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RIDE QUALITY CRITERIA AND THE DESIGN PROCESS

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SUMMARY

Conceptual designs for advanced ground transportation systems often hinge on obtaining acceptable vehicle ride quality while attempting to keep the total guideway cost (initial and subsequent maintenance) as low as possible. Two ride quality standards used extensively in work sponsored by the U.S. Department of Transportation (DOT) are the DOT-Urban Tracked Air Cushion Vehicle (UTACV) standard and the International Standards Organization (ISO) reduced ride comfort criteria.

These standards are reviewed and some of the deficiencies, which become apparent when trying to apply them in practice, are noted. Through the use of a digital simulation, the impact of each of these standards on an example design process is examined. It is shown that meeting the ISO specification for the particular vehicle/guideway case investigated is easier than meeting the UTACV standard.

INTRODUCTION

One of the more difficult problems associated with the conceptual design of advanced transportation systems is achieving acceptable ride quality while simultaneously avoiding guideway structures which will be expensive to build and maintain. In analyzing new transportation concepts, especially those involving elevated guideway structures, the analyst must consider the vehicle/guideway combination as a system. The elevated guideway structure will deflect elastically under the moving vehicle(s) load, thus introducing a periodic disturbance input to the vehicle. In addition, those guideway inputs broadly classified as "roughness" also introduce undesirable vehicle motion. In the case of elevated guideway structures, it has been shown [1]* that roughness can be directly related to such guideway construction tolerances as pier survey error, pier settlement, camber and surface finish. It has also been demonstrated that guideway flexibility and construction tolerances can, in turn, be related to the ride quality performance of the vehicle. The most commonly employed ride quality standards in research sponsored by the U.S. Department of Transportation include the Urban Tracked Air Cushion Vehicle (UTACV) specification [2] and the International Standards Organization (ISO) criteria [3]. In previous work on conceptual vehicle/guideway design [1,4], some difficulties were encountered by the author in applying the aforementioned standards. In particular, when finite acceleration time histories were obtained from a vehicle/guideway computer simulation [1,4], a lack of preciseness in the accompanying instructional material for both the UTACV and ISO criteria seemed to permit a wide area of judgment to be exercised by the user. Thus, it seemed possible that two analysts working with the same data record could arrive at different conclusions regarding ride quality compliance. It was also discovered that an identical acceleration record could be in compliance with one standard

*Numbers in brackets indicate references.

and not the other. These quantifiable problems, in addition to some subjective observations concerning the UTACV and ISO standards, will be discussed in the following sections of the paper.

VEHICLE/GUIDEWAY COMPUTER SIMULATION

It is worthwhile to devote a brief section of the paper to discuss the origin of the acceleration time histories to be discussed. A digital computer simulation was developed for the purpose of studying conceptual vehicle/guideway systems with the ultimate objective of relating vehicle ride quality to guideway design parameters and construction tolerances [1]. Figure 1 is a schematic representation of the simulation and illustrates the significant program elements and input/output quantities. In particular, the simulation was used to study the performance of the conceptual air cushion vehicle/guideway configuration whose major system parameters are listed in Table 1. The vehicle properties are essentially self explanatory while the guideway parameters include the span fundamental bending frequency and the pier spacing (span length) ℓ. The construction tolerance parameters are also shown in table 1 and they represent, in general, maximum expected values in a statistical sense; a detailed discussion can be found in Reference 1. It should be emphasized that the vehicle acceleration records obtained from such a complete vehicle/guideway simulation should be typical of records obtained from actual vehicle test runs. The problems of processing this acceleration data in the UTACV and ISO formats and the areas open to interpretation (or misinterpretation) will be discussed in the following sections.

THE UTACV RIDE QUALITY STANDARD

In part, the UTACV ride quality standard [2] requires that the spectral composition of passenger cabin acceleration time histories, in a spectral density format, must not exceed the boundaries shown in Figure 2 over the frequency range 0.1 to 50 Hz. The only requirements on processing the acceleration data are that the time history shall be 30 seconds or longer and that the spectral density calculation be made with a frequency resolution of 1.0 Hz, and plotted at 1.0 Hz and each succeeding integral frequency in the passband. Considering the problems associated with estimating spectral densities from finite data records, the above stated UTACV guidelines are at best not sufficient. First, there is no information as to which estimation procedure (Blackman-Tukey, Fast Fourier Transform or direct band pass filtering) is to be used in a given situation. This is important as these methods can sometimes produce somewhat different results. Second, guidelines related to the original data collection and the required accuracy of the spectral density estimate are not given. In order to expand on this, it is necessary to introduce some important parameters. The length of the original data record T is given by:

$$T = Nh \tag{1}$$

where N is the number of data points and h is the sample spacing. The standard (statistical) error ε is a measure of the "goodness" of the spectral density estimate and is given by [5]

$$\varepsilon = \sqrt{1/B_e T} \tag{2}$$

or from eq. (1),

$$\varepsilon = \sqrt{1/B_e Nh} \tag{3}$$

where B_e is the frequency resolution bandwidth. A seemingly curious fact is that the finer the resolution, the larger the error; this is related to the problem of trading off frequency resolution for the confidence level in the final spectral density estimate. Note that the UTACV specification does implicitly set a maximum allowable standard error by fixing B_e = 1.0 Hz and T to at least 30 seconds; thus

$$\varepsilon_{\mathrm{UTACV}} = \sqrt{\frac{1}{30}} = 0.183$$

An alternate way of expressing statistical error is to specify the statistical degrees of freedom (sdof) n where [5]

$$n = 2/\varepsilon^2 \tag{4}$$

For the UTACV specification,

$$n_{\mathrm{UTACV}} = 60$$

For any specification employing spectral densities, the values of ε and/or n should be explicitly stated since their importance may not be apparent to the uninitiated user employing a packaged processing routine. For example, Figure 3 depicts two acceleration spectral density estimates computed from the same record.[1] The differences in the spectral density estimate for the case where $\varepsilon = 0.22$ (n=40) and the case where $\varepsilon = 0.16$ (n=80) are significant. Only the latter case satisfies the implicit UTACV accuracy requirement. Some insight into the meaning of standard error or, equivalently, sdof, can be gained from Figure 4 taken from Reference 6; it may be seen that 60 sdof corresponds to a 50% confidence level that the spectral density estimate will be within ±12% of the true value and a 90% confidence level that the estimate will be within ±30% of the true value. Similarly, 40 sdof corresponds to a confidence level of 90% that the estimate will be within ±37% of the true value. Some other interesting relationships [5,6] are as follows: The lowest frequency f_ℓ in the spectral density band of interest is related to B_e through:

$$f_\ell = B_e/2 \tag{5}$$

The cut-off (Nyquist) frequency f_c for the case of a vehicle traveling at velocity V is:

$$f_c = V/2h \tag{6}$$

and the frequency f_h below which no aliasing (frequency masking) is to occur is:

$$f_h = f_c/p, \quad 3/2 \leq p \leq 2 \tag{7}$$

[1]The acceleration record is based on the vehicle/guideway parameters in Table 1 and a vehicle speed of 121 km/hr (75 mph).

The higher value of p gives the least amount of aliasing below f_h. Surprisingly, the UTACV specification gives no guidelines with respect to eliminating the potentially significant aliasing errors. Two interesting points with respect to the above formulas (5) through (7) should be noted: First, from eq. (5), substitution of the UTACV specified value of B_e = 1.0 Hz yields:

$$f_\ell = 0.5 \text{ Hz}$$

The UTACV specification however requires that f_ℓ = 0.1 Hz. and is therefore not self consistent. Secondly, equations (6) and (7) yield:

$$h = V/2p\ f_h.$$

Certainly if the upper frequency of interest for the UTACV specification is as stated, 50 Hz, then one would want no aliasing below 50 Hz; thus, setting p = 2 and f_h = 50 Hz.,

$$h = \frac{V}{200}$$

The time Δt between samples is then

$$\Delta t = h/V = 1/200 = .005 \text{ sec.}$$

For a 30 second record, 6000 data points are therefore required. Thus, the UTACV upper frequency of interest (50 Hz) can put a difficult and perhaps unnecessary burden on data collection requirements. In particular, for digital computer simulations, such requirements are costly. Moreover, most reasonably designed passenger compartments will be isolated from any significant 50 Hz disturbances and as 50 Hz is well beyond the critical frequency range for humans, there is no apparent reason why it should not be relaxed.

It seems clear that the lack of explicit guidelines within the UTACV standard, coupled with some inconsistencies and possible impractical data requirements, force the user to resort to "best engineering judgment". Under such conditions, it is not at all clear what it means to "meet" or "violate" the UTACV ride quality specification.

