TBM. Even at a distance of 50 ft, the operation of the TBM will create vibration levels which are just perceptible. The projected vibration levels from the operation of a TBM along the proposed alignment are shown in Figure 6-2 at a near distance and two further distances. The latter two distances correspond to a tunnel depth of approximately 35 ft and 125 ft with the nearest building being approximately 100 ft horizontal distance from the alignment. These data are based on a series of vibration measurements made by WIA in 1980 in Buffalo, New York, during the tunnel boring operations for construction of the NFTA light rail transit system. Although the TBM was operating in hard rock, we have projected the probable vibration levels for the type of soil which will be encountered along the Metro Rail alignment.

Figure 6-2 also shows the response of persons seated or standing to building vibration to allow for a comparison of the vibration levels which will be produced by the TBM with the typical human perception of vibration. The response of persons seated or standing is the same information presented in Figure 2.4-1 in Chapter 2 of this Final Report.

As previously stated, the possibility of noise impact from the TBM will be to occupants inside of buildings, similar to the possible noise impact from operations of transit trains in subway. For deep tunnel locations (approximately 125 ft below grade), the ground-borne noise from the TBM should be unnoticeable in buildings which are 100 ft or more in horizontal distance from the alignment. If the tunnel is approximately 35 ft below grade, then there is some possibility that the ground-borne noise would be noticed by building occupants at buildings which are approximately 100 ft in horizontal distance from the alignment. The relative noise levels would depend on the type of building structure, and type of activities in the building. However, the ground-borne noise and vibration from the tunnel boring machines is of very short duration since the machine passes by an area in, at most, a few days, so that there should be no significant impact.

6.4 Construction Noise Specifications

There are numerous procedures available for reducing the noise generated by construction equipment and activities. One of the most effective methods of assuring controlled noise and minimum acoustical impact is the inclusion of noise limit specifications in the construction contract documents. Recent construction projects of the New York City Transit Authority, the WMATA Metro, MARTA and NFTA systems have included noise restrictions in the contract specifications. The experience with these noise limit specifications and with the contractors working with the requirements is that considerable success in the reduction of construction noise has been realized.

For each design section of the Metro Rail system the construction contracts will include a section on permissible noise limits. In many instances noise standards or limitations applied to construction or other noisy type activities have been based on average conditions in a community or, alternatively, on the most severe or critical conditions. The noise limit law or standard has then been written with one set of restrictions which apply to every area. This procedure is not consistent with best economy or best benefit to the community. In many instances this results in either excessive noise in quiet residential areas or excessive cost for noise reduction in commercial or industrial areas where there is no benefit to be gained from the noise reduction. The noise limitation specifications for the Metro Rail project will be based on the character of development and land use in each area where construction is to be accomplished. Thus, the noise limits applied will be consistent with the type of community area in which the construction takes place.

Table 6-2 indicates construction noise and vibration level limitations from the Metro Rail project design criteria Section 7.11 which is repeated here for convenience. This provides an indication of the degree of noise impact expected from the Metro Rail system construction activities.

TABLE 6-1 TYPICAL NOISE LEVELS OBSERVED AT RAIL TRANSIT SYSTEM CONSTRUCTION PROJECTS

Equipment or Process	Normalized Noise Levels @ 50 ft
Air Hammer Cutting concrete	85-90 dBA
Crane & Pile Drilling Rig	
Moving Drill	90
Emptying Auger	86
Idling	82
Drilling	83-88
Placing Pile	74
Setting Pile	88
Concrete Mix Truck Placing Concrete	81-85
Diesel Hammer Pile Driver	90-100
Compressor	77-84
Hydraulic Cranes	82-84
Derrick Crane	88
Tamper	88
Scraper	88
Rock Drill	94-98
Trucks	85-91
Paver	89
Crawler Tractor (Dozer)	88-92
Vibratory Compactor	81-84

TABLE 6-2 NOISE AND VIBRATION LEVEL RESTRICTIONS

I. NOISE LEVEL RESTRICTIONS

A. NOISE LEVEL RESTRICTIONS IN ALL AREAS

In no case expose the public to construction noise levels exceeding 90 dBA (slow) or to impulsive noise levels with a peak sound pressure level exceeding 140 dB as measured on an impulse sound level meter or 125 dBC maximum transient level as measured on a general purpose sound level meter on "fast" meter response.

B. NOISE LEVEL RESTRICTIONS AT AFFECTED STRUCTURES

Conduct construction activities in such a manner that the noise levels 200 feet from the Construction Limits or at the nearest affected building, whichever is closer, do not exceed the levels listed in the following schedules:

1. Continuous Noise: Prevent noises from stationary sources, parked mobile sources or any source or combination of sources producing repetitive or long-term noise lasting more than a few hours from exceeding the following limits.

LIMITS FOR CONTINUOUS CONSTRUCTION NOISE

Affected Structure or Area	Maximum Allowable Continuous Noise Level, dBA	
Residential	Daytime	Nighttime
single family residence	60	50
along an arterial or in multi-family residential areas, including hospitals	65	55
in semi-residential/commercial areas, including hotels	70	60
Commercial	At All Times	
in semi-residential/commercial areas, including schools	70	
in commercial areas with no nighttime residency	75	
Industrial		
all locations	80	

2. Intermittent Noise: Prevent noises from non-stationary mobile equipment operated by a driver or from any source of non-scheduled, intermittent, non-repetitive, short-term noises not lasting more than a few hours from exceeding the following limits.

LIMITS FOR INTERMITTENT CONSTRUCTION NOISE

Affected Structure or Area	Maximum Allowable Intermittent Noise Level, dBA	
Residential	Daytime	Nighttime
Single family residence areas	75	60
along an arterial or in multi-family residential areas, including hospitals	80	65
in semi-residential/commercial areas, including hotels	85	70
Commercial	At All Times	
in semi-residential/commercial areas, including schools	85	
in commercial areas with no nighttime residency	85	
Industrial		
all locations	90	

C. SPECIAL ZONE OR SPECIAL CONSTRUCTION SITE

In areas outside of Construction Limits but for which the Contractor has obtained designation as a Special Zone or Special Construction Site from the agency having jurisdiction, the noise limitations for buildings in industrial areas apply.

In zones designated by the local agency having jurisdiction as a special zone or special premise or special facilities, such as hospital zones, the noise level and working time restrictions imposed by the agency shall apply. These zones and work hour restrictions shall be obtained by the Contractor from the local agency.

D. MORE THAN ONE LIMIT APPLICABLE

Where more than one noise limit is applicable, use the more restrictive requirement for determining compliance.

E. NOISE EMISSION RESTRICTIONS

Use only equipment meeting the noise emission limits listed below, as measured at a distance of 50 feet from the equipment in substantial conformity with the provisions of the latest revisions of SAE J366b, SAE J88, and SAE J952b (Refs. 7, 8, 9) or in accordance with the measurement procedures specified herein.

NOISE EMISSION LIMITS ON CONSTRUCTION NOISE

TYPE OF EQUIPMENT	MAXIMUM NOISE LIMIT	
	Date Equipment Acquired	
	Before 1-1-1983	On or After 1-1-1983
All equipment other than highway trucks; including hand tools and heavy equipment	90 dBA	85 dBA
	Date Equipment Acquired	
	Before 1-1-1983	On or After 1-1-1983
Highway trucks in any operating mode or location	83 dBA	80 dBA

Peak levels due to impact pile drivers may exceed the above noise emission limits by 10 dBA.

II. VIBRATION LEVEL RESTRICTIONS

A. Vibration Limits in All Areas: Conduct construction activities in such a manner that vibration levels at a distance of 200 ft from the Construction Limits or at the nearest affected building, whichever is closer, do not exceed root-mean-square (rms) vibration velocity levels of 0.01 inches per second in any direction over the frequency range of 1 to 100 Hz.

B. Special Zones: In zones designated by the local agency having jurisdiction as a special zone or special premise or special facilities, the vibration level and working time restrictions imposed by the agency shall apply. These zones and work hour restrictions shall be obtained by the Contractor from the local agency.

III. NOISE AND VIBRATION CONTROL REQUIREMENTS

Notwithstanding the specific noise and vibration level limitations specified herein, utilize the noise and vibration control measures listed below to minimize to the greatest extent feasible the noise and vibration levels in all areas outside the Construction Limits.

- Utilize shields, impervious fences or other physical sound barriers to inhibit transmission of noise.

- Utilize sound retardant housings or enclosures around noise producing equipment.

- Utilize effective intake and exhaust mufflers on internal combustion engines and compressors.

- Line or cover hoppers, storage bins and chutes with sound deadening material.

- Do not use air or gasoline driven saws.

- Conduct truck loading, unloading and hauling operations so that noise and vibration is kept to a minimum.

- Route construction equipment and vehicles carrying spoil, concrete or other materials over streets and routes that will cause the least disturbance to residents in the vicinity of the work. Advise the Engineer in writing of the proposed haul routes prior to securing a permit from the local government.

- Site stationary equipment to minimize noise and vibration impact on the community, subject to approval of the Engineer.

- Use vibratory pile drivers or augering for setting piles in lieu of impact pile drivers. If impact pile drivers must be used, their use is restricted to the hours from 8:00 a.m. to 5:00 p.m. weekdays in residential and in semi-residential/commercial areas.

