SAE INTERNATIONAL

SURFACE VEHICLE RECOMMENDED PRACTICE

J2834™ APR2025

Issued 2013-10
Revised 2019-10
Reaffirmed 2025-04

Superseding J2834 OCT2019

Ride Index Structure and Development Methodology

RATIONALE

This recommended practice indicates the current state of technology regarding the relationship between the human-to-vehicle interface vibration magnitude and human discomfort. The appendix is concerned with providing a uniform and convenient method of indicating the subjective severity of the motion and vibration but does not present limits. It is in no way related to quantifying health and safety aspects of motion and vibration for which an entirely different methodology would be needed. This methodology is intended to predict human sensitivity to motion and vibration for comparative purposes (i.e., condition A versus condition B) relative to a global (i.e., absolute) adjectival psychometric scale. See Appendix C for additional supporting rationale.

This revised edition incorporates changes due to the expanded scope of SAE J1441 to include vehicle ride, and a revised Figure 1 to clarify the potential non-equal spacing of adjectives for a rating scale developed using psychometric adjectives.

SAE J2834 has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

This new recommended practice was prepared by the SAE J6 Task Force as partial replacement for the SAE J6a "Ride and Vibration Data Manual." This new recommended practice represents a substantial updating and expansion of state-of-the-art in ride development methods used compared to the J6a Ride Vibration Data Manual which it partially replaces.

The J6a Ride Vibration Data Manual was last revised by the SAE Vehicle Dynamics Committee in October 1965. It is no longer published by the SAE but is included in Appendix B of Gillespie (1992).

INTRODUCTION

This recommended practice is a method for developing an objective model of human sensitivity to vibration due to road induced disturbances in the automotive driving environment (a.k.a., "ride"). This method is based on statistical analysis of a database of juried vehicle occupant discomfort ratings and measured acceleration at the various human to vehicle contact surfaces during representative over-the-road driving events with stationary or transient characteristics within the finite time period of interest. The database for this analysis should cover an array of roads, vehicles, raters and driving conditions that well represent the application domain of interest.

The recommended discomfort model is hierarchal in order to provide for allocation of performance objectives to various subsystems, ride diagnosis, and to reduce the statistical uncertainty of fitting a single stage model. The top level of the model expresses overall motion and discomfort as the weighted sum of several "interface" discomfort ratings. Each interface discomfort rating (e.g., seat back, steering wheel…) is the weighted sum of the discomfort ratings for the various axes of vibration at that interface (typically vertical, lateral and longitudinal). The axis discomfort ratings are based on frequency weighted acceleration signals. The frequency response filters are primarily taken from ISO 2631-1.

ISO 2631-1 is a very comprehensive and widely accepted standard for describing human sensitivity to vibration, but not specifically for the automotive driving environment. It is as relevant for vibrations in a building environment as it is in the automotive driving environment. It is based on human subjects seated on a rigid flat seat and subjected to a single axis of vibration at a time without the distractions and ancillary sensations of driving. This report describes a method for developing a human sensitivity model based on data taken in an actual ride environment.

TABLE OF CONTENTS

1. SCOPE

This recommended practice defines methods for the measurement of periodic, random and transient whole-body vibration. It indicates the principal factors that combine to determine the degree to which a vibration exposure will cause discomfort. Informative appendices indicate the current state of knowledge and provide guidance on the possible effects of motion and vibration on discomfort. The frequency range considered is 0.5 Hz to 80 Hz. This recommended practice also defines the principles of preferred methods of mounting transducers for determining human exposure. This recommended practice is applicable to light passenger vehicles (e.g., passenger cars and light trucks). This recommended practice is applicable to motions transmitted to the human body as a whole through the buttocks, back and feet of a seated occupant, as well as through the hands of a driver.

This recommended practice offers a method for developing a ride performance index but does not specifically describe how to apply this index to assessment or comparison of specific vehicles.

NOTE: This recommended practice may also be applicable to other types of ground vehicles (e.g., medium and heavy duty road vehicles) with seated occupants having similar seating posture, occupant/vehicle interfaces, and vibration magnitudes, frequencies, and durations as light passenger vehicles.

