Vibration Requirements for Ride Quality: Recent Progress and Trends

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This paper is an update of the author's 1975 review of ride quality with particular reference to the improvements planned for International Standard ISO 2631. Suggestions for future work are included with special attention to the problems of repeated shock-type motion.

Ride quality with particular respect to International Standard ISO 2631 (1) was critically reviewed for a 1975 symposium jointly sponsored by the U.S. Department of Transportation and the National Aeronautics and Space Administration (2). Since then, more information has become available from laboratory and field work, and important short-term amendments to ISO 2631 are expected to be published soon. Also, a major long-term revision of ISO 2631 has commenced. Therefore, the objectives of this paper are as follows: (a) to outline and discuss briefly the short and long-term amendments to ISO 2631; (b) to review some of the recent investigations on ride quality, particularly those originating in the United Kingdom; (c) to highlight areas that require further research, particularly the problems of shock-type motions; and (d) to encourage feedback from users of the standard to those evolving the long-term revision of ISO 2631.

SHORT-TERM REVISION OF INTERNATIONAL STANDARD ISO 2631

In a previous review (2), official work on improvements to ISO 2631 then proceeding or planned was described, together with suggestions for further improvements. Excluding the long-term revision of ISO 2631, which will be covered later in this paper, progress can be summarized as in the following three sections.

Progress to Date (As Shown by New Official Documentation on ISO 2631)

Draft Addendum 2 (DAD2) to ISO 2631 (Evaluation of Exposure to Whole Body z-Axis Vertical Vibration in the Frequency Range 0.1 to 1.0 Hz) at least partly fills the information gap for human response to vibration below 1 Hz, particularly in relation to motion sickness (3). More data are needed, however, to provide guidelines for the effects of vibration on human performance and the effects of other axes.

Draft Amendment 1 (DAM1) to ISO 2631, which should be finally approved and issued soon, provides the standard with several important interim improvements (4). In short, the amendment

1. Emphasizes the importance of individual variations in response to vibration, although these are not yet quantified due to lack of data;
2. Provides a definition of "crest factor" and a limited dispensation increasing the recommended maximum value from 3 to 6;
3. Notes that, for comfort and performance criteria only, the summed weighted method is now the preferred method for evaluating a complex single-axis vibration and that multiaxis vibration should be evaluated by rms weighted summation; and
4. Gives an alternative, more convenient mathematical time dependency relationship (a^2t = constant) that approximates, up to 8 h of exposure time, the vibration curve in the standard.

Progress to Date in Obtaining More Data

Those research areas in which significant progress has been made to date are noted below. It is likely that much of these data will be used in the preparation of the major long-term revision of ISO 2631.

Time Dependency

Since 1975, a comprehensive review of earlier data (5) and more recent experiments (6,7) support previous suggestions that the duration of vibration exposure has less effect on human performance and comfort than is implied in ISO 2631.

Tolerance Curves

Past investigations show that the shapes of the acceleration/frequency curves in ISO 2631 require considerable modifications to cover specific situations and different criteria (6,8-13). These curves are affected significantly by many variables such as seating, body posture, type of harness, feet versus seat-of-the-pants vibration, and the nature of the task itself. These important findings may be reflected in a revised ISO 2631, as will be discussed later in this paper. Perhaps the most fundamental discovery has been that so-called secondary, higher-frequency biomechanical resonances of the head and shoulders in many situations tend to flatten the ISO 2631 a_z and $a_{x,y}$ curves that, in some cases, rise too steeply at frequencies above 8 and 2 Hz, respectively.

Rotational Vibration

More data are now available (14-16) on human response to rotational vibration. Still, the translation of these data into standards will be complicated since human response is sensitive to the position of the axis of rotation.

Inadequate Progress to Date

Progress on human reaction to repeated shock-type inputs has been disappointing, in spite of the acknowledged need to fill this important gap in ride quality requirements (17). There has also been slow progress in agreeing on specific requirements for vibration in ships, in part because of the need to reconcile the views of ship designers (as represented in ISO Subcommittee ISO/TC108/SC2) with those concerned with human responses (as represented in ISO/TC108/SC4). This is an example of a basic problem in practically applying ISO 2631 to a particular situation--a difficulty that, it is hoped, will be overcome in the long-term revision of the standard. More feedback from the users of ISO 2631 would be helpful in solving this problem. There is also a need for a better, perhaps a "standard," definition of the instrumentation required to measure and analyze vibration. This need is being investigated currently by two ISO subcommittees and will be covered more adequately in the long-term revision of the standard.

Figure 1. Outline of draft long-term revision of ISO 2631.