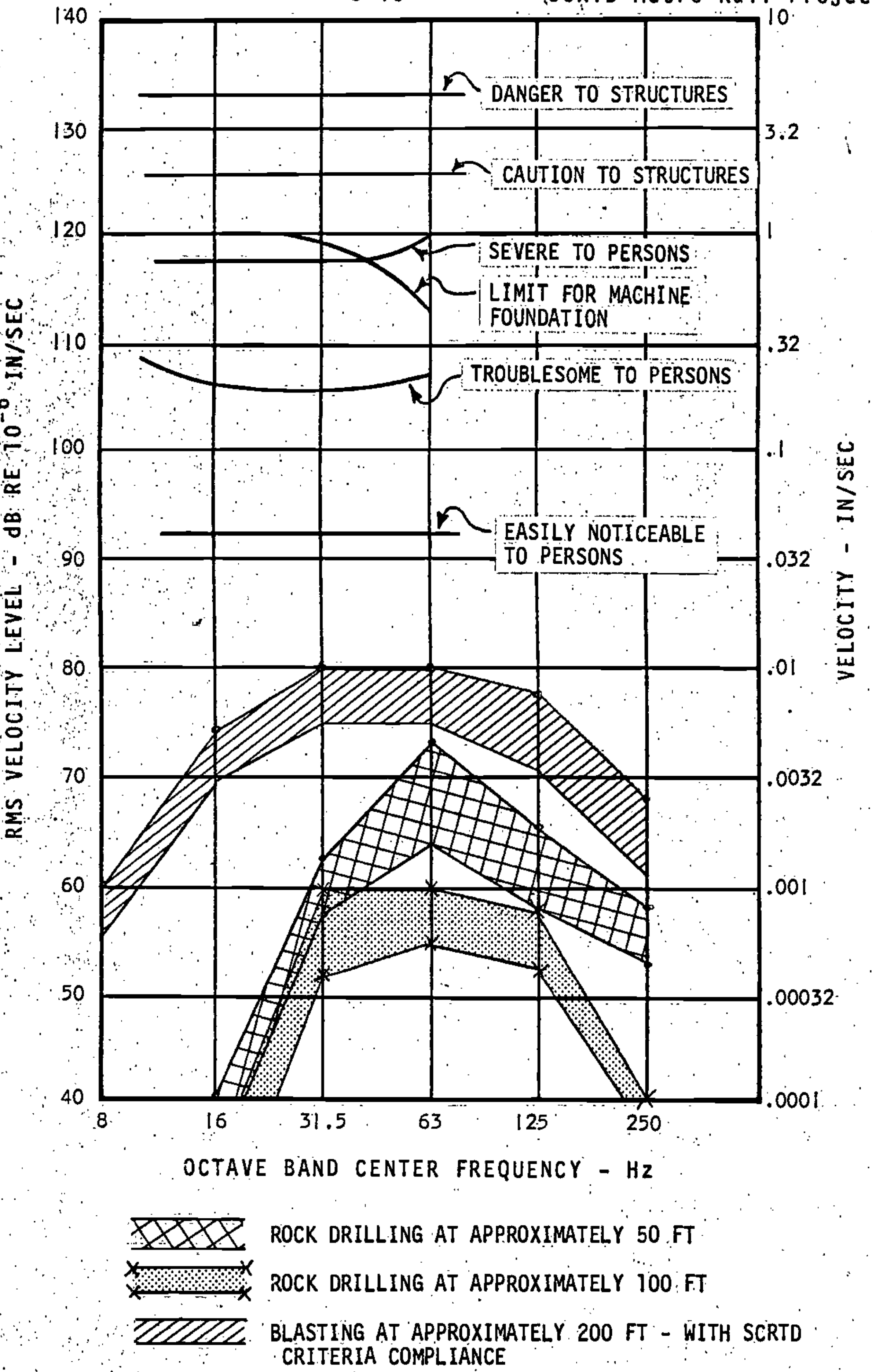

FIGURE 6-1 EXPECTED VIBRATION LEVELS DUE TO ROCK DRILLING AND BLASTING

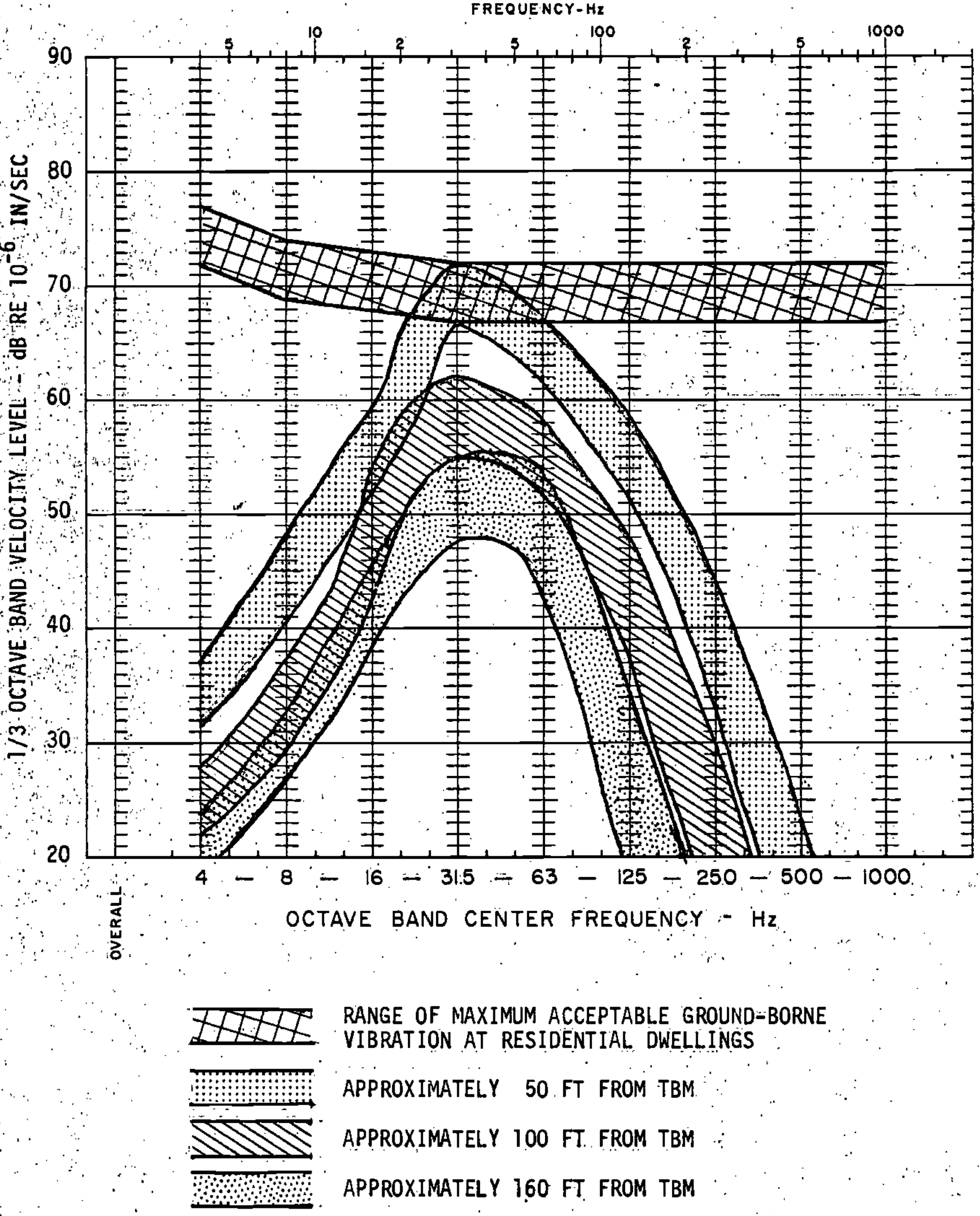

FIGURE 6-2 EXPECTED GROUND-BORNE VIBRATION VELOCITY LEVELS FROM OPERATION OF A TUNNEL BORING MACHINE

Chapter 7

PRESSURE TRANSIENTS

7. PRESSURE TRANSIENTS

This chapter concerns the prediction and alleviation of subway dynamic pressure transients at the Metro Rail system. Such air pressure transients, which occur during operations in subway, can adversely affect passenger comfort and can cause significant dynamic loading of subway structure components such as walls, doors, vent dampers, and ceilings. Car interior pressure transient magnitudes and rates of rise are predicted for trains passing the fan and vent shafts proposed along line sections of the subway tunnels. Pressure transients created at these locations will be the most severe of all transients generated within the system, and as such, will be the determining factor regarding criteria. Portals are not considered within this analysis since revenue operation will be confined entirely within the line subway tunnels. Worst case design pressure loads are given for fan and vent shaft dampers and cross passage doors. Finally a comment is included regarding suspended ceiling design within stations. Criteria for car interior and tunnel pressure transients are discussed.

Estimates of the subway wall friction and train skin friction are based on the literature contained in the "Subway Environmental Design Handbook, Principles and Applications," Volume 1, 2nd Edition (1976). A discussion of the nature of pressure transients, their magnitudes, and control techniques is presented in the Handbook of Urban Rail Noise and Vibration Control, published by the U. S. Transportation (1982). This latter work forms the starting point for the prediction techniques used for the Metro Rail system. Much of these techniques are based upon measurement data collected at BART and at the Washington Metropolitan Transit Authority over the past several years by Wilson, Ihrig & Associates.

This chapter is organized in four parts, the first part discusses the nature of pressure transients, including significant parameters and the significance of pressure transients for the Metro Rail system. The second part presents the input parameters used for predicting exterior and interior pressure transients within the subway system during fan and vent shaft passage. The third part concerns estimated car interior pressure magnitudes and rates of rise, and the fourth part concerns the expected maximum design loads for fan and vent shaft dampers and partitions between tunnels. Also contained in Section 7.4 is a note regarding the design of station ceilings located over the trackway.

7.1 Nature of Pressure Transients

The nature of pressure transient generation within subway systems is discussed in detail in the "Handbook of Urban Rail Noise and Vibration Control," Chapter 13. The pressure transient phenomenon is distinct from the pressures normally associated with airflow within ducts because the transients are of significantly higher magnitude than would be estimated on the basis of pressure due to flow. As a train enters a subway tunnel, or passes a fan or vent shaft, the "piston-action" of the train induces a pressure wave which propagates ahead of the train at sonic velocity and is reflected by cross passages, vent shafts, station structures, or other discontinuities in the subway geometry. The stiffness of the air ahead of the train prior to arrival of a reflected wave is extremely high, determined primarily by the acoustic impedance of air, which may be derived from linearized gas laws for compressible flow. As a result, most of the air displaced by a train entering a tunnel is forced out through the train-tunnel annulus, resulting in very high relative velocities between the annular air and train. The high relative velocity, in turn, produces a very high pressure transient ahead of the train.

The most severe pressure transients will be those generated during passage of line fan and vent shafts. Experience of WMATA and BART indicates that these transients are similar if not equivalent to those predicted for a train exiting a tunnel and immediately entering a second tunnel as though the second tunnel had a blunt portal. Thus the lead car interior transient consists of two parts. One part is the pressure rise to atmospheric as the lead car enters the fan or vent shaft area, followed by an additional and more severe rise as the lead car enters the next tunnel section. The subsequent rise continues until the train tail enters the tunnel or until a reflected wave arrives back at the train from a far-field cross-passage, station, or portal.

Two factors should be remembered when considering interior lead car pressure transients during passage of a fan or vent shaft. One factor is that if the tunnel is of sufficient length such that no reflected wave from the other end of the tunnel or cross passage arrives at the train before the train enters the subway tunnel, then the tunnel can be considered as infinite in length, throughout the duration of train entry. Secondly, the lead car interior pressure during train entry into a portal is primarily due to the effect of skin friction of the train and tunnel wall friction. If these two friction factors were zero, lead car interior pressures would be minimal, although some relatively minor variation of pressure would be experienced. Thus, minimization of train skin friction and to a lesser extent tunnel wall friction is of great value in subway structure design where high speed trains with high blockage ratios are encountered.

Other parameters which are significant include the blockage ratio or the ratio of the train cross sectional area and the tunnel cross sectional area. Generally, pressure transient magnitudes increase as the cube of the blockage ratio. Thus pressure transients are of critical importance within tunnels of blockage ratio in excess of about 0.4. Train speed is probably the next most important factor in pressure transient generation. Pressure transient magnitudes vary as the square of train speed, while the rate of pressure rise increases as the cube of train speed. Thus train speed reduction, although not attractive to the subway system designer, is one of the most effective means of controlling car interior pressure transients.

The tunnel and train designs proposed for the Metro Rail system offer the potential for very high pressure transient magnitudes and rates of rise, due to a number of factors. One factor is that the tunnel lengths between stations may be as high as three miles. Ventilation requirements dictate that line fan or vent shafts be located along these tunnel sections, and fire control requirements require that the cross passage doors be kept closed during subway operation. The result is that the trains will be passing fan and vent shafts at speeds of as high as 70 mph within tunnels of uninterrupted lengths on the order of about 1 mile. Secondly, the straight sides of the BRRT/Miami vehicle which has been proposed for the system, offers a relatively high blockage ratio compared to that of the BART vehicle operating within tunnels of comparable diameters. Note that the BART vehicle has sloping sides so that the cross sectional area of the BART vehicle may be somewhat less than the Baltimore/Miami vehicle.

Two precast concrete tunnel liner designs are proposed for the alluvial soil and Fernando Puente formation. Precast as well as cast-in-place concrete tunnel liners are also proposed for the rock tunnels, both with the same cross-sectional area and a smooth surface. Some of these long earth tunnel sections will evidently be constructed of precast concrete tunnel liners, with recesses for hardware, which necessarily offer a higher friction coefficient than the smoother cast-in-place concrete liners. Furthermore, the blockage ratio of the precast tunnel designs for the Fernando Puente formation and alluvial soils will evidently be 0.52 to 0.54 as compared with 0.49 for the rock tunnels. Although this difference in blockage ratio appears to be small, the cubic dependence of pressure magnitude on blockage ratio significantly compounds the pressure transient generation problem within the precast tunnel designs for soil. Thus, unless pressure transient control strategies are incorporated within the Metro Rail system, train speed will have to be limited to 50 mph or less during fan or vent shaft passage within the high blockage ratio tunnel sections to maintain car interior pressure transient magnitudes within appropriate criteria. Such controls may include opening of cross passage doors during operation, and, possibly, provision of a transition section within the line tunnels to help reduce the pressure transient magnitudes. These types of control procedures are discussed below.