1.1 Purpose

The primary purpose of this recommended practice is to define methods of quantifying human sensitivity to occupant motion and vibration in passenger cars and light trucks based on objective measurements of acceleration and sound in order to simplify and standardize the reporting, comparison and assessment of motion and vibration conditions. It contains methods for the evaluation of vibration containing occasional large peak values (i.e., having large crest factors). Human sensitivity is quantified in terms of predicted subjective discomfort levels, based on suitable psychometric and statistical methodologies. Passenger cars and light trucks and vans expose occupants to periodic, random and transient mechanical vibration which can cause various levels of subjective discomfort. This recommended practice does not contain vibration exposure limits and does not address potential effects of motion and vibration on health and safety, or on motion sickness, which involve different phenomena. This recommended practice does not address the potential effects of intense vibration on human task performance since these involve different phenomena which depend critically on the biomechanical and ergonomic details related to the operator, the situation and the task. Appendix C provides rationale for the assessment of human discomfort due to motion and vibration. More information may be obtained from the scientific literature, a portion of which is listed in 2.2.1 and Appendix B. Motion and vibration is often complex, contains many frequencies, occurs in several directions and changes over time. The effects of motion and vibration on human discomfort may be manifold. Exposure to whole-body vibration causes a complex distribution of oscillatory motions and forces within the body. There can be large variations between subjects with respect to discomfort effects. Whole-body motion may cause sensations (e.g., discomfort or annoyance). The presence of oscillatory force (i.e., vibration) with little whole-body motion may cause similar effects.

2. REFERENCES

2.1 Applicable Documents

The following standards contain provisions which, through reference in this text, constitute provisions of this recommended practice. At the time of publication, the editions indicated were valid. All standards are subject to revision, and users of this recommended practice are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J670 Vehicle Dynamics Terminology

SAE J1441 Subjective Rating Scale for Vehicle Ride and Handling

2.1.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO 2041:2005 Vibration and Shock - Vocabulary

ISO 5805:1997 Mechanical Vibration and Shock - Human Exposure - Vocabulary

2.1.3 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 1260:1995 Electroacoustics - Octave-Band and Fractional-Octave-Band Filters

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1477 Measurement of Interior Sound Levels of Light Vehicles

Amman, S., Meier, R., Trost, K., and Gu, P., "Equal Annoyance Contours for Steering Wheel Hand-arm Vibration," SAE Technical Paper 2005-01-2473, 2005, https://doi.org/10.4271/2005-01-2473.

Griffin, M., "Evaluation of Vibration with Respect to Human Response," SAE Technical Paper 860047, 1986, https://doi.org/10.4271/860047.

Herrick, T., "A Ride Metric System Utilized to Benchmark and Develop a Superior Riding Sport Utility Vehicle," SAE Technical Paper 942273, 1994, https://doi.org/10.4271/942273.

Mousseau, C., Karamihas, S., Gillespie, T., Sayers, M. et al., "Computer Synthesis of Light Truck Ride Using a PC Based Simulation Program," SAE Technical Paper 1999-01-1796, 1999, https://doi.org/10.4271/1999-01-1796.

Van Auken, R.M., Zellner, J., and Kunkel, D., "Correlation of Zwicker's Loudness and Other Noise Metrics with Drivers' Over-the-Road Transient Noise Discomfort," SAE Technical Paper 980585, 1998, https://doi.org/10.4271/980585.

von Gierke, H., "The ISO Standard Guide for the Evaluation of Human Exposure to Whole-Body Vibration," SAE Technical Paper 751009, 1975, https://doi.org/10.4271/751009.

Gillespie, T.D., (1992) Fundamentals of Vehicle Dynamics, SAE International, Warrendale, PA.

2.2.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO 2631-1:1997 Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements

ISO 5128:1980 Acoustics - Measurement of Noise Inside Motor Vehicles

ISO 5349-1:2001 Mechanical Vibration - Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration - Part 1: General Requirements

ISO 5349-2:2001 Mechanical Vibration - Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration – Part 2: Practical Guidance for Measurement at the Workplace

ISO 8041:2005 Human Response to Vibration - Measuring Instrumentation

ISO 8608:1995 Mechanical Vibration - Road Surface Profiles - Reporting of Measured Data

ISO 10326-1:1992 Mechanical Vibration - Laboratory Method for Evaluating Vehicle Seat Vibration - Part 1: Basic Requirements

2.2.3 Other Publications

The references for these publications are listed in Appendix B.