A more subjective observation about the UTACV specification is that its popularity with many users is based on the fact that guideway roughness disturbances are often presented in spectral density format: therefore, if $G(\omega)$ is the guideway spectral density input, and $H(j\omega)$ is the vehicle/suspension/guideway transfer function, the acceleration spectral density for linear, stationary, ergodic systems is:

$$A(\omega) = |H(j\omega)|^2\ G(\omega).$$

As $A(\omega)$ can be compared directly with the UTACV limit, the UTACV standard is particularly convenient for the analyst. This approach is however, somewhat simplistic and tends to obscure some of the thorny problems associated with processing actual data. A few other personal objections are, first, that there is no way to judge the relative ride quality for differing acceleration spectral densities which, in part, are due to the lack of any time element associated with the UTACV limit; i.e., will the ride be comfortable for 15 minutes, 1 hour, 3 hours? Second and most important, it is also due in part to the lack of any statistical data on what percentage of the population could be reasonably expected to find the UTACV ride comfortable.

THE ISO SPECIFICATION

The ISO ride comfort specification [3] for vertical acceleration is illustrated in Figure 5. More correctly, the solid lines represent "fatigue reduced proficiency" limits as a function of time spent in the vibration environment. The boundaries limit rms acceleration as a function of frequency within the range 1.0-80. Hz. According to the ISO specification, the fatigue reduced proficiency boundary "specifies a limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency in many kinds of tasks." The reduced comfort boundary is assumed to lie approximately at one-third (10 dB below) of the reduced proficiency boundary. For example, the one hour ISO reduced ride comfort boundary is illustrated by the dashed line in Figure 5. The TRW Corp. [7] has proposed an extension of the ISO specifications to below 1.0 Hz in order to limit acceleration at those frequencies where motion sickness is known to occur. When processing a finite data record, the user follows Paragraph 4.2 in the ISO Specification Document [3] and some problems arise almost immediately. For example, Par. 4.2.1 claims that the limits depicted in Figure 5 are valid for discrete frequency vibrations. Par. 4.2.2 states that when there are discrete multiple frequencies, i.e., "vibration present simultaneously at more than one discrete frequency in the range 1.0 to 80 Hz." the evaluation of ISO ride quality compliance is accomplished as follows: "The rms acceleration of each frequency component shall be evaluated separately with reference to the appropriate limit at that frequency". This instruction is disturbing for two reasons: Since no limit on the number of simultaneous multiple frequencies which can be processed is given, it implies (1) that there is no cumulative effect of multiple frequencies and (2) that any number of multiple frequency components, including those obtained from Fourier analysis could be evaluated according to Par. 4.2.2. Since acceleration output from the vehicle/guideway simulation discussed earlier was routinely processed by Fourier analysis, it was felt that the rms acceleration Fourier components at each frequency could be evaluated according to the ISO instructions for multiple frequency inputs. This procedure was initially adopted and applied to the nominal vehicle/guideway case defined in Table 1, with V = 242 km/hr (150 mph). The results are shown in Figure 6. It quickly became apparent, however, that for longer acceleration time histories of the same steady state vehicle response, the discrete frequency resolution became finer (more frequencies) and the rms value of each frequency component decreased, making it easier to "meet" the ISO specification. Obviously, the applicable paragraph for this situation is Par. 4.2.2 entitled "Broad-band Vibration"; this states that the rms acceleration in each 1/3 - octave band is to be evaluated separately with respect to the appropriate limit at the center frequency of that band. The result of this procedure is also illustrated in Figure 6. Nevertheless, Par. 4.2.2 on multiple frequencies remains vague for application purposes, and unsatisfying with regard to an intuitive feeling that a cumulative effect should exist. Other features lacking in the ISO specification include a limit on sustained acceleration and jerk (time derivative of acceleration) associated with vehicle operations such as starting and braking. As in the UTACV specification, statistical data on what segment of the population could be reasonably expected to find the ISO ride comfortable is not given.