PART I General Introduction 0 Introduction 1 Scope & Field of Application 2 References 3 Effects of Whole-Body Vibration 4 Variables Affecting Human Response to Vibration 5 Guide to Other Parts of the Standard 6 Bibliography PART II Techniques for the Measurement and Analysis of Vibration Affecting the Body 0 Introduction 1 Scope & Field of Application 2 References 3 Transducer Mounting 4 Signal Conditioning 5 Calibration 6 Analysis Procedures 7 Methods of Reporting 8 Bibliography PART III Guide to the Evaluation of the Effects of Vibration on Health	PART IV Guide to the Evaluation of the Effects of Vibration on Human Activities 0 Introduction 1 Scope & Field of Application 2 References 3 Taxonomy of Human Performance 4 Characterization of Vibration Exposure 5 Non-specific Effects of Vibration on Performance 6 Effects on Hand Manipulation and Control 7 Effects on Vision 8 Bibliography Figures for Frequency Weighting Curves PART V Guide to the Evaluation of the Effects of Vibration on Comfort 0 Introduction 1 Scope & Field of Application 2 References 3 Characterization of Vibration Environment 4 Vibration Evaluation Guide 5 Vibration Thresholds 6 Bibliography Appendix 1. Example applied to passenger car. Figures for frequency weighting curves. PART VI Guide to the Effects of Whole-Body Oscillatory Motion on Motion Sickness

LONG-TERM REVISION

The need for a long-term revision of ISO 2631 to take advantage of the new data available since the present standard was formulated (work on it started in 1964, although it was first published only in 1974) was agreed on by ISO/TC108/Subcommittee 4 in 1976. Only recently, however, has there been real progress by the subcommittee, and in view of the size, complexity, and technical, philosophical, and political problems of the task, it is unlikely to emerge as a draft international standard for several more years. The present proposals are intended to divide the standard into six major, self-contained parts--some of which may be completed and issued before others.

The main responsibility for developing the revised standard lies with a small working group of ISO members from the United States, Germany, France, and the United Kingdom. So far, a draft outline and questionnaire have been circulated for comments among ISO members, and, in the United Kingdom at least, to other interested organizations as well. As of this writing, responses have been received and analyzed to help the United Kingdom representative, Michael Griffen, redraft and, in some areas, expand the outline. This exercise and the collection of more than 2500 papers on body vibration at his disposal have enabled him to identify those areas in particular where more information is needed in order to formulate realistic requirements.

An outline of the first draft revision to ISO 2631 (18) is given in Figure 1. In this paper it is intended to consider in some detail the part of the revision concerned with the effects of vibration on comfort and other parts that may be particularly relevant to ride quality. Much of the literature critique in a later section of this paper also pertains to the draft revision.

General Remarks

The draft revision to ISO 2631 is evidence of hard work, of innovative thinking, and of the use of data from many investigations. The final document will be much more detailed and more complex than ISO 2631 because it will reflect the increase in knowledge of the complexity of vibration effects. This should reduce the present tendency to use ISO 2631 as a "cookbook" and to regard the acceleration/frequency curves as rigid limits without regard to their numerous qualifications. In fact, limits of any type are unlikely to be specified in any parts of the standard.

Care will be needed to ensure that the complexity of the revised ISO 2631 document does not inhibit practical user applications and acceptance and that it is suitable for design engineers and planners, not just for experts in human factors. It is my opinion that more guidelines may be needed that cover the detailed method of applying the standard to practical situations. For example, the increased complexity of measurement and analysis (12 acceleration measurements are now proposed instead of 3) may well cause considerable debate. Also, the difficult problem of determining "population cover," almost completely ignored in ISO 2631, does not seem to have been adequately resolved within the revised document.

The draft standard makes it clear that further elaboration and clarification are needed for several of its parts, and it is likely that these needs, once met, will meet many of the criticisms and suggestions made below on selected parts of the draft, particularly those relevant to ride comfort or quality.

Draft: Part 1, General Introduction

Some of the many variables affecting reaction to vibration are listed and most will apply to passenger comfort. However, paragraph 3.3 of part 1 (Effects on Activities) makes no mention of normal passenger activities such as reading, writing, eating, and drinking, etc., which can be degraded by vibration. Similarly, paragraph 3.4 (Effects on Comfort) implies that part 5 of the standard will be confined to the effects of vibration on body discomfort per se. As will be discussed later in this paper, this important gap in the standard should be filled as soon as appropriate data are available.

Draft: Part 2, Techniques of the Measurement and Analysis of Vibration Affecting the Body

At present, this important part is incomplete but eventually is expected to be much more comprehensive than the corresponding part of ISO 2631. I feel that the complexity and numbers of vibration measurements and weighting curves and the evaluation of such measurements in relation to human reaction (parts 3, 4, 5, and 6 of the standard) call for explicit recommendations, perhaps even standards for instrumentation, recording, analyses, and evaluation. Therefore, part 2 will need to contain more information on the practical measurement, analysis, and assessment of vibration for a complete journey, e.g., how many measurement points are required, how often and for how long to record them, etc. It may be necessary to advise on two types of measurement and analysis: a complex one for a comprehensive appraisal, or "type test" of a new vehicle or vibration situation; the other for quick-look purposes or to obtain simplified statistical information in the field.