3. DEFINITIONS

For the purposes of this recommended practice, the terms and definitions given in SAE J670, ISO 2041, and ISO 5805 apply. In addition, the following definitions apply.

3.1 MOTION

Whole-body dynamic movement of a human, periodic or aperiodic in nature, the frequency content of which is typically mainly at the lower end of the relevant frequency range (e.g., below 5 Hz).

3.2 PSYCHOMETRIC

Pertaining to the measurement of the subjective impression of a person exposed to a given condition, by requesting the person to place a mark on a vertical linear scale, which has a subjective title describing a psychological state (i.e., “discomfort”) and adjectives positioned along its length describing the intensity of the psychological state (e.g., “a little”), such adjectives being positioned from least at the top to most at the bottom, based on adjectival placement data previously collected using a suitable experimental protocol (see Figure 1).

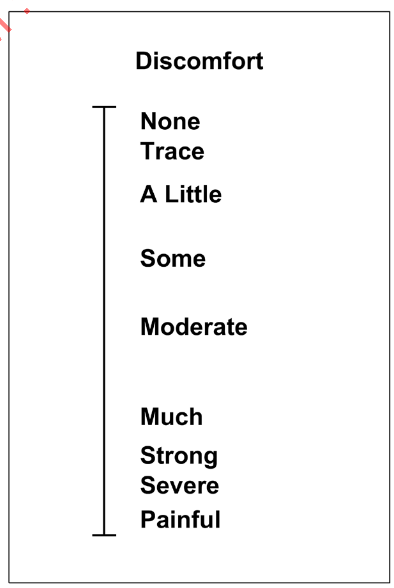

Figure 1 - Conceptual discomfort rating scale developed using psychometric methods(e.g., SAE 980585)

NOTE: A global, continuous, interval, adjectivally anchored psychometric rating scale is better suited for correlating large numbers of subjective ratings with objective measurements spanning a wide range of input levels than relative rating or threshold detection methods sometimes used in psychoacoustics research, which have different purposes.

3.3 ROUGH ROAD RIDE EVENT

An over-the-road ride event which at a given vehicle speed results in continuous and typically random-like motion and vibration disturbance of the occupant with stationary characteristics within the finite time period of interest (i.e., 8 seconds minimum and ideally the same measurement period for all rough road ride specimens), as further defined in 5.3.2.1.

3.4 TRANSIENT RIDE EVENT

An over-the-road ride event which at a given vehicle speed results in one or more discrete motion and vibration disturbance(s) of the occupant, within the finite time period of interest (i.e., 8 seconds minimum and ideally the same measurement period for all transient ride specimens), as further defined in 5.3.2.1.

3.5 VIBRATION

Periodic dynamic movement of that surface of a human which is in contact with a given vehicle interface, and typically involving frequency content at the middle or upper end of the relevant frequency range (e.g., above 5 Hz).

4. SYMBOLS, SUBSCRIPTS AND ABBREVIATIONS

4.1 Symbols

DR	Numerical discomfort rating. The numerical value of the discomfort rating corresponds to a unique location on a psychometric discomfort rating scale developed by suitable psychometric methods (see Figure 1).
a	Vibration acceleration. Translational acceleration is expressed in meters per second squared (m/s^2) and rotational acceleration is expressed in radians per second squared (rad/s^2). Values are quoted as root-mean-square (RMS) or root-mean-quad (RMQ) unless stated otherwise.
f	Frequency expressed in Hz.
$H(s)$	Transfer function, or gain, of a filter expressed as a function of the imaginary angular frequency (complex frequency).
$j = \sqrt{-1}$	The imaginary unit number.
$s = j2\pi f$	Imaginary angular frequency.
W	Frequency weighting.
ω	Frequency expressed in radians per second.