EXAMPLE

Using the simulation discussed earlier in the paper, a design exercise was carried out to determine the effect of changing the guideway pier spacing on vehicle ride quality compliance. It is useful to know the range of acceptable span lengths (pier spacing) since a detailed design will generally involve an optimum economic pier spacing which involves a trade-off between smaller span cross sections (less span material) and shorter span lengths (more piers). A convenient non-dimensional span length parameter is the vehicle-to-guideway span length[2] ratio L. The nominal value for the case illustrated in Table 1 is $L = 0.3$. Two additional cases were run with $L = 0.24$ and $L = 0.4$. Conditions of interest included the situation where guideway flexibility is the only disturbance, and where both flexibility and nominal construction tolerances (see Table 1) are included. Figure 7 shows the acceleration response spectral density due to the flexibility input only for V = 242 km/hr (150 mph) and $L = 0.24$, $L = 0.3$, and $L = 0.4$. There is no major effect on UTACV ride quality compliance the significant difference being in the shift of the major peak. The frequency f_p associated with this peak is given by $f_p = V/\ell$. When the nominal construction misalignments are added, Figure 8 illustrates that there is a broader band response characteristic and that the UTACV ride quality standard is violated in all three cases. Moreover, the shorter pier spacing ($L = 0.4$) produced the "rougher" ride[3] despite the greater relative flexural rigidity associated with shorter span lengths. The reason for this is that the pier survey and pier settlement misalignments, assumed equivalent over the range $0.24 \leq L \leq .4$, produced a rougher guideway profile over the shorter span length. Comparing Figure 8 to Figure 6 however, it is clear that for the nominal case (including flexibility and construction misalignment) the one-hour ISO specification is easily met while the UTACV limit is exceeded. At this time there is no definite information on the relative stringency or leniency in the two standards. It would be costly, perhaps prohibitively so, to design new systems to meet ride quality standards which are overly stringent. On the other hand, people cannot be subjected to rides which are so rough, that the passenger feels in imminent danger. From a personal viewpoint, the major fault in the ISO and UTACV ride quality standards is the lack of statistical information which would provide system planners and designers with some information on what percentage of the population would refuse to ride a vehicle meeting a particular ride quality standard. Only then can the systems analyst determine the trade-off between increased cost to meet a more stringent standard and the additional revenues to be derived from increased ridership.

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[2]Vehicle length is conveniently taken as the length between fore and aft suspension mid-points; in the case of an automobile this would be the wheelbase.

[3]"Rougher" ride is arbitrarily defined in this paper by the higher rms acceleration level.

CONCLUSIONS

Designing advanced transportation systems to meet ride quality standards will place requirements on the vehicle suspension system, guideway construction tolerances and subsequent guideway maintenance. These requirements have a significant impact on initial capital costs and ongoing maintenance costs. It therefore seems imperative that reliable and meaningful ride quality criteria be developed. While the obvious operational shortcomings in the ISO and UTACV specification can be remedied, the lack of information on the percentage of ride quality acceptability by the population cannot be easily retrieved, thereby depriving the designer of important trade-off information. It is hoped that this paper has adequately emphasized the importance of meaningful ride quality criteria in terms of the potential design and cost impacts involved and that it has also illustrated the need for precise guidelines and language with regard to processing vehicle data in the required ride quality format.

REFERENCES

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2. Anon., "Performance Specification and Engineering Requirements for Urban Tracked Air Cushion Vehicle," DOT-UT-10026, May 10, 1971.

3. Anon., "Guide for the Evaluation of Human Exposure to Whole-Body Vibration", International Standard ISO/DIS 2631, 1974E, International Organization for Standardization, 1974.

4. Katz, R. M., Nene, V. D., Ravera, R. J., and Skalski, C. A., "Performance of Magnetic Suspensions for High Speed Vehicles Operating over Flexible Guideways", J. Dyn. Sys. Meas. Cont., V. 96, N. 2, June 1972, pp. 204-212.

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6. Sussman, N. E., "Statistical Ground Roughness", MITRE MTR-6621, Feb. 1974.

7. Burkeland, P. W., et. al., "Investigation of Reduced Cost Guideway Designs for the Tracked Air Cushion Research Vehicle." FRA-ORD&D-74-55, (TRW Report #96030-L002-0, Available from NTIS).

TABLE 1

EXAMPLE SYSTEM PROPERTIES

PASSENGER CABIN MASS = 22664 kg (1553 slugs)

PASSENGER CABIN PITCH MOMENT OF INERTIA = 1.7×10^5 kg-m^2 (1.5×10^6 lb-in-sec^2)

CUSHION MASSES(2) = 569 kg (39 slugs)

SUSPENSION BASE = 9.2 m (30 ft)

UNSPRUNG CABIN HEAVE FREQUENCY = 1.0 Hz

NOMINAL PIER SPACING = 30.5 m (100 ft)

NOMINAL SPAN FUNDAMENTAL FREQUENCY = 3.52 Hz

MAXIMUM PIER SURVEY ERROR = 1.27 cm (0.5 in.)