Draft: Part 3, Guide to the Evaluation of the Effects of Vibration on Health

At present, this part consists only of the following interim paragraph:

> A revision of the current guidance concerning the effects of whole-body vibration on health is not yet complete. It is recognized that in giving careful consideration to other parts of this revision, it is desirable to relate their guidance to that which will appear in Part 3. For these purposes it is recommended that they be compared with the exposure limits given in ISO 2631 (1978).

The final sentence of this quotation is puzzling. If it implies that, for the time being, the exposure limits in ISO 2631 will apply also to the revision of part 3, then there is a conflict concerning the steep time-dependency in ISO 2631 and the indications in the revision that there is little evidence of such time-dependency.

Draft: Part 4, Guide to the Evaluation of the Effects of Vibration on Human Activities

Part 4 includes nine frequency-weighting curves (inverse in shape to acceleration/frequency tolerance curves) that illustrate the effects of three axes of linear vibration inputs at three body locations (seat-of-the-pants, seat back, and the hand) on manual control or vision. (See Figure 2.) Three curves of one shape and two each of two others appear to be identical so that at present there are five different weighting curves in all, with probably more to come in the future. The a_z curves do not reflect the usual whole-body resonance around 6 Hz. Also, biomechanical reasoning suggests that the weighting curves should fall (attenuate) much more steeply above 30 Hz (19).

A method is given in this part of the standard to determine the total equivalant weighted accelerations at each of two or three input positions (seat-of-the-pants, seat back, and hand control) that will affect manual control or vision. Paragraphs 6.6 and 7.6 in this part imply that both manual control and vision are not affected by the duration of vibration. The possible additive effect of these different inputs does not seem to be covered. The relationship of the equivalent weighted accelerations with the decrement in manual control or visual performance is at present confined to two short paragraphs only. This area will probably need considerable expansion if the complexity of the evaluation method is to be really worthwhile for practical use. As a protagonist of the need for several different weighting (or tolerance) curve shapes, these additional shapes will undoubtedly complicate evaluation, particularly if different weighting curves for different input positions to the body are also used for precision.

The practical usefulness, or at least the practical application, of seat back vibration input for evaluation of performance or comfort (as is discussed in part 5 of the standard) is open to debate. The effects of seat back vibration, and hence the relevance of the proposed weighting curves, will be very dependent obviously on variables such as posture, anatomy, seat contours, use of seat harness, etc. No mention is made of the effects of vibration of ordinary passenger activities such as eating, drinking, writing, etc. Most likely, this is probably due to a lack of data; nonetheless, this omission deserves at least some comment.

Perhaps most importantly, no mention is made of population cover. Ideally, users will want some guidance on what variances are required from the weighting curves in order to give various percentile covers. At present, no indication is given at all of the population cover afforded by the weighting curves. Some suggestions as to how population cover might be evaluated are given in the Appendix to this paper.

Draft: Part 5, Guide to the Evaluation of the Effects of Vibration on Comfort

Part 5 is of the most interest to those concerned with ride comfort or quality. It includes an ingenious, novel method for measuring, weighting, and, to some extent, integrating all of the acceleration inputs that contribute to vibration-induced discomfort, thereby enabling accurate, comparative measurements of the behavior of different vehicles. In its present form, however, it gives little or no guidance on the degree of discomfort such inputs cause, and therefore will most likely require major additions to provide a balanced, worthwhile evaluation method.

The method described above is similar to, but more comprehensive than, that described in part 4 of the standard since it provides 18 frequency weighting curves of 11 different forms (see Figures 3 and 4). The curves cover three linear and three rotational axes of vibration inputs to the feet, seat-of-the-pants, and back, for seated, standing, and recumbent persons; they are different from the five shapes given in part 4. An rms method of combining the weighted accelerations at each input is given to obtain a total "discomfort rating" (D_T) at each point, although, as in part 4, interaction between the different input locations does not seem to be covered.

Whereas no attempt is made to quantify the discomfort reactions to various D_T levels, it is stated that a table of typical D_T values could be compiled for inclusion in a later draft of the document. A table of D_T values for a passenger car given in an appendix to the draft needs elaboration to be of any practical use. Criticisms mentioned above about the shape of the weighting curves and about the seat back vibration input also apply in principle to this part.

No advice is provided on the effects of the duration of vibration, and it is stated that forthcoming sections of the draft on repeated shock motions and thresholds await further consideration. It is hoped that these sections will include data not only for perception thresholds, but also for subjective thresholds such as "just uncomfortable," "noticeably uncomfortable," etc.

As with part 4 of the standard, part 5 gives no advice on percentile population cover. Such advice should be included in any forthcoming additions to part 5 that relate D_T values to levels of discomfort.

Draft: Part 6, Guide to the Effects of Whole-Body Oscillatory Motion on Motion Sickness

At present, a revision of current guidance (ISO 2631 DAD2) on the effects of whole-body oscillatory motion on motion sickness has not yet commenced. Some of the weighting curves for discomfort given in part 5 on motion sickness go down to as low as 0.5 Hz and do not agree with those given in ISO 2631 DAD2.