4.2 Subscripts

0, b, c, d, e, sl	Refer to the various human discomfort frequency-weighting curves recommended for evaluation with respect to motion and vibration comfort and discomfort (see Table 1).
w	Refers to frequency-weighted acceleration values.
x, y, z	For translational or rectilinear motion, refer to the fore-aft, lateral and vertical directions of motion and vibration (see Figure 2).
φ, θ, and ψ	Refer to roll, pitch and yaw rotational motion about x-, y-, and z- axes, respectively (see Figure 2).

Table 1 - Guide for the application of human discomfort frequency-weighting curves

Frequency weighting	Occupant interface and direction
W_0	All
W_b	*z*-axis, seat/buttock interface *x*-, *y*-, *z*-axes, floor/feet interface
W_c	*x*-axis, seat/back interface
W_d	*x*-, *y*-axes, seat/buttock interface *y*-, *z*-axes seat/back interface
W_e	φ, θ, and ψ-axes, seat/buttock interface
W_{sl}	*x*-, *y*-, *z*-axes, steering wheel/hands interface

NOTE: The recommended W_b, W_c, W_d, and W_e frequency weightings for the seat/buttock, seat/back, and floor/feet interfaces are based on SAE 860047. The W_b weighting is within 3 dB of the ISO 2631-1 (1997) weighting W_k in the 0.4 to 100 Hz frequency range.

NOTE: A recommended weighting for the steering wheel/hands interface has not been established. W_{sl} is a low frequency realizable approximation to the W_s weighing from Giacomin et al. (2004). The Giacomin W_s weighting is based on rotational hand-arm vibration. W_h from ISO 5349-1 is for workplace hand vibration issues that are more severe than passenger vehicle driving comfort applications. Preliminary indications (SAE 2005-01-2473 and Giacomin et al. (2004)) are that the constant velocity sensitivity of W_{sl} is appropriate for passenger vehicle steering wheel comfort from 10 to 60 Hz. For steering wheel comfort, the frequency of peak sensitivity seems to be about 2 to 3 Hz for *x* and *z*, and perhaps 1 Hz for *y* (rather than the ISO 5349-1 W_h peak at 10 Hz). WorkSafeBC used ISO 5349-1 for steering wheel vibration (Eaton, 2003).