MAXIMUM CAMBER TOLERANCE ERROR = 20%

MAXIMUM ALLOWABLE PIER SETTLEMENT = 1.91 cm (0.75 in.)

CALIFORNIA PROFILE INDEX (SURFACE FINISH) = 2.5 cm/km (1.6 in./mi)

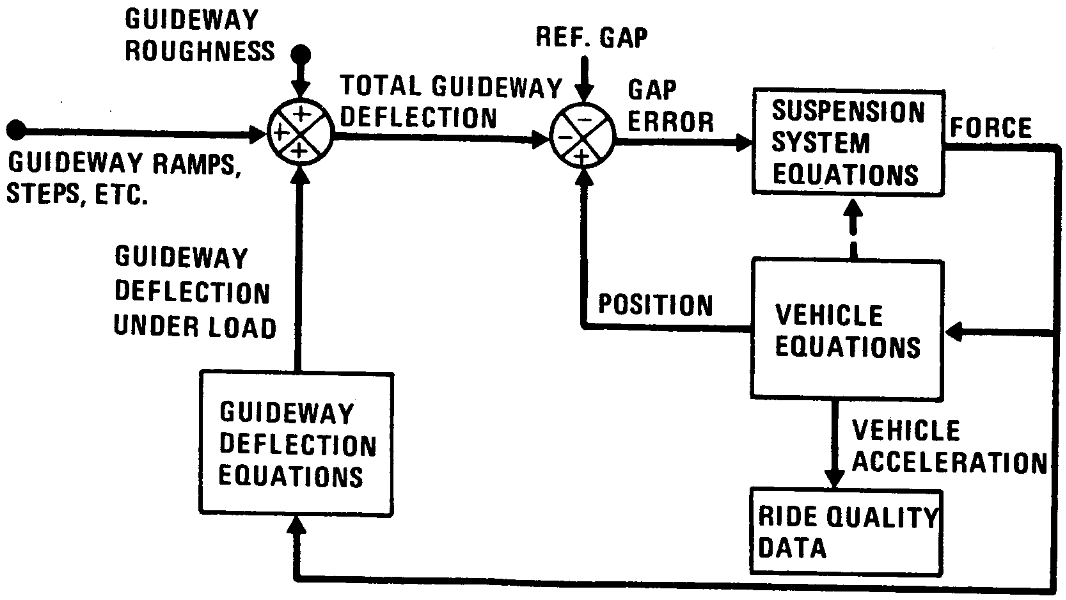

Figure 1 - General Simulation Flow Diagram