REVIEW OF RECENT RIDE QUALITY INVESTIGATIONS

In light of previous extensive reviews of ride quality in 1975 (20), this paper concentrates on investigations published during or after that year, although a few earlier relevant papers have also been considered. From the 75 or so papers available, effort has been concentrated on the 34 referenced papers from the United Kingdom, although 16 referenced papers from the United States also are briefly reviewed.

Overall, there has been a great deal of useful work done on ride quality in the last five years and certain important aspects are generally agreed on. However, considerably more work is needed: first, to translate the work into practical ride quality requirements, and, second, to fill gaps in information or resolve discrepancies.

Areas of Broad Agreement

Generally, there is reasonable agreement on the average shapes of the acceleration/frequency curves for an equivalent level of discomfort for vertical, lateral, and fore-and-aft vibration, and for seated, physically fit males (8,9,11-13). There is also reasonable agreement (12,21,22) on the approximate acceleration threshold levels that will cause noticeable discomfort per se, that is, excluding the effects of activities that are likely to lower the basic threshold level.

Experiments show (8,10,11,21,23-25) that there are wide variations in individual responses to vibration, both in the levels and in the shapes of the acceleration/frequency contours. There is much less variation in an individual's response when he or she

Figure 2. Frequency weighting curves for vibration inputs for human activity at three body locations (ISO 2631 draft revision).

1 X + Z AXES AT SEAT-OF-PANTS, AND X AXIS AT SEAT BACK (MANUAL CONTROL)

2 Y AXIS AT SEAT-OF-PANTS (MANUAL CONTROL)

3 X + Y AXES AT HAND CONTROL

4 Z AXIS AT HAND CONTROL, AND Z AXIS AT SEAT-OF-PANTS (VISION)

5 Y + Z AXES AT VIEWED OBJECTS

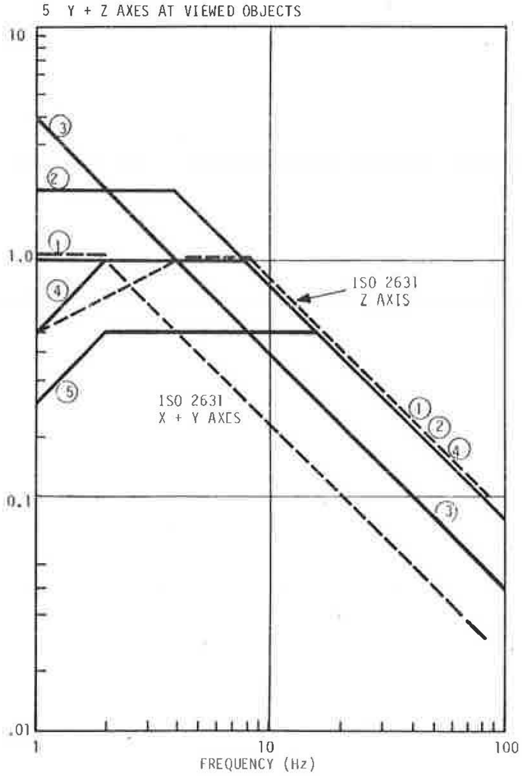


Figure 3. Frequency weighting curves for vibration inputs for human comfort (ISO 2631 draft revision): first set.

1 X AXIS AT SEAT-OF-PANTS, AND FEET (STANDING SUBJECT)

2 Y AXIS AT SEAT-OF-PANTS AND FEET, AND Y+Z AXES (RECUMBENT SUBJECT)

3 Z AXIS AT SEAT-OF-PANTS AND FEET, AND X AXIS (RECUMBENT SUBJECT)

4 X AXIS AT SEAT BACK

5 Y AXIS AT SEAT BACK

6 Z AXIS AT SEAT BACK

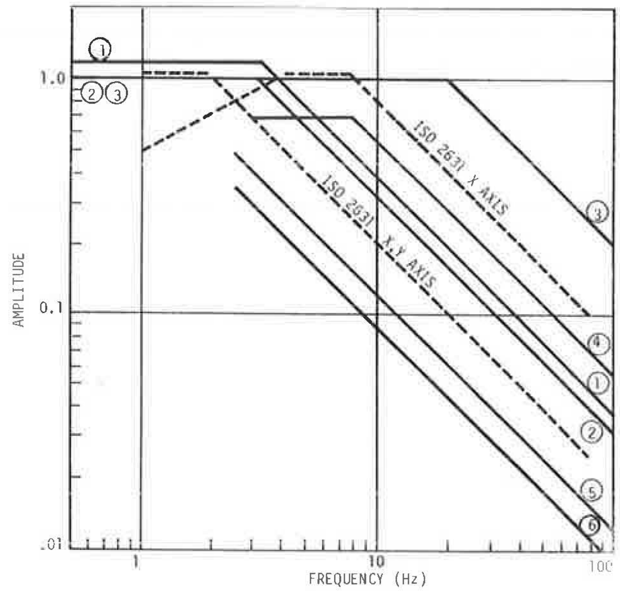


Figure 4. Frequency weighting curves for vibration inputs for human comfort (ISO 2631 draft revision): second set.