Finally, cross passage doors and line ventilation shaft dampers will have to be constructed to withstand significantly higher pressure loads for the precast tunnel sections proposed for alluvial soil and Fernando Puente formation than for the poured-in-place circular rock tunnels.

Although pressure transients are created as the subway trains enter tunnel sections from station areas, train speeds are generally low at these locations, and, secondly, the time duration is spread out over the period of time required for acceleration of the train so that the severity of pressure transients are generally insignificant in the region of the stations. Because of this, the detailed analysis presented herein does not consider pressure transients generated at station entrances to subway tunnels.

7.2 Prediction Data Used for the Metro Rail Project

The input parameters used for prediction of the fan and vent shaft passby pressure transients for the Metro Rail system are based on transmittals from SCRTD dated January 7, 1983 and March 10, 1983, on data given in the Subway Environmental Design Handbook, and data collected at BART and WMATA Metro by WIA. These parameters are presented and discussed below.

7.2.1 Train Parameters

All of the predictions of subway pressure transients presented herein are based on the Baltimore/Miami vehicle which has been proposed for use on the Metro Rail system. Estimates of blockage ratio and wetted perimeter were determined from the clearance diagram given in Drawing No. AC-16AAA-C-008, sheets 4, 5 and 6. The train skin friction was assumed to be 0.02, which is comparable with the factor 0.021 given in the Subway Environmental Design Handbook for the BART vehicle and with the factor 0.018 estimated by WIA for the WMATA vehicle. The train parameters are given in Table 7-1. Vehicle length is assumed to be 75 ft, and the maximum consist is assumed to be 6-cars. Predictions were done for both 2-car trains and 6-car trains.

7.2.2 Tunnel Parameters

Three basic tunnel designs were considered in the prediction of pressure transients for the Metro Rail system. These are the liners proposed for the: 1) alluvial soils, 2) Fernando Puente formation, and 3) rock. Although the tunnel diameters are comparable, the slight variation in tunnel diameter results in a significant change in blockage ratio, and, secondly, the friction factors associated with the precast tunnel liners proposed for the alluvial soils and Fernando Puente formation, will be significantly higher than for the rock tunnels. The parameters associated with each of these basic subway designs are listed in Table 7-2.

Additional tunnel parameter data are presented in Table 7-3 for the train/tunnel annulus. Because of the presence of the train, the effective hydraulic diameter is reduced, thus requiring re-evaluation of relative wall roughness height and related parameters. Blockage ratios are also presented in Table 7-3.

7.2.2.1 Alluvial Soil Tunnel

The cross sectional area and wetted perimeter for the tunnel liner proposed for the alluvial soils were estimated from drawing No. AC-16AAA-C-005. This tunnel liner consists of precast concrete sections bolted together with recesses in each of the precast segments to accommodate the bolts. Based on this drawing the wall roughness height was assumed to be about 0.4 ft with an effective rib separation of about 1.3 ft, although these liners are not ribbed in the sense of the steel tunnel liners used on may systems. The tunnel parameters for the alluvial soil tunnels are given in Table 7-2 together with estimates of relative roughness height, relative rib separation, and an overall tunnel friction factor. These latter estimates are based on procedures given in the Subway Environmental Design Handbook.

The blockage ratio for the alluvial soil tunnel is 0.54 and the hydraulic diameter for the annulus is estimated to be 6.8 ft for purposes of computation of relative wall roughness height and relative rib separation in the annulus. The resulting overall friction factor for the annular tunnel wall friction is 0.1, considerably higher than the friction factor estimated for the subway tunnel without train.

7.2.2.2 Fernando Puente Formation

The second tunnel liner design considered in the prediction of pressure transients is that proposed for the Fernando Puente formation. Estimates of cross sectional area and wetted perimeter were based on Drawing No. AC-16AAA-C-006. Since the tunnel liner includes recesses for bolts, a roughness height of about 0.4 ft was assumed together with an effective rib separation of 1.3 ft, as was done for the alluvial soils tunnel. Inspection of the drawings indicates that the Fernando Puente formation interior surfaces are perhaps smoother than the alluvial soil tunnels, so that the estimate of overall tunnel friction of 0.042 may be excessive for this tunnel.

The blockage ratio is 0.52 with a hydraulic diameter of the annular cross-section of 7.3 ft. Again a wall roughness height of 0.4 ft gives an overall annular tunnel wall friction factor, including track fixation and miscellaneous hardware, of 0.1, the same as for the alluvial soil tunnel. As noted above, the friction factor for the annulus in the case of the Fernando Puente formation tunnel is relatively high, compared with the tunnel wall friction factor in the absence of trains.

7.2.2.3 Rock Tunnel

The estimates of cross sectional area and wetted perimeter for the circular rock tunnels were based on drawing AC-16AAA-C-003 which shows two basic tunnel designs. One design is a circular cast-in-place concrete tunnel and the other design is a precast concrete liner which evidently has a smooth interior surface. In both cases a wall roughness height of 0.003 ft was assumed and the overall tunnel friction factor was estimated to be 0.028, consistent with that given in the Subway Environmental Design Handbook for a typical smooth bore tunnel.

For the estimation of annular tunnel wall friction, the wall roughness height for the concrete is again assumed to be 0.003 ft and the hydraulic diameter of the annulus is estimated to be 8 ft. The resulting overall friction factor, including that due to the track fixation and miscellaneous hardware, is estimated to be 0.03. The rock tunnel exhibits both the lowest friction factor, as well as the lowest blockage ratio of all three subway tunnel designs, and thus we predict that the pressure transients created within the circular rock tunnels will be the least severe of the three designs.

7.2.3 Miscellaneous Factors

For estimation of steady state pressures prior to vent shaft passage, air-flow loss factors of 0.0 and 1.0 were estimated for air entering and leaving the subway tunnel sections, respectively. These factors are losses due to turning of air as it enters and leaves the subway tunnel through the vent shafts at either end of the tunnel section. They have not been estimated by detailed study of vent or fan shaft design, since such designs are presently not available, and since the turning losses associated with these fan and vent shafts are less significant than the overall losses due to friction along the tunnel. Finally for estimation of the pressure transient rise following the passage of the vent shaft, the loss factor for air exiting the train annulus and venting through the vent shaft is assumed to be 1.0.

For estimation of the steady state pressure prior to passage of the line vent or fan shafts, the train nose and train tail loss factors were assumed to be 0.1. For the post passage pressure rise, the train nose loss factor was assumed to be 0.0 since it contributes negligibly to the overall pressure transient. Since the train tail is not considered in the prediction of tunnel entry pressure transients, no loss factor is required for the tail.

7.2.4 Tunnel Configuration

Estimates of tunnel lengths for use in prediction of fan and vent shaft pressure transients were based on the Metro Rail starter line schematic diagram Drawing AB-14AAA-C-103. Based on this drawing, and on line vent shaft location information supplied by the SCRTD letter dated March 10, 1983, the pressure transients created at each of the line vent or fan shaft structures will be essentially similar in most respects. Thus a typical configuration was assumed for prediction purposes, consisting of a line vent or fan shaft positioned midway within a tunnel of 10,000 ft length. Thus, for modeling purposes, we assumed that the train leaves a 5,000 ft section, passes the shaft, and enters the second 5,000 ft tunnel section beyond the vent shaft location.

Further information supplied by SCRTD indicates that cross passages will be located at approximately 500 ft intervals within each of the tunnel sections. Prediction of car interior pressures were developed for two cases. The first case was with all cross passage doorways closed, and the second case was with the cross passage doors nearest the fan and vent shafts open, all other cross passage doors being closed. The purpose in investigating the latter case was to investigate a practical and inexpensive pressure transient control strategy for the Metro Rail system. All of the cross passage doors are intended to be kept closed for fire and smoke control purposes. However, opening a cross passage at approximately 500 ft from the fan or vent shaft will be one of the most effective means of controlling air pressure within the subway car during passage of the fan or vent shaft, and it will be the only effective method for controlling such pressure if speed restrictions are not imposed.

7.2.5 Train Speed

A speed profile was included with the letter from SCRTD dated March 10, 1983, indicating that the maximum train speed during passage of the line fan or vent shafts will be 70 mph, the maximum speed projected for the system. Pressure magnitudes tend to vary as the square of train velocity, thus the associated pressure transient magnitude will be extreme. Since an effective means for controlling the pressure transients includes speed restrictions at fan or vent shaft locations, speeds of 50 mph and 60 mph were also considered in addition to the speed of 70 mph for the purpose of prediction.

7.3 Car Interior Pressure

This section presents estimates of car interior pressure transient magnitudes which may be experienced by people riding the Metro Rail trains. Although a number of significant causes of pressure transients are considered in this section, the emphasis is placed on the pressure transients occurring during fan and vent shaft passage. Detailed predictions are thus given only for these events. Note that portal entry is not a significant concern for the Metro Rail system since revenue operation is not anticipated at portal locations. This section also includes criteria for car interior pressure, a listing of the significant causes of pressure transients, and results of pressure transient predictions at fan and vent shafts.

7.3.1 Criteria For Car Interior Pressure Transients

The recommended criteria for rapid pressure changes, applicable when the change in pressure is greater than 0.1 psi, is that no person, patron or employee shall be subjected to a rate of pressure change greater than 0.06 psi/sec. Slightly more restricted criteria have been applied to the BART system during the 1960's and early 70's. The criteria stated above have been applied to most of the transit systems currently under design within the United States, and as of this writing, we are unaware of any recommended changes in the criteria.

An extensive discussion of the criteria and the relationship to aircraft pressure criteria are presented in the Subway Environmental Design Handbook. The criteria are also discussed in the Handbook of Urban Rail Noise and Vibration Control, where it is pointed out that the rise rate criterion is difficult to apply to certain complex pressure transients. The reason for this is that the pressure transient signature can be very complex, exhibiting multiple peaks, so that the actual rate of rise is difficult to determine. Finally, as pointed out in the Handbook of Urban Rail Noise and Vibration Control, these criteria are exceeded on almost every modern transit system with high speed trains and high blockage ratios. The criteria will also be exceeded on the Metro Rail system at the fan and vent shaft locations without some provision for air pressure control, either in the way of a far-field open cross passage, speed restriction, or both.

7.3.2 Significant Causes of Car Interior Pressure Transients at the Metro Rail System

This section presents a short discussion regarding each of the anticipated significant causes of pressure transients on the Metro Rail system, together with an estimate of their relative significance. Note that portal entry pressure transients are not considered, since portals will not be located along revenue sections at the system.

7.3.2.1 Fan and Vent Shafts

As previously discussed, by far the most significant pressure transients will be created at the fan and vent shafts on the line sections of the subway tunnels. The nature of the pressure transients created at these locations is discussed in detail in Appendix C.

7.3.2.2 Cross Passages

Significant car interior pressure transients will be created when trains encounter cross passages between subway tunnels. However, our experience is that these pressure transient magnitudes are generally below 0.1 psi, provided that the cross passage cross sectional area is relatively small compared to the subway tunnel cross sectional area so that frictional losses through the cross passage will be high enough to induce or maintain significant air velocities ahead of the cross passage location prior to train passage. In this regard, large open cross passages between tunnels should be avoided. Note that for the Metro Rail system, the cross passages between tunnels will be kept closed primarily for fire and smoke control. Since no pressure transient will be created if the cross passage is closed, these types of transients have not been considered in detail.