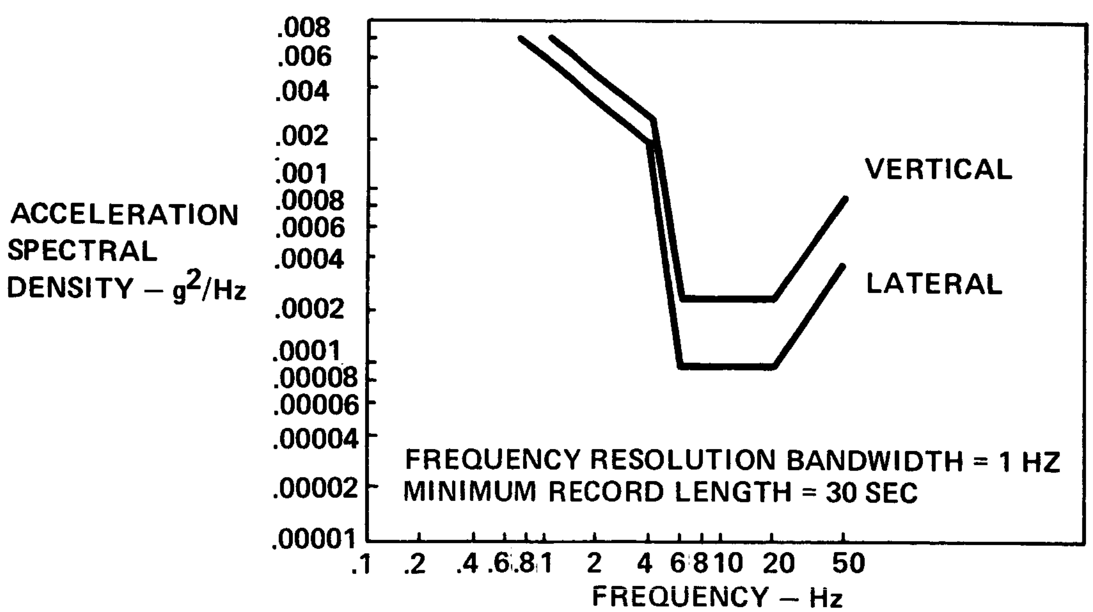

Figure 2 - The UTACV Ride Quality Standard

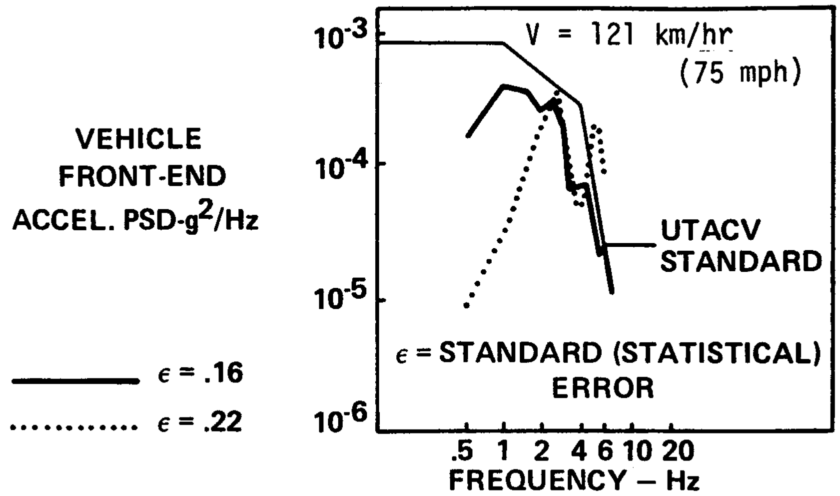

Figure 3 - Effect of Standard Error on PSD Estimate

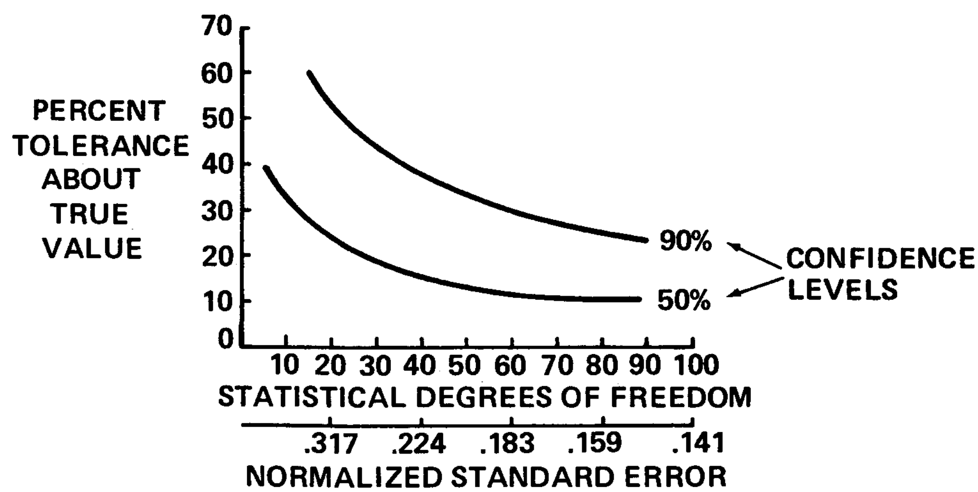

Figure 4 - Relationship Between Standard Error on Confidence in PSD Estimate