1 ROLL AXIS (R_x) AT SEAT-OF-PANTS
2 PITCH AXIS (R_y) AT SEAT-OF-PANTS — ANGULAR VIB$^{\underline{N}}$
3 YAW AXIS (R_z) AT SEAT-OF-PANTS

4 X + Z AXES, FEET, SEATED — LINEAR VIB$^{\underline{N}}$
5 Y AXIS, FEET, SEATED

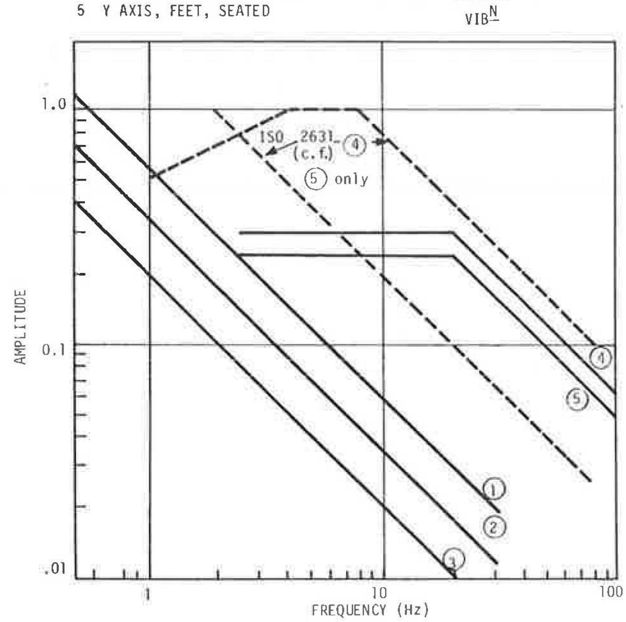
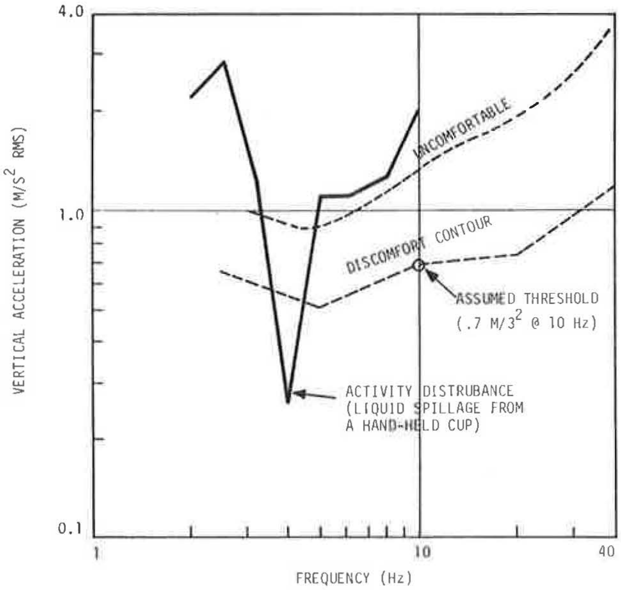


Figure 5. Body discomfort versus activity disturbance for seated subjects.



is subjected to similar repeated vibrations (8,11,21).

There is agreement that comfort reaction is considerably affected by both seating conditions and vibration input locations (e.g., feet versus seat or back). Some quantification of these effects has been made (9,15,26,27).

Conventional, soft, sprung passenger seats tend to amplify vehicle vibration considerably in the range of 2-4 Hz, but attenuate it noticeably to above 10 Hz (28-30).

Within the limitations of investigations there is little evidence of a significant increase in discomfort due to duration of vibration up to 3 h (5-7).

There is an additive effect for complex vibrations (multifrequency, random, and multiaxis); summed rms weighted, rather than the worst rated, is the better method of evaluation (17,25,31-34). This is in contrast to current ISO 2631 recommendations, but is in line with Draft Amendment 1 to ISO 2631.

As indicated by Draft Addendum 2 to ISO 2631, there is general agreement on the shape and level of the vertical acceleration/frequency curves below 1 Hz necessary to minimize severe discomfort (as characterized by motion sickness). These curves show a critical frequency region aroung 0.2 Hz. The limited evidence on reduced comfort below 1 Hz indicates a much less frequency-dependent response.

Current Areas of Uncertainty

Notwithstanding general agreement on discomfort contours, most of the laboratory investigations have up until now used short periods of vibration of 5-10 s. The relevance of such work in relation to discomfort over long periods is uncertain (ISO 2631, for instance, specifies a 1-min exposure). One investigation using 1-min exposures gave noticeably steeper frequency dependence around 6 Hz (12), whereas in another investigation, pulses of 32 s gave a considerably greater discomfort reaction than those of 5-10 s (35).