7.3.2.3 Tunnel Entrances at Stations

Relatively minor pressure transients are created as trains enter tunnel sections from subway platform areas. However, at these locations, train speed is generally low, although increasing at a constant acceleration. The result is that the pressure transient due to train entry at the station is reduced in magnitude and extended over a much longer time period than that which might be normally associated with a high speed entry into a blunt portal. Measurement data collected at WMATA suggest that pressure transients at station entrances do not exceed criteria.

7.3.2.4 Other Trains

Other trains operating in the subway will have negligible effect on car interior pressure transients. This is because the entire subway system is proposed to be built with single track tunnels without adjoining open cross passages. Even at line vent structures, no cross passage is proposed. The only area where some possible interaction may occur exists at locations where double crossovers are positioned. However, since these are located near stations, train speed should be low, and resulting pressure transients should be minimal.

7.3.2.5 Speed Variation

Speed variation will have a minimal effect on car interior pressure transients due to the long time periods required for acceleration and/or deceleration of the train.

7.3.3 Predicted Car Interior Pressure Transients During Fan and Vent Shaft Passby

This section concerns prediction results for lead car and trailing car interior pressure transient magnitudes and rates of rise during passage of the line vent structures on the Metro Rail system. The predictions are for three train speeds of 50, 60 and 70 mph, the three proposed tunnel designs: for the alluvial soils, the Fernando Puente formations, and the rock tunnels, and for two-car and six-car trains. Predictions are given for two cases: the first case with all cross passage doors closed, the second case with the first cross passage door beyond the fan or vent shaft open.

7.3.3.1 Lead Car Interior Pressure

Lead car interior pressure magnitudes and rates of rise, generated during fan and/or vent shaft passbys, are presented in Table 7-4 for two and six-car trains. The computed lead car interior pressure transient signatures for each of the three basic tunnels are plotted in Figures 7-1 through 7-3 for 70 mph train speeds. The time 0.0 seconds corresponds to the time at which the lead car enters the tunnel beyond the shaft. The lead car interior pressure transient consists of a pressure rise as the lead car enters the fan or vent shaft area, followed by a further rise as the lead car penetrates the tunnel section beyond the fan or vent shaft. The rise continues until the tail of the train passes the vent shaft, (these times are indicated in Figures 7-1 through 7-3) or until a reflected wave from a far field cross passage ahead of the train arrives back at the train nose.

The maximum predicted pressure transient is for a six-car train passing at 70 mph within the alluvial soil tunnel, with the cross passages closed. The predicted total rise is approximately 0.5 psi, with an overall rate of rise of 0.12 psi/sec. The corresponding pressure for the two-car train is significantly lower than for the six-car train. However the rate of rise is higher. Although the length of the two-car train compared with the six-car train results in a significant lowering of the overall pressure rise, the shorter train length decreases the effective duration of the pressure transient, thereby increasing the rate of rise. At 50 mph, the overall rise within the alluvial soil tunnel will be 0.2 and 0.29 psi/sec for two-car and six-car trains with an overall rate of rise 0.09 and 0.05 psi/sec. Note that the car interior pressure transient criterion is that the rate of rise shall not not exceed 0.06 psi/sec for a transient in excess of 0.1 psi. Thus, lead car interior pressure transients within the alluvial soil tunnels will be near criterion for train speeds of about 50 mph.

The overall magnitudes and rates of rise for lead car interior pressures for two and six-car trains operating within the Fernando Puente tunnels will be slightly less than those predicted for the alluvial soil tunnels, primarily due to a slightly lower blockage ratio for the Fernando Puente tunnel, compared with the alluvial soil tunnel. Again, speed restrictions of approximately 50 mph will be required in the neighborhood of the fan or vent shafts for the Fernando Puente tunnels if the cross passages remain closed.

The lead car interior pressure transient for two and six-car trains operating within the rock tunnels are predicted to be very much lower than the pressure transients for the alluvial and Fernando Puente tunnel designs. This is due to both a significantly lower blockage ratio compared with the former two tunnels, together with a lower tunnel wall friction factor, which results in less severe steady state negative pressures prior to vent passage. However, the effect of tunnel wall friction is less than the effect of the blockage ratio for this type of pressure transient.

The overall predicted magnitudes for the trains operating in the rock tunnels are consistent with observed pressure transient magnitudes measured at the WMATA Metro System for trains operating within a rock tunnel with 0.47 blockage ratio. Judging from the predicted pressure transient magnitudes and the rates of rise given in Table 7-4, the overall rate of rise for the six-car train operating at 70 mph will be just above criteria, although the total rise will be 0.31 psi. The two-car train however will produce a car interior pressure rise of significantly lower magnitude but higher average rate of rise, as computed over the duration of the transient. However, the pressure transient predicted for the two-car train will be much less irritating to passengers than that predicted for the six-car train, primarily because of the much lower amplitude. For the six-car train at 70 mph the rate of rise is determined by dividing the overall rise by the duration of the transient, and because of the length of the transient, the overall rate of rise is about 0.07 psi/sec. The initial part of the pressure transient for the six-car train, will actually have significantly higher rate of rise than that given in Table 7-4, and will be comparable with that given for the two-car train.

Lead car interior pressure transients are predicted for the case of two car and six-car trains passing the fan or vent shafts with the first cross passage beyond the fan or vent shaft open. Opening the cross passage door will cause a wave to be reflected back to the train nose, thus helping to reduce the pressure transient magnitude. The initial shape of the pressure transient signature will remain essentially unchanged until the arrival of the reflected wave. For all three subway tunnel designs, the effect of opening the cross passage door is very significant. The reduction in overall pressure transient magnitude for the two-car train achieved by opening the cross passage is about twenty percent, whereas for the six-car train the reduction is about fifty-six percent. For the two-car train, the average rate of rise is also increased significantly due to shortening of transient duration. For the six-car train, the average rate of rise, calculated over the now shortened duration of the overall transient, is higher than that calculated for the case with the cross passages closed. However this again is due to the method for which the overall rate of rise is computed. The initial rate of rise over the first 0.1 psi change in pressure <u>will not be effected by the cross passage opening</u>, since the initial part of the transient is not affected until the reflected wave arrives from the cross passage. The time of arrival required for the cross passage reflected wave is approximately 1 second, since the cross passage is assumed to be about 500 ft from the fan or vent shaft.

The prediction data given in Table 7-4 indicate that the lead car interior pressure transient magnitude will vary less severly than the square of the train speed by a small amount. The pressure transient magnitudes for 50 mph are about forty percent less than those given for the 70 mph speeds. The lowest pressure transients predicted for either two or six-car trains, are for train speeds of 50 mph with the first cross passage beyond the fan or vent shaft opened. Under these conditions, the car interior pressure transient should be generally close to the acceptability criteria for the rock tunnels.

Although the opening of the first cross passage beyond the fan or vent shaft significantly reduces the car interior pressure transient magnitude, the additional effect achieved by opening additional cross passages beyond the first will be of marginal significance, with respect to the transient generated during passage of the vent shaft. This is because of the way that pressure waves interact and reflect at the second cross passage. In effect, the wave generated by the train passing the fan or vent shaft encounters the first cross passage and equal wave amplitudes are induced in both tunnel sections beyond the first cross passage, so that their effect is to cancel each other at the second cross passage. However, this is only for the first few seconds of the pressure transient. The opening of the second cross passage, will result in a reduction of the pressure transient created within the lead car as the lead car passes the first open cross passage, although the pressure transient created during passage of the first cross passage should be much less significant than that generated during passage of the fan or vent shaft. Nevertheless, opening of the second cross passage would be of overall benefit for car interior pressure transients.

7.3.3.2 Trailing Car Interior Pressure Transients

Trailing car interior pressure transient magnitudes and rates of rise are presented in Table 7-5 for the alluvial soil, Fernando Puente formation,, and rock tunnels. These trailing car interior pressure transients begin as the train nose passes the fan or vent shaft, and continue until the train tail completes passage of the fan or vent shaft. Prior to passage of the fan or vent shaft, the steady state pressure within the trailing car is depressed below atmospheric by an amount consisting of the sum of the Bernoulli drop at the train nose and the pressure due to frictional losses along the train in the annular space. As the train progresses by the fan or vent shaft, these pressure drops must be overcome, so that as the trailing car passes the fan or vent shaft, the pressure rises to about atmospheric level. As the trailing car enters the tunnel section beyond the fan or vent shaft, the trailing car pressure decreases due to a Bernoulli drop associated with the air leaving the annular space at the train tail, effectively terminating the pressure transient.

The highest pressure transients are predicted for the alluvial soil tunnel while the lowest are predicted for the rock tunnels, because the alluvial soil tunnels will have the highest blockage ratio and tunnel wall friction. Whereas tunnel wall friction is not of great importance for lead car interior pressure during tunnel entries, the trailing car interior pressure prior to a fan or vent shaft or for a train leaving a tunnel, are strongly influence by the tunnel wall friction in addition to the train skin friction. The trailing car interior pressure transient magnitudes are almost exactly proportional to the square of the train speed.

The pressure transient magnitudes predicted for the six-car train are only slightly higher than that predicted for the two-car trains. The rates of rise for the six-car trains are much lower than those predicted for the two-car trains. The lower rate of rise predicted for the six-car train is due to the much longer time period required for the six-car train to pass the fan or vent shaft as compared to that for the two-car train. Thus, for all three tunnel designs, and for all three train speeds, the pressure transient in the trailing car will be similar to or less than the rate of rise of 0.06 psi/sec, even for pressure rises of as much as 0.3 psi as predicted for the alluvial soil tunnel for 70 mph train speeds. However, for the two-car trains, the rates of rise will exceed the criterion at all speeds greater than 50 mph. For the rock tunnels, operation at 60 mph will result in a predicted rate of rise of only about 0.08 psi/sec for an overall magnitude of 0.13 psi. Although this pressure transient is somewhat in excess of the criterion, it is not particularly severe.

No distinction was made between tunnels with cross passages nearest the fan or vent shaft open or closed since the opening of those cross passages closest to the fan or vent shaft will probably have only a small effect on the trailing car interior pressure transient magnitudes. The general effect would be to reduce the pressure transient magnitude and also reduce the rate of rise. If all of the cross passages were kept open, trailing car interior pressure would probably be significantly reduced, because of reduced drag on the train.

7.4 Subway Design Considerations

Estimates of maximum loads due to pressure transients within the subway system are presented in this section for fan and vent shaft dampers and partitions between line tunnels. Partitions between line tunnels may consist of cross passage doors or concrete masonry walls erected at line fan or vent shaft locations. An additional comment is included regarding the design of suspended ceilings within the stations.

Historically, fan and vent shaft dampers and partitions between tunnels, specifically cross passage doors and concrete masonry walls, have suffered damage due to pressure transient loading and have required redesign and retrofit. The estimated maximum loads given herein are worst case maximum loads, so that no additional margin of error is required for design purposes, other than safety factors associated with component fatigue and reliability.

7.4.1 Vent and Fan Shaft Damper Loads

Maximum anticipated loads for fan and vent shaft dampers are presented in Table 7-6 for three configurations. These include vents located near stations, single fan or vent shafts located within line tunnel sections, and finally multiple fan or vent shafts located within a single tunnel section. Here a tunnel section is a tunnel terminated at either end by stations. Although portals are not included in the analysis, a line vent or fan shaft located within a subway section terminated at at least one end by a portal, should be considered as a multiple fan or vent shaft tunnel section. All maximum loads are estimated for a train speed of 70 mph. Should higher train speed be anticipated in the future, these magnitudes should be increased by a factor proportional to the square of train velocity.