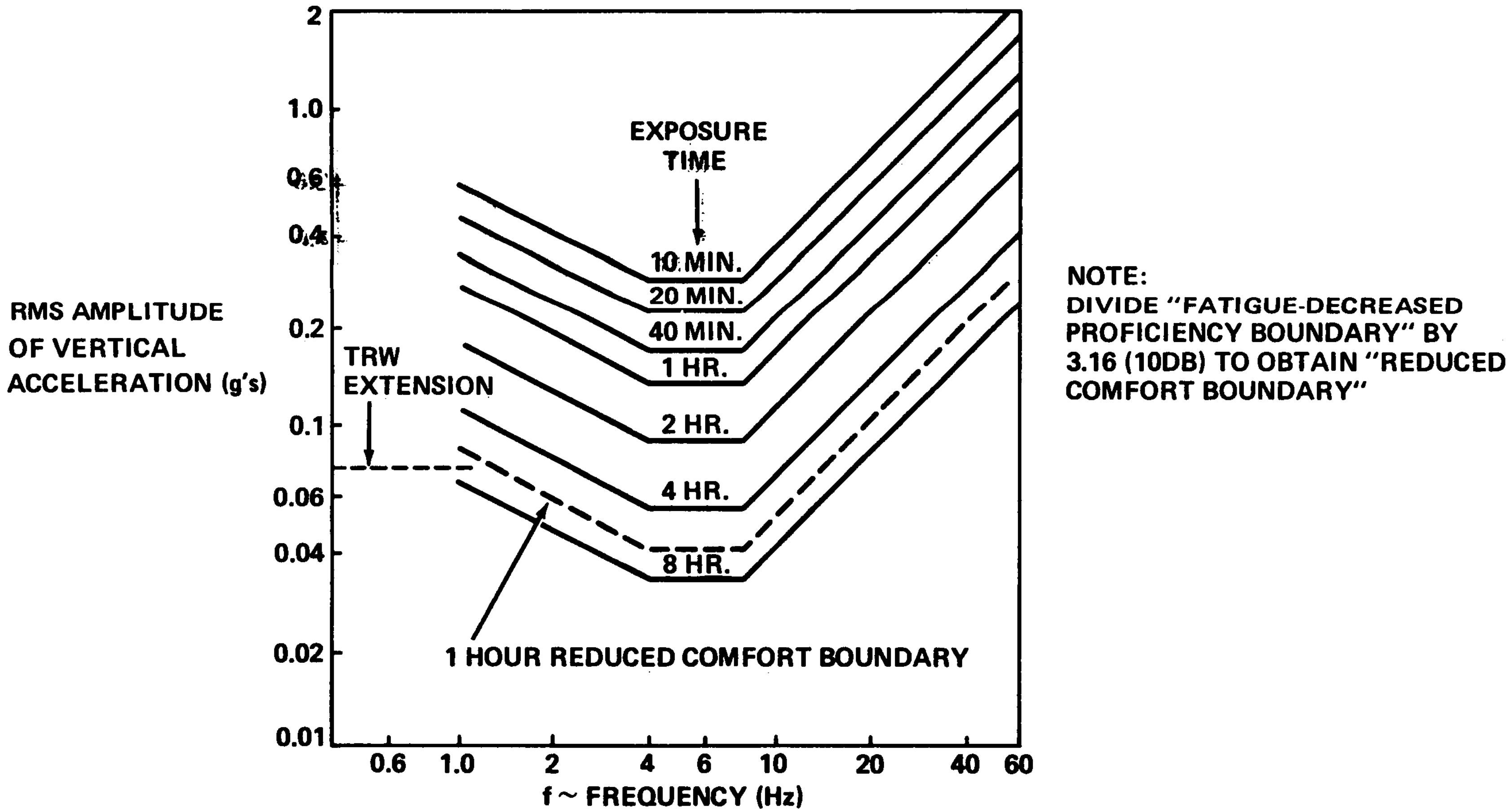

Figure 5 - The ISO Ride Quality Standard

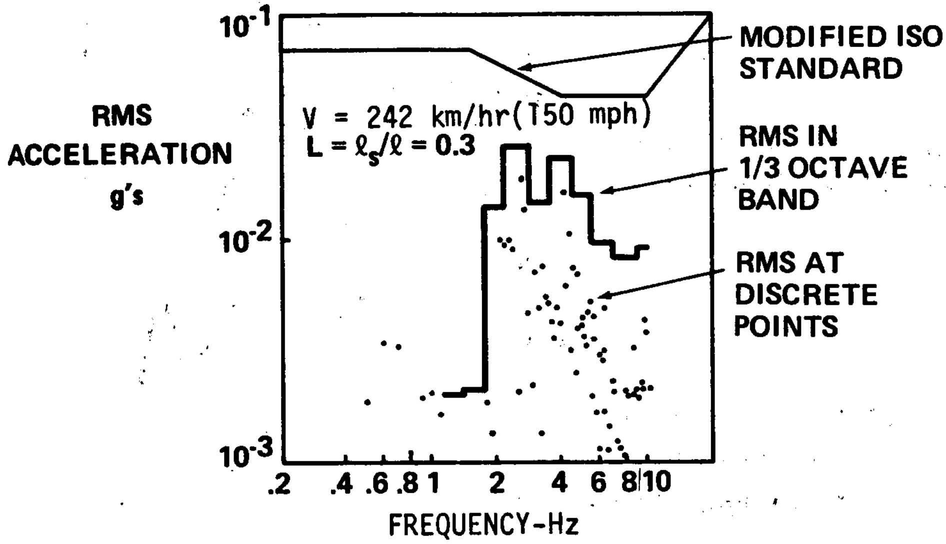

Figure 6 - Cabin Acceleration Spectrum in the ISO Format - Guideway Flexibility and Roughness Included