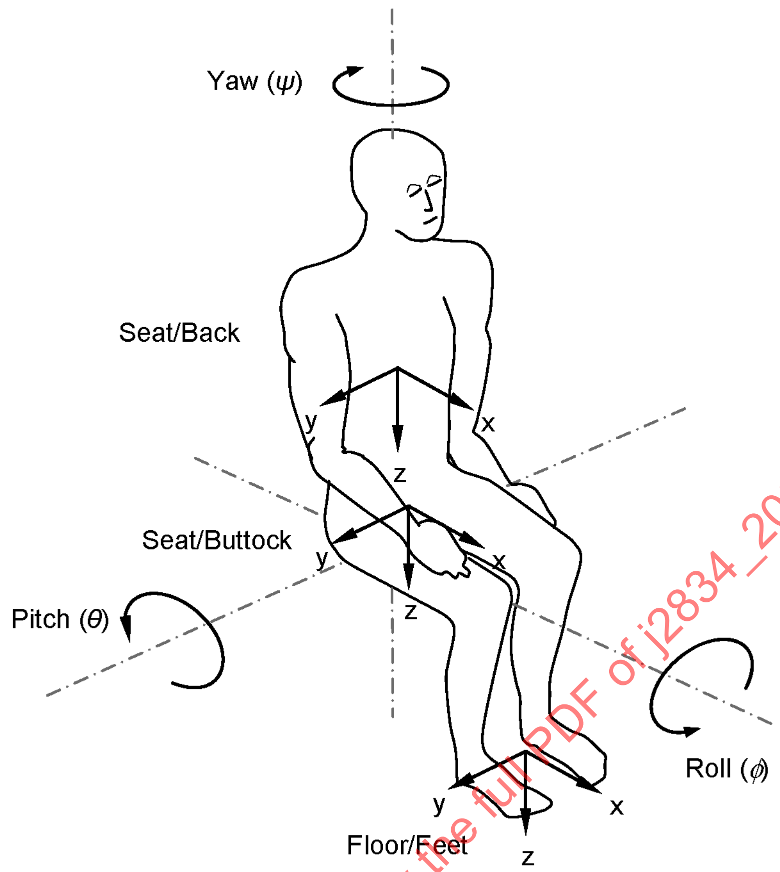

Figure 2 - Basicentric axes of the human body

NOTE: The basicentric x-y-z axes define a right-handed orthogonal coordinate system at each human body/vehicle interface. The x-axis is nominally aligned with the fore-aft direction, the y-axis aligned with the lateral direction, and the z-axis nominally aligned with the vertical direction. The z-axes of the seat/buttock and floor/feet interfaces are in the direction normal to the respective interface contact planes and may not necessarily be parallel to the gravity vector. The x-axis of the seat/back interface is in the direction normal to the interface contact plane and may not necessarily be horizontal. The basicentric y-axes are parallel to and in the same direction as the vehicle y-axes.

NOTE: A right-handed z-down coordinate system is illustrated in Figure 2. A z-up coordinate system may also be used. A right-handed axis system is recommended but not required. It is also recommended but not required that the directions of the axes be nominally aligned (i.e., within 15 degrees) with the vehicle axis system as defined in SAE J670.

5. SUBJECTIVE AND OBJECTIVE DATA REQUIREMENTS

5.1 Psychometric Ratings for Human Sensitivity Data

Subjective data describing human sensitivity to motion and vibration shall be based on psychometric discomfort ratings (associated with correspondingly measured objective acceleration data) obtained from several human subjects, vehicles, and ride specimens, using suitable human subject experimental protocols for controlled in-vehicle over-the-road tests, or alternatively, simulator tests which replicate real, recorded in-vehicle over-the-road motions at all interfaces, in all axes, and across the frequency range of interest, to within 3 dB.

5.1.1 Discomfort Ratings

The separate psychometric discomfort ratings shall include, at a minimum:

- Overall Motion and Vibration Discomfort;
- Seat/Buttock Interface Discomfort;
- Seat/Back Interface Discomfort;
- Steering Wheel/Hands Interface Discomfort (for drivers only);
- Floor/Feet Interface Discomfort.

NOTE: Sound may influence the perception of motion and vibration discomfort (Howarth and Griffin, 1990). Therefore, a psychometric acoustic Noise Discomfort Rating is also recommended.

5.1.2 Human Subjects

The human subjects shall comprise a representative sample of the relevant vehicle occupant physical and market segment characteristics. The ride index models should be based on data for a minimum of 12 human subjects in order to reduce the effects of subject-to-subject variation on the jury average ratings.

NOTE: The predictive capability of the resulting ride index model is substantially degraded when there are fewer than 20 non-expert evaluators or 10 expert evaluators.

5.1.3 Rating Scales and Usage

The subjective rating data shall be collected using the global, continuous, interval, adjectivally anchored psychometric rating scale shown in Figure 1. The scale shall not have numbers on it which are visible to the human subjects. Each rating scale shall be presented in printed or in electronic form to each human subject.

A separate rating scale for each of the five discomfort categories listed in 5.1.1 shall be presented to each human subject for each motion and vibration condition, with the category (e.g., “Seat/buttock interface”) displayed above the “Discomfort” title of each scale.

Each human subject shall report a discomfort rating for each vehicle and ride specimen by marking or otherwise indicating the position on the scale which corresponds most closely to his or her subjective feeling of discomfort for that specimen.

The ratings marked or otherwise indicated on this scale shall be digitized on a 100-point basis, with zero at the bottom extremity and 100 at the top extremity, in order to obtain a numerical rating suitable for correlation with objective indices.

NOTE: SAE J1441 describes a ten point subjective rating scale for vehicle handing. The ratings on the ten point scale of SAE J1411 were developed for comparative evaluations for a given set of conditions and therefore may not be suitable for the subjective evaluation of ride discomfort in terms of a global (i.e., absolute) adjectivally anchored psychometric rating scale that can be digitized and correlated with objective indices. For example the adjectives on the SAE J1441 rating scale such as “Good” or “Excellent” are not related to ride discomfort.