The maximum anticipated damper loads for fan or vent shafts located within line tunnels with two or more fan shafts are based on the maximum predicted static pressure developed ahead of the train as it passes a fan or vent shaft at 70 mph. In this case the dampers of the fan or vent shaft being passed are assumed to be open, while the dampers of the fan or vent shaft ahead of the train are assumed to be closed. This may or may not represent the anticipated operating condition, but it does reflect a possible mode which can result in significant damage to the dampers of the closed fan or vent shaft located ahead of the train. If the dampers of the fan or vent shaft being passed are also closed, then no pressure transient would be generated during train passage.

For tunnel sections with a single line vent or fan shaft between stations, the maximum damper load is difficult to predict, since the magnitude depends on train speed variation as the train enters the tunnel section from the station area. However, as the train passes the line vent, the steady state pressure in the neighborhood of the train as the train passes the fan or vent shaft will result in significant pressure loads at high speed, especially for two-car trains. For tunnels with single line vent or fan shafts, the maximum damper loads are simply estimated to be about 60% of the maximum estimated pressure for the multiple line vents.

The maximum estimated damper loads for vent shafts located at station ancillary areas are about 20 lb/sq ft, and are based on measurements at the WMATA. These maximum loads for station vent shafts are also recommended in the Handbook of Urban Rail Noise and Vibration Control.

7.4.2 Partitions Between Tunnels

Maximum pressure transient loads for inter-tunnel partitions and cross passage doors are presented in Table 7-7 for anticipated train speeds of 70 mph. The term "inter-tunnel partitions" in this case refers to structures such as CMU (concrete masonry unit) walls at line tunnel locations, such as at a fan or vent shaft location. Similarly these maximum design loads are for cross passage doors located within line tunnel sections. Pressure transient loads for CMU walls and/or cross passage doors located at tunnel ancillary facilities adjacent to stations will suffer much lower pressure transient loadings.

The maximum design loads given in Table 7-7 are based on the pressure differential produced by a train passing a fan or vent shaft in one tunnel and the negative static pressure at the train tail of a train passing the cross passage door or partition in the adjacent tunnel. Thus, the maximum anticipated loads for the intertunnel partitions or cross passage doors are significantly greater than the loads anticipated for the fan or vent shaft dampers. For tunnels without line fan or vent shafts, the maximum anticipated loadings are anticipated be about one-half those given for tunnels with line vents or fan shafts, although detailed estimates have not been made for these configurations. Should a train speed in excess of 70 mph be anticipated in the future, the design load given in Table 7-7 should be increased by the square of train velocity. Finally, the predicted pressure transient loads for inter-tunnel partitions within the alluvial soil tunnels with line fan or vent shafts are approximately 50% higher than the design loads recommended for the rock tunnels. This is due to a combination of higher blockage ratio and higher tunnel wall friction factor for the alluvial soil tunnels.

Finally, sliding doors may be preferable to hinged doors since hinged doors, if the hardware is broken, may slam open and closed due to pressure transients and air flow within the tunnels. Sliding doors would be less prone to this problem.

7.4.3 Stations

The only critical design consideration in station construction concerns the pressure loading of suspended ceilings directly over the track. Generally speaking, suspended ceilings should be avoided over the track since the passing train induces a positive or upward pressure load against the bottom of the ceiling, followed by a rapidly decreasing pressure as the head of the train passes the location. If an air volume exists behind the suspended ceiling, the suspended ceiling will be subjected to a significant transient load as the train travels down the track. The Washington Metropolitan Transit Authority has experienced significant problems with suspended ceilings over the trackways. The measurements at WMATA Metro indicated that for train speeds normally encountered at stations, i.e. 40 mph or less, the dynamic pressure loads acting on the station ceilings are less than 15 lbs/sq ft. Based on this experience, suspended ceilings should either be entirely avoided or the ceiling elements should be designed to withstand a pressure transient load of 15 lbs/sq ft.

7.5 Recommendations

7.5.1 Alternative Vehicle Designs

The proposed vehicle for the Metro Rail system is the existing Baltimore/Miami vehicle, manufactured by BUDD, which has vertical sides. The blockage ratio for this type of vehicle operating within the tunnels proposed for the Metro Rail system is high compared with the blockage ratios at the Bay Area Rapid Transit system. BART vehicles have sloping slides which result in a lower cross-sectional area for the vehicle than would be the case with vehicles with vertical sides. Typical blockage ratios on the BART system are 0.43 for the four-mile-long Berkeley Hills tunnel. The blockage ratio for the BART vehicle in the transbay tube is about 0.49. These figures may be compared with the blockage ratio anticipated for the Metro Rail system with the BRRT/Miami vehicle of 0.49 to 0.54 for the proposed tunnel designs. Since the magnitude and rate of rise of pressure transients varies strongly with blockage ratio, the conclusion is that the use of a vehicle with sloped slides will result in significantly lower pressure transient magnitudes. Since it is proposed to operate trains at maximum speed within the line subway sections, and since these subway sections are very long, attention should be focused upon reduction of blockage ratio by vehicle selection.

7.5.2 Control of Pressure Transient Generation at Fan and Vent Shafts

Since high speed passage of fan or vent shafts is estimated to produce car interior pressure transient magnitudes in excess of the criteria, attention should be focused on some type of pressure transient control strategy, especially if speed restrictions are not included. One such strategy essentially consists of the provision for an open cross passage between the tunnels at about 500 ft beyond the fan or vent shaft. Since the proposed tunnel designs include provision of cross passages at about a 500 ft separation, this type of pressure transient control technique can be easily accomplished simply by opening a cross passage door. However, the fire and smoke control techniques currently considered require the cross passage doors be kept closed. Thus, some alternative procedure for controlling pressure transients is required, if speed reductions are not incorporated.

One possible technique for reducing the pressure transient magnitude and rate of rise during passage of a fan or vent shaft, is to include some type of active control of the fan or vent shaft dampers during the passage of the train. Specifically, if the dampers were closed approximately ten seconds prior to passage of the fan or vent shaft by the train nose, air flow would be induced in the tunnel ahead of the train prior to passage, thus resulting in a lowering of the pressure transient magnitude and a lengthening of its duration. The dampers could then be opened as soon as the train tail passes the fan or vent shaft. This type of pressure control strategy has not been used on any transit system in the U.S.A. The prediction of the pressure transient which occurs during passage of the vent shaft with this type of active damper control is not possible with the current models in use. However, the pressure transient magnitude should be reduced and its duration should be increased so that the overall rate of rise will be significantly reduced relative to those transients generated during passage of a fan or vent shaft with dampers open. If this type of pressure transient control strategy can be incorporated on the Metro Rail system, additional analyses are recommended to determine the most appropriate timing for the closing and subsequent opening of the dampers. Note that the actual timing can also be evaluated in the field and adjusted to achieve acceptable car interior pressure transients.

A third pressure transient control strategy for the fan or vent shaft passby consists of the provision of a flared transition section within the subway. This would extend the duration of the pressure transient and provide a delay of car interior pressure transient rise during penetration of the tunnel beyond the shaft until a reflected wave from an open cross passage arrives at the lead car to help reduce the pressure transient magnitude. Since this type of control provision necessarily involves significant cost due to enlarging the tunnel bore, this type of technique has not been considered in detail. However, it has been used for control of portal entry pressure transients at the Baltimore system, as well as at WMATA Metro, where measurements have been performed to document the characteristics of portal entry pressure transients at flared portals.

The effect of flared transition sections will be relatively small if a cross passage door cannot be maintained open to provide a reflected wave which will reduce the car interior pressure transient magnitude. Experience has shown that flaring of a tunnel portal has little effect on car interior pressure for trains entering very long tunnels. The interaction of the tunnel flare with the cross passage is necessary to achieve a reduction of car interior pressures. If the use of flared transition sections at the fan and vent shaft locations can be accommodated on the Metro Rail system, additional analyses are recommended to define the appropriate length of the transition section and flare rate together with the distance of the cross passage from the end of the transition flare to achieve an optimum control technique.

Finally, maintaining all cross passage doors open will reduce pressure transient magnitudes and rates of rise in a general way simply by reduction of tunnel viscous lengths, and thus train drag. Since tractive energy requirements may be significant, SCRTD may be interested in maintaining all cross passage doors open to reduce train drag as well as transient magnitudes, fire and smoke control requirements notwithstanding.

TABLE 7-1 TRAIN PARAMETERS (BALTIMORE/MIAMI VEHICLE)

Cross Sectional Area	107 ft^2
Wetted Perimeter	42 ft
Skin Friction Factor	0.02
Vehicle Length	75 ft
Consists	2- and 6-car

TABLE 7-2 TUNNEL PARAMETERS

Tunnel Type	Internal Diameter	Open Area (ft)	Wetted Perimeter (ft)	Hydraulic Diameter (ft)	Relative Wall Roughness Height	Relative Rib Separation	Overall Tunnel Friction Factor
Alluvial Soil	17'-2"	200	54	14.8	0.027	0.09	0.042
Fernando Puente Formation	17'-4"	205	54	15.2	0.026	0.09	0.042
Rock	18'-0"	220	56	15.7	0.00019	--	0.028

TABLE 7-3 ANNULUS DATA (FOR TUNNEL ENTRY)*

Tunnel Type	Blockage Ratio	Open Area (ft)	Wetted Perimeter (ft)	Hydraulic Diameter (ft)	Relative Wall Roughness Height	Relative Rib Separation	Overall Tunnel Friction Factor
Alluvial Soil	0.54	92	54	6.8	0.06	0.19	0.1
Fernando Puente Formation	0.52	98	54	7.3	0.05	0.18	0.1
Rock	0.49	112	56	8.0	0.0004	--	0.03

* Based on train cross-section of 107 ft^2 (Baltimore/Miami Vehicle)

Ref: Subway Environmental Design Handbook, Volume 1, Principles and Applications, 2nd Ed. (1976)

TABLE 7-4 LEAD CAR INTERIOR PRESSURE

			2-Car		6-Car	
Tunnel Type	Speed (mph)	Cross Passage	Rise (psi)	Average* Rate (psi/sec)	Rise (psi)	Average Rate (psi/sec)
Alluvial Soil	50	Closed	0.20	0.09	0.29	0.05
	60	Closed	0.26	0.14	0.39	0.08
	70	Closed	0.35	0.22	0.52	0.12
	50	Open	0.13	0.13	0.11	0.11
	60	Open	0.19	0.20	0.17	0.17
	70	Open	0.27	0.29	0.73	0.24
Fernando Puente Formation	50	Closed	0.17	0.08	0.26	0.04
	60	Closed	0.24	0.13	0.35	0.08
	70	Closed	0.31	0.19	0.45	0.10
	50	Open	0.12	0.12	0.12	0.12
	60	Open	0.18	0.18	0.15	0.15
	70	Open	0.25	0.26	0.21	0.22
Rock	50	Closed	0.11	0.05	0.17	0.03
	60	Closed	0.16	0.09	0.24	0.05
	70	Closed	0.17	0.13	0.31	0.07
	50	Open	0.09	0.09	0.07	0.07
	60	Open	0.13	0.13	0.10	0.11
	70	Open	0.18	0.19	0.15	0.15

*Average Rate Of Rise Calculated Over Transient Duration

TABLE 7-5 TRAILING CAR INTERIOR PRESSURE

		2-Car		6-Car	
Tunnel Type	Speed (mph)	Rise (psi)	Average Rate (psi/sec)	Rise (psi)	Average Rate (psi/sec)
Alluvial Soil	50	0.13	0.064	0.15	0.024
	60	0.18	0.11	0.22	0.043
	70	0.25	0.17	0.29	0.066
Fernando Puente Formation	50	0.12	0.059	0.14	0.023
	60	0.17	0.10	0.20	0.039
	70	0.23	0.16	0.27	0.062
Rock	50	0.09	0.04	0.10	0.016
	60	0.13	0.076	0.15	0.029
	70	0.14	0.096	0.20	0.046