There is considerable uncertainty on how to convert individual variations into limits for percentile population cover, both in regard to variations in levels and in sensitive frequencies. Averaging these variations tends to mask the sensitive frequencies, and curves that give nominal standard deviations or percentile cover can be misleading, particularly since such curves cannot be applied to any one individual at all frequencies.

The integrative effects of vibration at the feet, seat, and back on overall discomfort do not seem to have been adequately explored.

The value of several important field and laboratory investigations of discomfort versus vibration (36-38) has been limited by measuring floor rather than seat-of-the-pants vibration. These data could well be supplemented by also measuring seat/floor transmissibility. Although in at least one investigation (39), discomfort reaction has usually correlated equally well with floor vibration as with seat vibration, this does not necessarily negate the importance of seat characteristics. Such correlations only indicate that subjective response is approximately linear with acceleration level, and that where different vehicles are compared, the vibration spectra are similar. The issue of whether to measure vibration at the floor or at the seat needs to be carefully considered.

Research findings on time-dependency effects (5-7,35,40) are equivocal, particularly in relation to ISO 2631. Some investigations do not explore beyond the recommended ISO 2631 reduced comfort exposure time, and others compare their vibration values with a reference vibration value to assess changes in discomfort with time. Recent investigations have been confined to vibrations above 2 Hz, since earlier work (2) suggests that below 2 Hz, physical efforts to reduce postural disturbances can give pronounced time (fatigue) effects.

Some Important Information Gaps

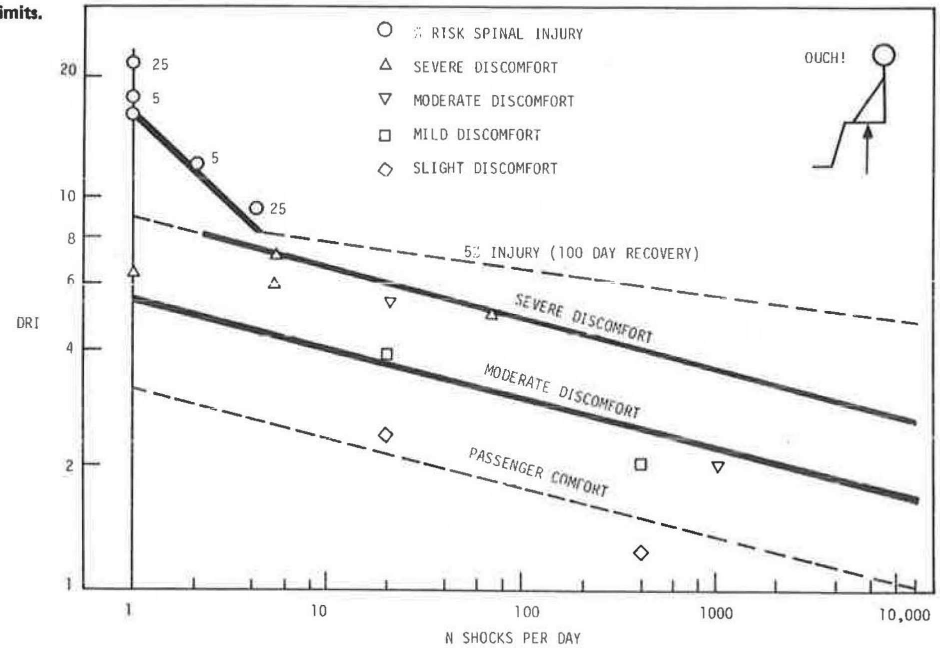
As previously mentioned, there is a surprising lack of laboratory and field information on the effects of vibration on normal passenger activities such as eating, drinking, reading, writing, conversing, and sleeping. Only one recent experiment (41) and two earlier ones (42,43) were found on what are acknowledged to be important aspects of ride quality (44-46). Two of these experiments (41,43) indicate that passengers are more sensitive to vibrations that interfere with normal passenger activities than those that cause body discomfort per se (see Figure 5).

At least two investigations (22,38) show that passengers' comfort/vibration ratings in different types of transport vary with expectancy or experience of ride quality. More work on these psychological weightings seems desirable to follow up the considerable work that has been done in the United States on this topic. A catalogue of measured and weighted vibration in various types of transport, perhaps based on work by Stevens (38), Stikeleather and others (47), and others, would help in this respect. This raises the fundamental problem of how best to mathematically define a vehicle vibration time history in relation to human response. As agreed at the ride quality conference in 1975, either acceleration/frequency spectra or power spectral density functions alone do not indicate the severity of the ride, particularly when investigators fail to report any variance from the mean spectra.

I feel that investigators need to give more consideration to specific user needs in planning their work. In the same way, customers should declare early on what practical information they would like to obtain from ride quality investigations, and equally pertinent, from ride quality.

At least one investigation (24) has shown some correlation between discomfort and biomechanical characteristics of individuals, yet there remains a

Figure 6. Shock data and tentative limits.



need for more biomechanical modeling of discomfort and allied reactions to vibration. A previous paper (19) reasons that this information could help explain and quantify discomfort contours, individual variations, the effects of transient vibrations, and repeated shocks.