5.1.4 Subject Experimental Protocols

Subject experimental protocols shall be used to minimize repeat-run and subject-to-subject rating variation. This shall include:

- Subject screening with regard to ability to discern different motion and vibration conditions on a gross level (e.g., can the subject detect a difference between an extremely smooth ride and a severely rough ride), ability to place adjectives on a blank rating scale in roughly the same order and spacing as a sample of subjects (e.g., comprehension typicality of the subject), and training (i.e., ability to follow relevant instructions).

- Reporting the ratings as soon as possible (e.g., ideally within a few seconds and always within 1 minute) after exposure to each ride specimen, so that memory effects are minimized.

Include at least one repeat run of each vehicle-ride specimen.

NOTE: The accuracy of the results depends on the frequency bandwidth and time duration of the ride specimen and the number of repeated runs. See note in 5.2.4.

5.1.4.1 Rating Interval and Description

Each human subject shall be exposed to each ride specimen for the same interval of time (or at the same location and distance interval on the road) and at the same target vehicle speed within ±4 km/h (see 5.2.5). This may be done by using landmarks along the side or on the surface of the road. The subject shall be instructed to ignore all motion and vibration discomfort which occurs before or after the specified interval.

5.1.4.1.1 Rough Roads Ride Events

For rough road ride specimens, the subject shall be instructed to rate the average motion and vibration discomfort during the interval.

5.1.4.1.2 Transient Ride Events

For transient ride specimens, the subject shall be instructed to rate the worst motion and vibration discomfort during the interval.

5.2 Objective Motion and Vibration Measurement

5.2.1 General

The primary quantity of motion and vibration magnitude shall be acceleration (see 1.1).

NOTE: Sound may influence the perception of motion and vibration discomfort, therefore sound measures such as sound pressure or sound pressure level are also recommended (refer to SAE J1477).

5.2.2 Motion and Vibration Measurement

5.2.2.1 Direction

Motion and vibration shall be measured according to an orthogonal rectilinear coordinate system originating at a point from which vibration is considered to enter the human body. The principal relevant basicentric coordinate systems are shown in Figure 2.

If it is not feasible to obtain precise alignment of the motion and vibration transducers with the preferred basicentric axes, the sensitive axes of transducers may deviate from the preferred axes by up to 15 degrees about the y-axis (i.e., pitch) where necessary. For a person seated on an inclined seat, the relevant orientation should be determined by the axes of the body, and the z-axis will not necessarily be vertical with respect to gravity. The orientation of the basicentric axes to the gravitational field should be noted.

Transducers located at each measurement location shall be positioned orthogonally. Translational accelerometers orientated in different axes at a single measurement location shall be as close together as possible. If rotational accelerations are to be calculated from pairs of translational accelerometers, each translational accelerometer in the pair should be separated by as much distance as possible, and both accelerometers shall be attached to a mount which has a lowest resonant frequency in the axis of interest which is greater than the frequency range specified in this recommended practice (see 5.3.3.1.1).

5.2.2.2 Location

Transducers shall be located so as to indicate the motion and vibration at the interface between the human body and the respective vehicle surface. Motion and vibration which is transmitted to the body shall be measured at the interface between the body and that surface.

A minimum of three principal areas shall be used for measurement of motion and vibration of seated occupants: the supporting seat/buttocks surface, the seat/back surface and the floor/feet surface. For drivers, the steering wheel/hands surface shall also be measured. Measurements on the supporting seat/buttocks surface should be made beneath the ischial tuberosities. Measurements on the seat/back surface should be made in the area of principal support of the body. Measurements at the floor/feet should be made on the surface on which the feet are most often supported. In all cases the location of measurement shall be fully reported.

NOTE: The principal areas of contact between the body and a surface may not always be self-evident.

Motion and vibration which is transmitted to the body from a non-rigid or resilient material (e.g., the seat cushion) shall be measured with the transducer interposed between the person and the principal contact areas of the surface. This should be achieved by securing the transducers within a suitably formed mount which has a lowest resonant frequency in the axis of interest which is greater than the frequency range specified in this recommended practice. The mount should not greatly alter the pressure distribution on the surface of the resilient material. The mount may be covered with a comfort retaining material such that the rated stationary interface discomfort of seated occupants is similar to that which occurs without the mount and its sensors being present. For measurements on non-rigid surfaces, a person shall use a normal position and posture.