TABLE 7-6 DESIGN LOADS FOR FAN AND VENT SHAFT DAMPERS
TRAIN SPEED = 70 mph

Tunnel Type	Station Vents (psf)	Single Line Vents (psf)	Multiple Line Vents (psf)
Alluvial Soil	20	50	83
Fernando Puente Formation	20	40	77
Rock	20	30	58

TABLE 7-7 DESIGN LOADS FOR INTER-TUNNEL PARTITIONS AND CROSS-PASSAGE DOOR-TRAIN SPEED = 70 mph

Tunnel Type	Tunnels with Line Vents (psf)	Tunnels Without Line Vents (psf)
Alluvial Soil	120	60
Fernando Puente Formation	110	55
Rock	78	40

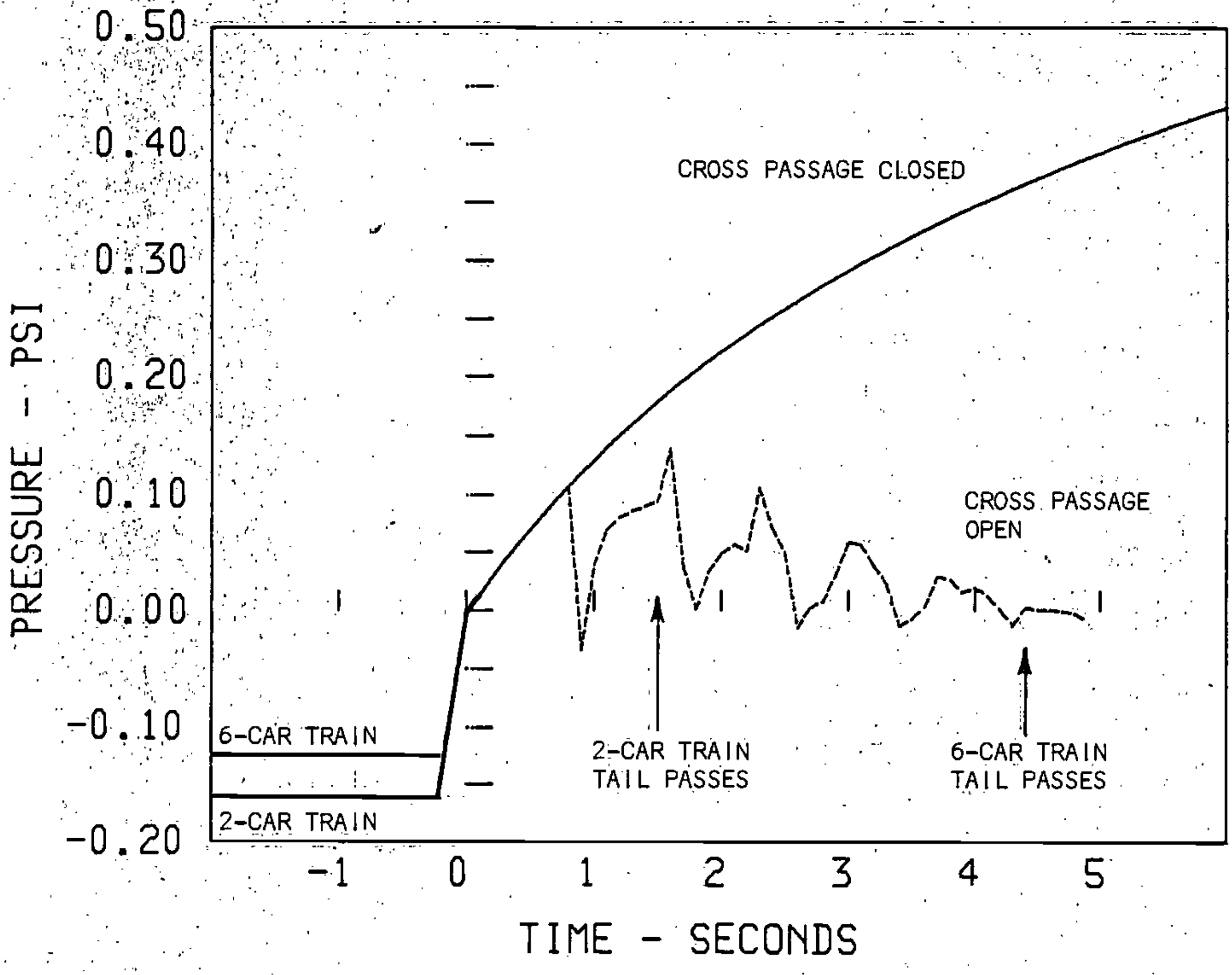

FIGURE 7-1 LEAD CAR INTERIOR PRESSURE DURING PASSAGE OF LINE VENTILATION SHAFTS

- ALLUVIAL SOIL TUNNELS -

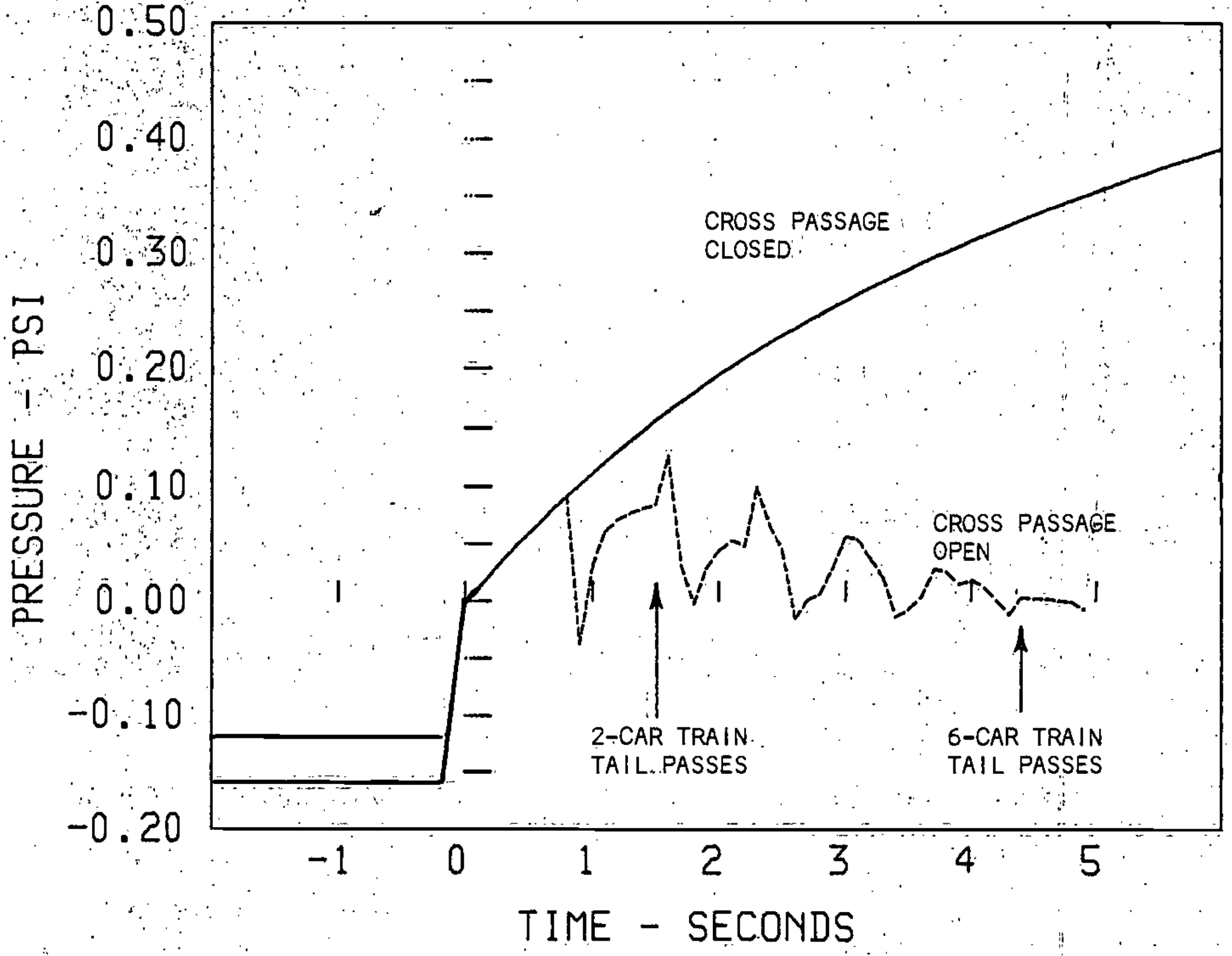

FIGURE 7-2 LEAD CAR INTERIOR PRESSURE DURING PASSAGE OF LINE VENTILATION SHAFTS

- FERNANDO FORMATION TUNNELS -

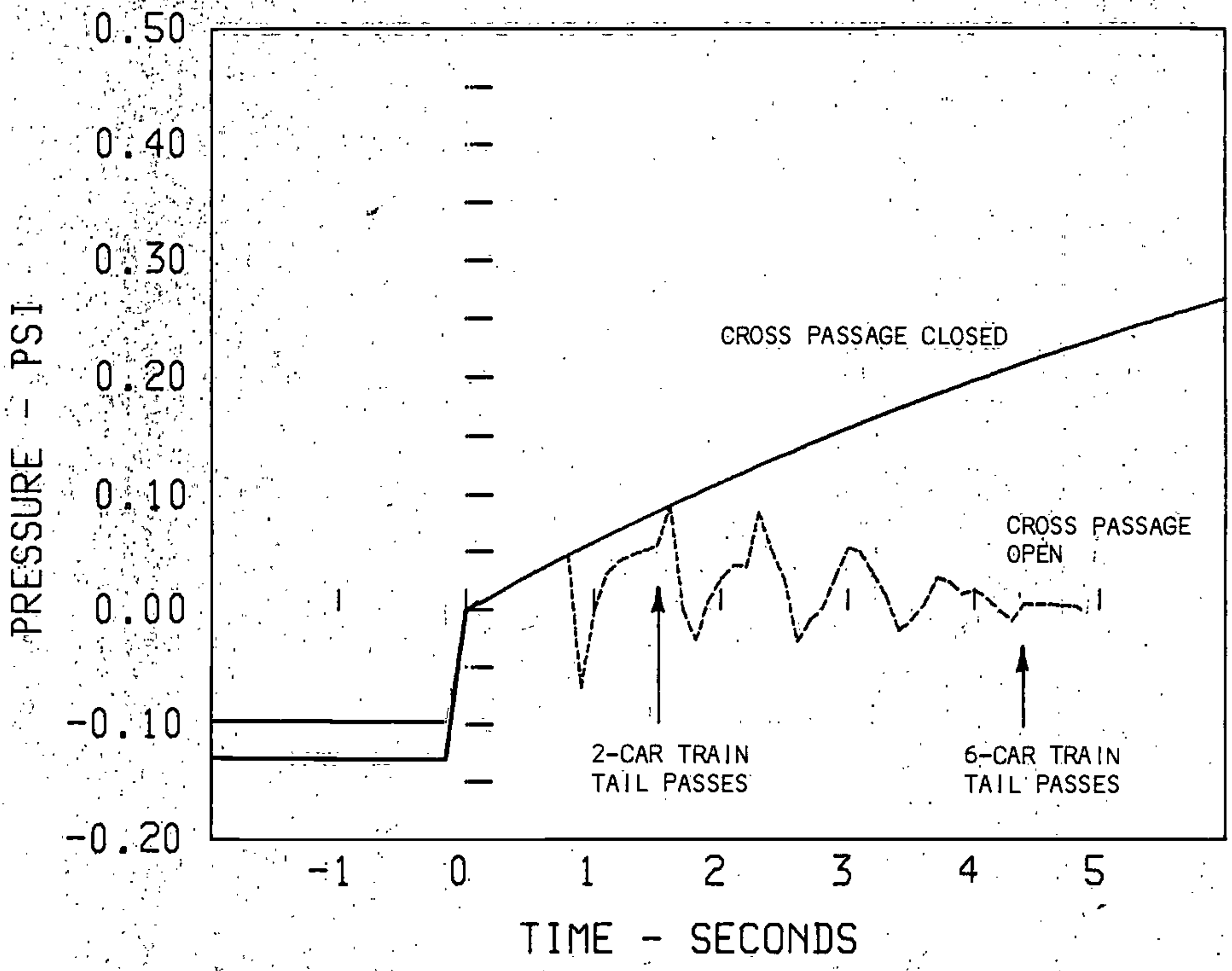

FIGURE 7-3 LEAD CAR INTERIOR PRESSURE DURING PASSAGE OF LINE VENTILATION SHAFTS

- ROCK TUNNELS -

Chapter 8

VEHICLE NOISE AND VIBRATION

8. VEHICLE NOISE AND VIBRATION

8.1 Introduction

The specifications for the proposed Metro Rail transit vehicle have been developed by Kaiser Engineers. Rather than prepare separate noise and vibration specifications for the transit vehicle, WIA's defined task is to review the previously prepared noise and vibration specifications for the transit vehicle.