More information is needed on the effects of angular vibration.

As will be discussed later, much more research is needed on the effects of transient vibrations, that is, vibrations with high crest factors and repeated shock-type excitations.

Both the draft addendum to ISO 2631 and a recent experiment (48) underscore the need for more research into the effects of very low frequency vibration (inertial, whole-body vehicular motion below 1 Hz) on ride comfort and passenger activity. For marine craft, low frequencies below 0.2 Hz particularly need to be explored. More generally, the effects of angular motion must also be investigated.

There are still very limited data on different reactions to vibration for different segments of the population such as men, women, and young and old people. Differentiation between physically fit and ill individuals is also necessary because ambulance ride quality is vital to a small but significant segment of the population.

The effects of combined environmental stresses on vibration ride quality may also require further work.

EVALUATION OF REPEATED SHOCK-TYPE MOTIONS

In many vehicular rides, shocks or jolts may disturb passengers more than vibration itself. Several years ago, ISO/TC108/Subcommittee 4 agreed that collection of data and development of a specification for such shock-type motions were urgently needed to fill this major gap in ISO 2631.

In developing any shock-type motion specifications either for equipment or for passenger comfort, it is difficult to compare the effects of different types of shock input. As far as human tolerance to a vertical disturbance is concerned, one approach to the problem specifies that different shock (acceleration) inputs be converted into a standard form, known as the dynamic response index (DRI). The DRI represents the peak compressive load that a particular shock produces within the human spine; it is obtained by applying the input acceleration pulse to a mathematical model of the spine. Tolerance curves that plot the numbers of shocks received per day against DRI levels can then be postulated for various criteria that range from the prevention of injury to the prevention of discomfort. Two variations on this approach were published with very tentative specifications in 1976 and 1977 (49,50) mainly to stimulate thought and the production of more data. Since then, two follow-up papers have been issued; one paper compares repeated shock tolerance with tolerance of vibration with high crest factors (51), while the other is a critical look at biodynamic modeling of specifications for human tolerance to vibration and shock (19).

The need to evaluate human tolerance to repeated shocks was further recognized in 1979 when ISO/TC108/Subcommittee 4 set up a new working group to investigate this topic. Although few new data have been published on this subject since 1977, one relevant paper (35) includes an experiment in which seated subjects were asked to match the discomfort of various numbers and levels of suddenly applied vertical "bumps" (each bump consisting of 4 cycles of 8 Hz vibration varying in amplitude) against the discomfort of a 10-s adjustable level reference vibration of 8 Hz. Although the results are not reported in terms of DRI values, one can infer that on the average, one bump with a peak DRI of about 0.8 was slightly more uncomfortable (about a 50 percent higher reference level) than 16 bumps each with a peak DRI of about 0.2. These results have a somewhat steeper slope than that suggested in Figure 6, but the levels are much lower than in previous shock experiments; thus rating discomfort of a bump against a steady vibration may not be the best method to compare the effects of different numbers of bumps and levels.

In summary, the last three years have seen disappointing progress as far as knowledge of human tolerance to repeated shock-type motions is concerned. A list of unsolved problems in this area was given in a previous paper (50); this list is still valid and is repeated below:

1. Adequacy of (spinal) DRI,

2. Sudden shocks versus slow loading,
3. Effects on other parts of body,
4. "Exceedances" versus "peak levels,"
5. Evaluation of multiple shocks,
6. Shock "recognition" in complex waveform,
7. Critical levels of shock (8-10 DRI?),
8. Shapes of shock/occurrences curves,
9. Combined effects of shock and vibration,
10. Lateral and fore-and-aft shocks,
11. Recovery effects,
12. Cumulative long-term effects, and
13. Effects on activities.

(The population was covered according to individual sensitivity, age and sex, and health.)

If the DRI technique of quantifying shock-type motions is acceptable, then the next fundamental question must be to ask what are the appropriate biomechanical analogues--that is, what critical parts of the body are involved in reacting to repeated shocks. If these are the same parts of the body that react to vibration, then assuming the body is passive, the same model should, at least in theory, enable us to quantify response to any type of input, whether it is a short, sharp shock or a continuous vibration.

Closely linked with the problem of defining repeated shock-type motions is the problem of defining and determining the significance of high crest factors. Draft Amendment 1 to ISO 2631 addresses this problem, one aspect of which is analyzed in Allen (51). At present, the conventional definition (as per International Standard ISO 2041) defines the crest factor of an oscillating quantity as "the ratio of the peak value to the rms value." Arising from a critical look at the conventional definition of crest factor and its use in a recent investigation on impulsive vibration (35), I suggest that the following revised definition is more appropriate, particularly when the implusive motion itself makes a significant contribution to the average (rms) level of the vibration history under consideration. The suggestion is that crest factor be defined as "the ratio of the peak acceleration to the rms value which excludes the impulsive portion of the waveform."

CONCLUSION

This paper has reviewed progress in ride quality requirements and research since 1975. It is hoped that it will be of use to those engaged in revising ISO 2631 and to those who plan further work on this important aspect of man's reaction to his physical environment.