NOTE: A commonly used design for accelerometer mount for seat vibration measurements is given in ISO 10326-1.

5.2.3 Signal Conditioning

The motion and vibration evaluation procedures for rough road conditions defined in this recommended practice incorporate methods of averaging motion and vibration over time and over frequency bands.

The frequency response of the vibration transducer and associated signal conditioning prior to signal processing shall exhibit deviations no greater than 1 dB from a flat response across the range of frequencies specified in the relevant clauses of this recommended practice.

The dynamic range of the signal-conditioning equipment shall be adequate for the highest and lowest signals recorded. Signals to be recorded for later analysis may first be passed through a low-pass filter of at least sixth order having a cutoff (-3 dB) frequency of approximately 1.5 times the highest frequency of interest in order to maximize the signal-to-noise ratio and the phase characteristic shall be linear within the range of frequencies specified in the relevant clauses of this recommended practice. The signal-to-noise ratio of each channel of the data acquisition system, defined as the ratio of the data acquisition output range to the root-mean-squared signal level of each sensor when the sensor is at rest, electrically excited and connected to the data acquisition system, measured at the output of the data acquisition system, and scaled in the same units as the data acquisition system range, shall be at least 66 dB.

5.2.4 Duration of Measurement

The duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed. The duration of measurement shall be reported. The measurement duration shall be a minimum of 8 seconds. The location of the specimen may be defined by using landmarks along the side or on the surface of the road. During the recording, the speed of the vehicle shall be displayed to the driver and shall remain constant to within ±4 km/h.

NOTE: The choice of measurement duration depends on a number of factors, constraints and tradeoffs, including the type of ride events (e.g., rough road or transient), the availability of suitable over-the-road ride specimens, the ability to subjectively evaluate the vehicle-ride events, the frequency weighted bandwidth of the driver interface accelerations, and the desired accuracy (refer to Bourne (1993)). It is recommended that the duration of measurement be the same for all ride specimens (i.e., 8 seconds minimum) in order to eliminate the measurement duration as a source of variation in the results when comparing the results to the ratings from a global (i.e., absolute) adjectivally anchored psychometric rating scale and to the results from other ride specimens. For stationary random signals, the accuracy depends on the signal bandwidth and measurement duration. For example, to obtain a measurement error of less than 3 dB at a confidence level of 90% requires a minimum duration of 108 seconds for a one-third octave bandwidth signal centered at 1 Hz (i.e., 0.23 Hz total bandwidth). However, it may be not be practical or even feasible to measure over-the-road ride specimens with such long durations, particularly at higher travel speeds or for transient ride events, due either to physical space limitations or the likely presence of (dissimilar types of) transients. Instead it may be more practical and feasible to measure the same vehicle-ride specimen multiple times (e.g., six repeated runs) and assess the accuracy of the results based on the observed run-to-run variation. The number of repeated runs can then be increased until the desired accuracy of the mean value for the vehicle-ride specimen is achieved.

5.2.5 Vehicle Speed Measurement

Vehicle forward speed shall be measured and shall be recorded using the same data acquisition system used for the motion and vibration recording, for purposes of quality control screening of runs and documentation. The speed shall be measured with a sensor within an accuracy of ±1%.

5.2.6 Reporting of Measurement Conditions

Proper use of this recommended practice should result in clear documentation of results. This should involve a reference to the appropriate clauses and appendices of this recommended practice and to one or more of the frequency weightings.

Users of this recommended practice should report both the magnitude and duration of any motion and vibration exposure being assessed. If additional evaluation methods are applied both the basic value and the additional value shall be reported. If alternative methods are applied, the methods used shall be clearly reported. If the crest factor is determined, the time period of its measurement should be reported.

The specification of the severity of complex motion and vibration conditions by one, or a few, values should be provided. However, more detailed information on vibration conditions should also be made available. Reports should include information on the frequency content (i.e., vibration spectra), vibration axes, how conditions change over time, and any other factors which may influence the effect.