The recommended revisions that are presented as part of this chapter are based on over 15 years of practical experience in preparing the noise and vibration sections of transit vehicle specifications, in measuring the noise and vibration produced by the transit vehicles and in designing noise control techniques for reducing the noise produced both inside and outside the transit vehicle. WIA has been involved in the area of transit vehicle acoustics for a number of transit systems, including BART, CTA, WMATA, MARTA, BRRT, MBTA, NFTA, Vancouver ALRT and Detroit CATS. Thus the changes to the vehicle specifications recommended in this chapter are based on experience with noise and vibration levels which can be practically achieved by vehicle manufacturers and which provide for a pleasant environment for patrons, employees and the wayside community. Section 8.2 presents Sections 3.19 NOISE CRITERIA AND CONTROL, 3.20 RIDE QUALITY and 3.21 VIBRATION AND SHOCK CRITERIA of the vehicle specifications with recommended changes indicated. Section 8.3 presents a brief discussion of each of the recommended changes.

8.2 Vehicle Specification Sections 3.19, 3.20 and 3.21 With Recommended Changes.

(Edited sections begin on following page.)

8-2

3. Annunciators and reset functions as specified in Section 13.

4. Exterior lights as specified in Section 8.

5. Auxiliary system on-off control as specified in Section 13 and as indicated.

6. Parking brake control as specified in Section 15 and as indicated.

3.18 PASSENGER COMFORT ENVIRONMENT

The vehicle shall carry the passenger in a comfortable environment as specified by the noise, ride, vibration and shock criteria in this Section as well as in a controlled ambient air environment as specified in Section 18.

3.19 NOISE CRITERIA AND CONTROL

3.19.1 General

The following contains the general requirements for maximum allowable sound pressure levels in passenger spaces, train operator locations and at the wayside. The Contractor shall devote particular attention to the design of the transit vehicle and equipment to obtain quiet operation. Enclosures, baffles, seals, acoustical absorption, body panels with adequate sound transmission loss, or other methods shall be incorporated into the transit vehicle design to adequately attenuate noise and vibration generated by wheels, rails, wind, motors, and all elements and equipment to ensure that the limitations on interior and wayside noise and vibration shall not be exceeded. The Contractor shall submit a report* which shall include engineering estimates of all specified noise levels inside and outside of the car and the engineering basis (pertinent structural data, tests, calculations, etc.) for such estimates.

* Include a specific deadline for report submission early in design phase.

3.19.2 Definitions

a. Sound Pressure Level

The sound pressure level in decibels is defined as 20 log p/po, where p is the measured rms sound pressure and po is the reference pressure, 20 micropascals.

b. Measurement

For acoustical tests and measurements, the Contractor shall use a sound-measuring system meeting the requirements for a Type I instrument, as defined in THE LATEST REVISION OF ANSI Standard S1.4. Where octave band or 1/3 octave band measurements are specified, the Contractor shall use an analyzer meeting the requirements for Class II filters, as defined in the latest revision to ANSI Standard S1.11. Narrow band noise or pure tones shall be identified using filters with a band width not exceeding 1/3 octave.

c. Environment

Noise criteria specified herein for the stationary car are based on measurements taken in an essentially free-field environment, such as outdoors, away from any reflective surfaces other than ballast and tie trackbed upon which the transit vehicle is parked and the adjacent flat, clear ground.

d. Auxiliary Subsystem

An auxiliary subsystem is any mechanism or structure other than the carbody, traction motor, or propulsion system gearing which performs a function at some time during the operation of the car, e.g., heating and air conditioning system, pumps, car door operators, motor alternator, air compressor or hydraulic power unit, fluorescent lamps and ballast, and braking systems. Noise created momentarily by emergency brake vent valves and wheel slip control valves shall not be included in any car noise measurements.

e. Pure Tone or Narrow-Band

If the sound pressure level of any 1/3 octave band from the 315-Hz band to the 4,000-Hz band exceeds the average of levels in the two adjacent 1/3 octave bands by 4 dB or more, that band shall be considered to contain pure tone or narrow-band components. ✓

3.19.3 Requirements for Noise Control

a. Interior Noise

The noise level along the car longitudinal centerline 4.5 ft above the floor and 2 ft or more from the end walls shall not exceed the limits set forth below. ✓

Condition	Maximum Noise Level
In open on dry, level tangent ballast and tie track at any speed up to 60 mph in any normal mode of acceleration, deceleration, or coasting with all auxiliaries operating.	69 dBA ✓
On tangent track on concrete invert in concrete horseshoe tunnel subway with direct fixation with no sound absorption and at any speed up to 50 mph in any mode of acceleration, deceleration or coasting with all auxiliaries operating. (See Figure 2-12 for tunnel details.)	78 dBA ✓

Condition	Maximum Noise Level
Car stationary in open on ballast and tie track with all auxiliaries operating simultaneously at maximum capacity, including any propulsion system components capable of operating with the car stationary.	68 ~~65~~ dBA and 80 ~~77~~ dBC

b. Wayside Noise

Sound pressure levels at the wayside shall not exceed the values shown below for the specified test condition, for a married pair on dry, level, tangent track. Measurements shall be made at the indicated distance from the track centerline 5 ft above top of rail.

Condition	Maximum Noise Level	
All auxiliaries operating simultaneously, car stationary	60 dBA at 50 ft	✓
Each auxiliary system alone, car stationary	65 dBA at 15 ft	✓
Two-car train at 60 ~~70~~ mph on ballast and tie track	80 ~~82~~ dBA (fast) at 50 ft	

Note: Change due t[illegible] limited test Track length. [illegible]als equivalent.

c. Equipment Noise

1. Traction Motors Prior to Installation on car

The noise produced by the traction motor alone or by the traction motor and gearbox assembly alone shall not exceed 87 ~~89~~ dBA 15 ft from the center of the motor while the equipment is operating at any speed from zero to the equivalent of 70 mph transit vehicle speed, and at loads equivalent to maximum electric braking in either direction. Normal cooling air flow shall be provided via ductwork and blowers that will be present in the finished car. This noise requirement may be relaxed with approval upon demonstration that the noise requirements of interior noise and wayside noise shall be obtained.

2. Propulsion Subsystem Gearbox

If the traction motor is tested alone, then the gearbox alone shall not create noise levels in excess of ~~84~~ 82 dBA 15 ft in any direction from the center of the gearbox with the gears rotating in either direction at all speeds from zero to the equivalent of 70 mph transit vehicle speed and at loads equivalent to maximum electric braking. This noise requirement may be relaxed with approval upon demonstration that the noise requirements of interior noise and wayside noise shall be obtained.

3. Auxiliary Equipment Prior to Installation on Car.

The noise produced by the individual operation of each item of auxiliary equipment or each complete operating subsystem, including refrigeration and air compressors, vents and valves, propulsion control equipment and cooling blowers, brakes, condensers, evaporators, motor generators, choppers and hydraulic power units but excluding traction motors and gearboxes, shall not exceed 65 dBA 15 ft in any direction from the center of the equipment while the equipment is operating at 700 Vdc and 68 dBA at 900 Vdc. All ductwork, baffles or appurtenances which form a part of the installed assembly shall be included as part of the equipment for noise tests.

4. Auxiliary Equipment Installed on Car

The noise produced by the individual operation of each item of auxiliary equipment or each complete operating subsystem, except traction motors and gearing, shall not exceed 65 dBA at 700 Vdc or, 68 dBA at 900 Vdc 15 ft from the car centerline on either side of the car, measured in the horizontal plane passing through the shaft or equipment centerline, while the equipment is operating at rated conditions with the car at rest. The equipment must be complete, installed on the car, and all components of each subsystem operating during tests for noise level.

5. Doors

Noise produced by operation of all side doors on one side of the transit vehicle, except the audible warning tone, shall not exceed neither 74 dBA (slow) nor 80 dBA (fast) ~~72 dBA, using the fast meter response,~~ at any point in the car 1 ft or more from the doors or door pockets and between 3 ft and 6 ft above the floor.

6. Service Brakes

The noise produced by full or partial application of the service brakes at speeds from 0 to 15 mph shall not exceed 75 dBA (fast) 15 ft from the car centerline in the horizontal plane passing through the axles.

7. Public Address (PA) Equipment

Noise generated by the PA equipment in the standby condition shall not exceed 40 dBA 1 ft from any loudspeaker with the electrical equipment energized at its nominal level. PA equipment with amplifiers unpowered except

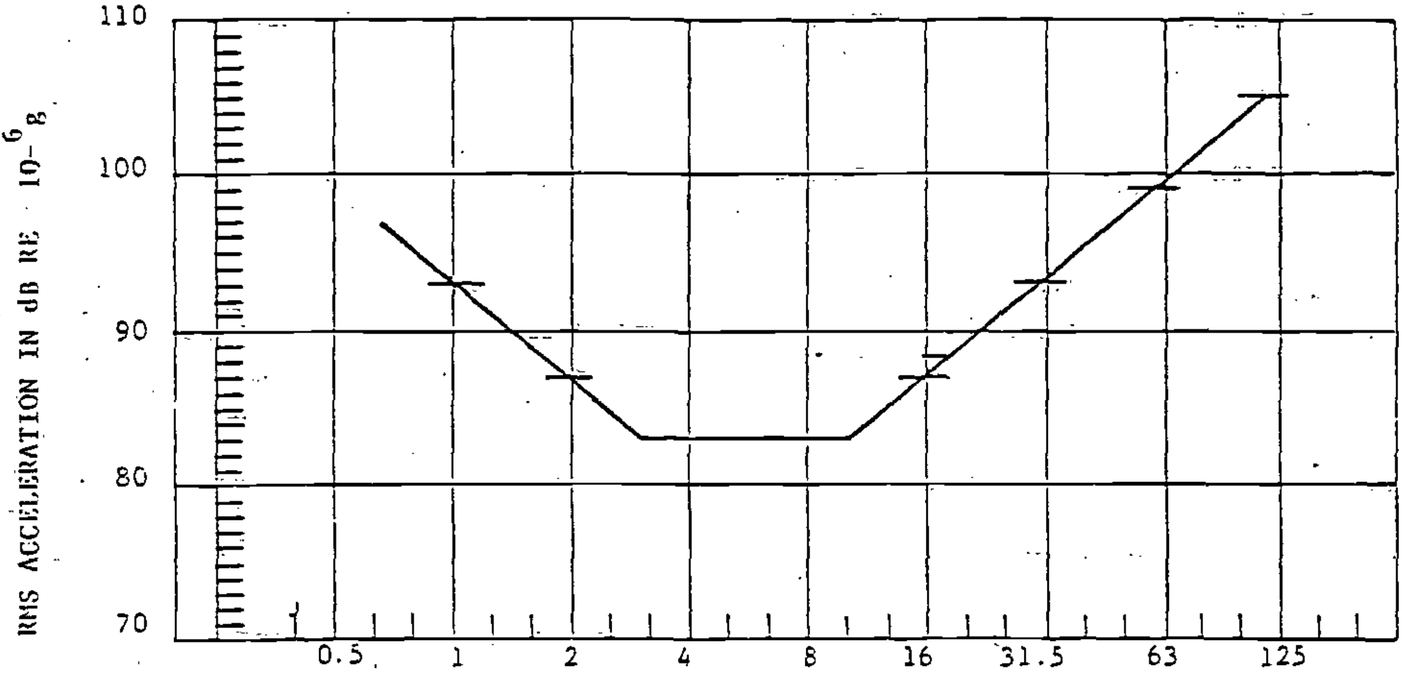

FIGURE 3-3
RIDE CRITERIA

during announcements shall be deemed to comply with this requirement unless hiss or hum from the speakers is audible with all auxiliaries off but the electrical equipment energized at its nominal level.