ACKNOWLEDGMENT

The efforts of many investigators have made this review possible. Thanks are due particularly to Michael Griffen of the Institute of Sound and Vibration Research at Southhampton University (United Kingdom) for his help in providing data, references, and the latest information on the revision of ISO 2631. The suggestions in this paper do not necessarily reflect those of either the International Organization for Standardization or the British Standard Institute.

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Appendix

The problem of predicting population cover for response to vibration was ignored in ISO 2631 and so far has not been addressed in the major draft revision of that standard. The following suggestions are offered for debate. They are intended to illustrate a method of approach rather than to provide specific data for the revision. However, a hypothetical example is given to illustrate how the revision could be improved and also related to practical situations. The suggestions are confined mainly to ride comfort, but the principles apply to population cover for the effects of vibration on health and performance. They do not ride acceptance, which involves important variables beyond the statistical analyses described herein.

In this appendix, population cover is defined as the percentage of passengers in a particular transport vehicle who will be comfortable, at or above the threshold of discomfort, noticeably uncomfortable, or whatever criterion is chosen. To quantify it, three major statistical variables are involved:

1. Population response to vibration per se. Here we will assume, with some support from laboratory results, that the distribution is approximately Gaussian and that the standard deviations are similar for the different mean levels of vibration (which vary with the particular criterion of discomfort chosen). The following mathematical description of population sensitivity to vibration has been selected:

Criterion (threshold)	Mean Vibration Level m/s^2 rms (summed weighted)	SD m/s^2 rms (summed weighted)
Interference with drinking	0.5	0.2
Discomfort	0.7	0.2
Noticeable discomfort	0.9	0.2
Considerable discomfort	1.05	0.2

2. Vibration distribution in the vehicle. For a triphibious vehicle, three simplified cases of vibration distribution will be evaluated: (a) case 1, equal vibration throughout the vehicle of 0.8 m/s^2 rms (summed weighted acceleration); (b) case 2: vibration level increasing linearly along the vehicle from 0.5 to 1.1 m/s^2 rms (i.e., 0.8 m/s^2 mean value); and (c) case 3: vibration level 0.5 m/s^2 rms in the center of the vehicle, increasing to 1.1 m/s^2 rms each end (i.e., 0.8 m/s^2 mean value).

3. Population distribution within the vehicle. To simplify analysis, we will assume that the passengers are evenly distributed through the length of the vehicle. Those variations that occur in practice can be accounted for by elaboration of the processing statistics.

Thus, combining the three variables described above, we obtain the following population cover:

	Population			
Type of Vibration	Interference with Drinking	At or Above Threshold of Discomfort	With Noticeable Discomfort	With Considerable Discomfort
Equal at 0.8 m/s^2	93	69	31	11
Varying between 0.5 and 1.1 m/s^2	86.5	64	36	18

As can be seen from the above table, when the vibration level in a vehicle varies significantly, prediction of population cover based on mean vibration level is inaccurate. For the example considered, it would overestimate the number of passengers who found it difficult to drink, and overestimate the number who were at or above the threshold of discomfort. Conversely, it would underestimate the number of passengers who had noticeable discomfort and the number who had considerable discomfort.

Measurement and Evaluation of Ride Quality in Advanced Ground Transportation Systems

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Ride quality criteria and characteristics are reviewed for advanced ground transportation systems, including automated guideway transit systems, downtown people movers, and tracked, levitated magnetic and air suspended vehicle systems. Data available for these advanced systems are described and the use of computer analyses and multiaxis ride simulators is discussed to predict system ride characteristics at the design stage. Recommendations are formulated for specification of ride quality requirements in advanced ground transportation systems.

In the last decade a number of new public transportation systems have been developed. Automated guideway transit (AGT) systems that use rubber-tired vehicles operated on dedicated guideways under automatic control have been developed (1) and are operating at the Dallas-Fort Worth Airport; in Morgantown, West Virginia; and in Dearborn, Michigan. Proposals have been formulated to implement systems similar to these systems in several central-city business districts as part of the downtown people mover (DPM) project (2). Research has also been performed on tracked, levitated vehicle (TLV) systems that use magnetic or air suspension in the United States, Japan, Germany, and England (3). Because of their high-speed capability, these systems have been proposed primarily for city-to-remote airport sites and intercity routes, although interest in their application to city-center use has been under evaluation within the United States (4).

Effort has been devoted to development of monorail-type systems that use either wheel or magnetic support systems (5) and systems that use conventional steel-wheel rail technology coupled with linear induction motor propulsion (6).

The advanced systems cited above are characterized by the use of a fleet of vehicles operated under automatic control on a dedicated guideway. These systems will be operated by a public or quasi-public authority. One of the contractual requirements these advanced systems must satisfy for acceptance by the operating authority is a ride quality specification. This specification has a direct influence on vehicle and guideway design and on operation in these systems; thus, it has an impact on system performance and cost. A number of studies