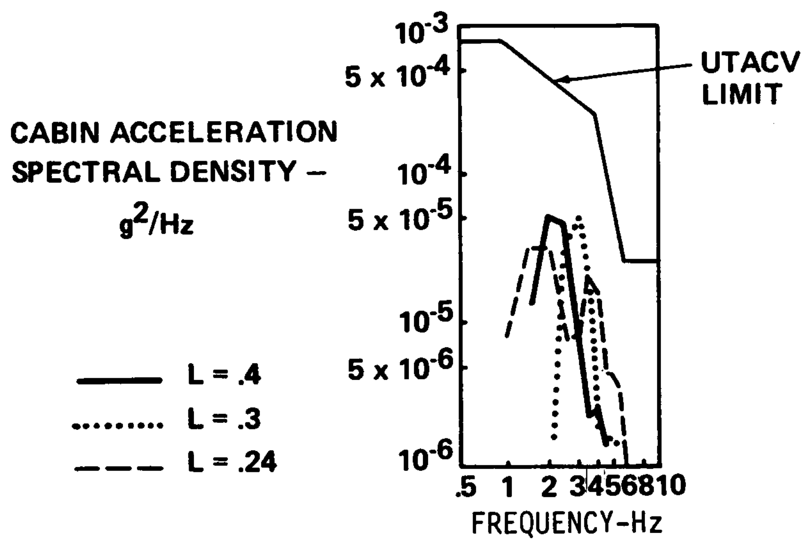

Figure 7 - Cabin Acceleration PSD Due to Guideway Flexibility Only: V = 242 km/hr (150 mph)

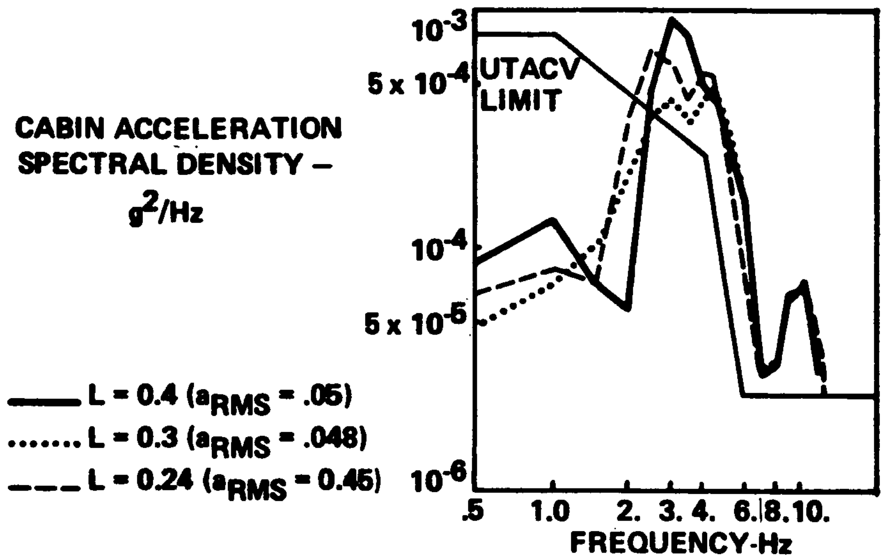

Figure 8 - Cabin Acceleration PSD Due to Guideway Flexibility and Roughness: V = 242 km/hr (150 mph)