8. Lighting Subsystems

Noise generated by fluorescent lamps, fixtures, and ballasts installed in the car with all fixtures energized at the rated voltage and frequency shall not exceed 45 dBA 1 ft from any lighting fixture. ✓

d. Pure Tone or Narrow-Band Noise

If noise produced by traction motors or gears or auxiliary equipment contains pure tone or narrow-band components as defined in section 3.19.2 e, the noise limits ~~indicated~~ shall be lowered by 3 dBA.

3.20 RIDE QUALITY

3.20.1 Vibration Levels

With car in motion on track complying with track quality criteria herein, floor structure acceleration on car centerline over truck pivots and at midpoint of car shall not exceed the following limitations:

a. Steady-State Conditions

1. At any steady car speed up to 70 mph on level tangent track, acceleration of car floor in the vertical and lateral axes shall not exceed limits shown on Figure 3-3.

2. Measurements shall be made using 1/3 octave bands, and limitations shown on Figure 3-3 at center of each 1/3 octave band shall apply.

3. If a single discrete frequency component determines the magnitude of vibration within a particular 1/3 octave band, then the limitation shown at the vibratory frequency shall apply.

4. Steady-state ride quality shall be measured repeatedly or continuously with rms responding instrumentation having integration time or effective averaging time of from 1 to 4 sec.

5. Average vibration level during any 10-sec period shall not exceed the values shown on Figure 3-3.

b. Transient Conditions

During any slow or rapid linear acceleration or deceleration, or at switches or crossovers, maximum car floor structure acceleration shall not exceed 0.15 g in any direction when measured ~~recorded~~ to include all frequencies ~~of~~ from 1 to 30 Hz simultaneously.

3.20.2 Body Roll

Body roll shall not cause the vehicle to exceed the indicated clearance in any condition. Roll rate shall be commensurate with ride conditions as specified herein.

3.21 VIBRATION AND SHOCK CRITERIA

3.21.1 General

The general requirements for component design and for maximum allowable vibration magnitudes in passenger spaces and operator locations of the transit vehicle follow.

3.21.2 Component Design Criteria

a. General Provisions

All components mounted on the carbody, truck or axle shall be designed to have structural integrity and be operationally reliable over the life of the transit vehicle in the vibration and shock environment existing at the point of attachment of the component. In addition, these components and mounting systems shall be designed to prevent unacceptable vibration levels at any location in the car.

b. Vibration and Shock Environment

The following minimum vibration and shock environment, at the points of attachment, for which components and mounting systems shall be designed, is specified below. The Contractor shall design to higher values where experience or analysis so indicates.

1. Components mounted on the carbody shall be designed and mounted to withstand continuous sinusoidal vibrations of 0.4 g rms at any frequency from 1 Hz to 100 Hz in the three major axes, and randomly oriented shock impulses of 3-g peak with a duration of from 4 milliseconds to 10 milliseconds.

2. Truck frame-mounted components shall be designed and mounted to withstand, without fatigue or deterioration for the life of the vehicle, the normally occurring random shock and vibration magnitudes present at the support points on the truck frame. These magnitudes shall be considered to be one g rms with a crest factor (ratio of peak to rms acceleration level) of five, within the frequency range from 20 Hz to 10 kHz in all directions, and

shocks occurring up to 100 times per operating day of 40-g peak in the vertical axis and 12-g peak in the lateral axis with pulse durations of from 4 milliseconds to 10 milliseconds.

3. Axle-mounted components shall be designed to withstand, as a minimum, continuous random vibrations of 10 g rms within the frequency range from 10 Hz to 10 kHz in all directions and shock pulses of 100 g in each major axis, with durations from 0.5 milliseconds to 2.0 milliseconds occurring approximately 100 times per operating day.

c. Vibration Levels

With the car stationary, the maximum permissible car interior levels resulting from operation of all auxiliary equipment shall be as specified herein.

1. Traction Motors

The vibration of a traction motor, detached and supported on resilient mounting providing at least 0.25-in static deflection, shall not exceed 0.0015 in peak-to-peak displacement at the motor bearing housings and mounting bosses while the motor is rotating at any speed between 50% and 100% of the maximum normal operating speed.

2. Auxiliary Equipment

With the car stationary and with each individual auxiliary unit operating at rated capacity and with all auxiliaries operating simultaneously, the vertical or horizontal vibrations of the floor, walls, seat frames, or any surface with which the passengers or the operator can come in contact shall not exceed any of the following values.

Displacement, peak-to-peak	0.10 in
Acceleration, peak value	0.01 g below 20 Hz
Velocity, peak value	0.03 in/sec above 20 Hz

3.22 ELECTROMAGNETIC INTERFERENCE AND NOISE CONTROL

3.22.1 Electrical Interference

Design techniques, construction methods, and equipment shall be employed to prevent interference caused by internal sources from affecting proper operation of vehicle systems. In addition to coordinating frequencies, necessary balancing, filtering, shielding, modulation techniques, and isolation shall be provided to maintain signal-to-noise ratios within clearly workable limits.

a. Electrostatic and magnetic electrical shielding methods shall be employed to minimize effect of stray signals and transient voltages on low-level interconnecting cables. Interconnecting power and signal cables shall be physically separated where practical, and magnetically shielded where necessary. Suppression devices shall be employed on relay circuits where necessary to protect low-level circuits from relay transients.

b. Components and functional circuits shall be grouped according to their similar sensitivities to electrical interference and power supply needs, and to reduce effects of voltage drops in ground circuits. Power and return leads shall be routed in same raceway or harness. Suppression devices shall be used on power-supply leads where necessary to suppress interference at the input to sensitive circuits.

8.3 Discussion of Recommended Changes

3.19.1 General

Line 5

Insert a comma after "acoustical absorption" to clarify the intent of that statement.

Line 11

A specific schedule for submission of the acoustical analysis and report early in the design cycle should be imposed to assure that a report is submitted in a timely manner. Past experience indicates that, although the requirement for such a report is stated in the specification, without a deadline the report will not be submitted and, far more importantly, the analysis and preliminary engineering required to prepare the report is not performed. The result is that the vehicle is built without any significant consideration of acoustical characteristics and, by the time acceptance testing is performed, it is far too late in the design cycle to have any significant influence on the vehicle noise and vibration characteristics. We cannot recommend a specific time for submission of the report because we do not know the schedule of submissions required for other aspects of vehicle design. However, in some contracts there has been a CRITICAL DESIGN REVIEW (CDR), early in the design phase, at which time it would be appropriate to require submission of the acoustical report. If an early design review period is not scheduled for other purposes, then a calendar time like two or three months following contract signing would be an appropriate time for submission of an acoustical design report.

3.19.2B Measurement

Line 3

Insert immediately prior to ANSI S1.4 "the latest revision of". This is because ANSI Standards are continuously updated and it should be clear that the contemporary standard at the time of contract initiation is the appropriate version.

3.19.3A (3rd Condition)

The maximum noise level for the car stationary on ballast and tie track with all auxiliaries operating simultaneously may be 68 dBA in accordance with APTA Guidelines. 80 dBC is also acceptable.

3.19.3B(3rd Condition)

The maximum wayside noise levels for the 2-car train on ballast and tie track may be 80 dBA at 60 mph which is equivalent in performance to the value of 82 dBA at 70 mph, contained in the initial draft. The reason for suggesting specification at the lower speed is that a very limited length of surface ballast and tie test track will be available in the SCRTD yards and a lower test speed will be easier to attain within those space limitations. The change will not influence the noise emission of the vehicle because it is equivalent to 82 dBA at 70 mph.

3.19.3C1 Traction Motors

Heading

Add "Prior to Installation on Car" to clarify.

Line 3

The noise produced by the traction motor alone or by the traction motor and gearbox assembly alone, should be specified at 87 dBA rather than 89 to be in accordance with APTA Guidelines. The traction motor noise is of crucial importance in attaining satisfactory wayside noise levels in the complete vehicle and traction motor noise exceeding state-of-the-art performance will be reflected later in the program in excessive wayside noise levels from the complete vehicle.

Line 9

The statement, "This noise requirement may be relaxed...." should, in our opinion, be deleted from the specification in this and the following paragraph on the propulsion system gearbox, for two reasons: The engineer always has the power to relax specifications without stating the possibility beforehand in the specification. Making that statement in the specification extends an open invitation to the car builders to request a variance. Invariably, such a request is based upon the fact that they would prefer not to perform the noise reduction engineering on the motor and would prefer to postpone grappling with noise control until the motor is installed in the finished vehicle and they know where they stand. The request rarely, if ever, is backed up by valid engineering estimates of the performance of any feasible noise control measures intended to be applied to the completed vehicle. Once a complete prototype vehicle is available for testing, it is far too late in the program to modify noise emission from the motor, or vehicle design for noise control purposes.

3.19.3C3 Auxiliary Equipment

Heading

Add "Prior to Installation on Car", to differentiate it from the following paragraph for the same equipment after installation on the car.

3.19.3C5 Doors

Line 3

A review of measured door noise levels in a variety of vehicles in 1980 indicated that contemporary door operating equipment with appropriately designed mounting and door pockets was better described and controlled by the specification of "neither 74 dBA slow nor 80 dBA fast". This accounts for the short transient occurring at the moment of the doors hitting the stops without completely eliminating control of the long-term, average door operation noise.

3.19.3D Pure Tone or Narrow Band Noise

Line 3

Something has been lost in transcription. The sentence should state "... narrow band components as defined in Section 3.19.2E, the noise limits shall be lowered by 3 dBA."

3.20.1A3

Line 1

This section should read, "If a single, discrete frequency component determines the magnitude of vibration within a particular 1/3 octave band, then the limitations shown at the vibratory frequency shall apply".

3.20.1B Transient Conditions

Line 4

Should read, "... direction when measured to include all frequencies from 1 to 30 Hz simultaneously." This is to clarify that this measurement should be essentially a wide-band measurement from 1 Hz to 30 Hz, not a narrow band spectrum analysis. However, note that it is most likely that the resonant characteristic of the car body will probably result in a single spectral component controlling the peak acceleration in the 1 to 30 Hz band and that, therefore, it may be acceptable to demonstrate by narrow band spectrum analysis compliance with this section. It is intended, however, that the measurement be performed with a filter with a band pass extending from 1 Hz to 30 Hz and a peak indicating instruments such as a high speed oscillograph, storage oscilloscope, true peak reading and holding vibration meter, or similar device.

3.21.2C2 Auxiliary Equipment

Line 6

The last portion of the sentence should say, "... contact shall not exceed any of the following values." This clarifies which of the limitations controls in cases where it may seem that more than one could control at a given frequency. This change does not change the intent or the meaning of the specification as it was originally stated.