NOTE: Other factors may also affect human sensitivity to motion and vibration: population type (age, sex, size, fitness, etc.); experience, expectation, arousal, and motivation (e.g., difficulty of task to be performed); body posture; activities (e.g., driver or passenger); financial involvement. Therefore, a jury comprising a representative sample of subjects and recording and/or controlling for such variables by means of suitable protocols is recommended.

5.3 Processing of Vibration Data

5.3.1 Basic Processing Method Using Weighted Root-Mean-Square and Root-Mean-Quad Acceleration

The vibration processing according to this recommended practice shall always include measurements of the weighted root-mean-square (RMS) acceleration for rough road ride conditions, and root-mean-quad (RMQ) acceleration for transient ride conditions, as defined in this sub clause.

The weighted RMS acceleration is expressed in meters per second squared (m/s^2) for translational vibration and radians per second squared (rad/s^2) for rotational vibration. The weighted RMS acceleration shall be calculated in accordance with the following equation or its equivalents in the frequency domain.

$$RMS(a_w,T)=\left[\frac{1}{T}\int_0^T a_w^2(t)\,dt\right]^{\frac{1}{2}} \quad \text{(Eq. 1)}$$

where:

$a_w(t)$ is the frequency-weighted translational or rotational acceleration as a function of time (time history), in meters per second squared (m/s^2) or radians per second squared (rad/s^2), respectively;

T is the duration of the measurement, in seconds.

NOTE: It is assumed that the frequency-weighted acceleration has zero mean value.

The weighted RMQ acceleration is expressed in meters per second squared (m/s^2) for translational vibration and radians per second squared (rad/s^2) for rotational vibration. The weighted RMQ acceleration shall be calculated in accordance with the following equation.

$$RMQ(a_w,T)=\left[\frac{1}{T}\int_0^T a_w^4(t)\,dt\right]^{\frac{1}{4}} \quad \text{(Eq. 2)}$$

Frequency-weighting curves recommended and/or used for the various directions and their applications are listed in Table 1 and discussed in the following sub clauses. Numerical values of the weighting curves are given in Table 2 and exact definitions are given in Appendix A.

5.3.2 Applicability of the Basic Processing Method

5.3.2.1 Categorizing Rough Versus Transient Specimens

The ratio of the RMQ/RMS shall be calculated to determine whether the ride specimen shall be processed using the RMS method for rough roads or the RMQ method for transient ride specimens. If the RMQ/RMS ratio is greater than 1.5, then the ride specimen should be considered to be a transient ride specimen. Otherwise, the ride specimen should be considered to be a rough road ride specimen.

NOTE: The RMQ/RMS ratio for ideal stationary Gaussian random signals is approximately 1.32. See rationale in C.3.3.

Table 2 - Human discomfort frequency weightings in one-third octaves

Frequency band number[1] k	Frequency f Hz	W_0		W_b		W_c	
		factor x 1000	dB	factor x 1000	dB	factor x 1000	dB
-10	0.1	62.4	-24.10	24.4	-32.27	62.4	-24.10
-9	0.125	97.2	-20.25	37.9	-28.42	97.2	-20.25
-8	0.16	158	-16.03	61.7	-24.20	158	-16.03
-7	0.2	243	-12.30	94.6	-20.48	243	-12.30
-6	0.25	364	-8.78	142	-16.96	364	-8.78
-5	0.315	527	-5.56	205	-13.76	527	-5.56
-4	0.4	707	-3.01	275	-11.22	708	-3.01
-3	0.5	842	-1.49	326	-9.73	843	-1.48
-2	0.63	927	-0.65	358	-8.92	929	-0.64
-1	0.8	970	-0.26	372	-8.59	972	-0.24
0	1	987	-0.11	376	-8.49	991	-0.08
1	1.25	995	-0.05	377	-8.47	1000	0.00
2	1.6	998	-0.02	383	-8.34	1007	0.06
3	2	999	-0.01	408	-7.80	1012	0.10
4	2.5	1000	0.00	482	-6.34	1017	0.15
5	3.15	1000	0.00	646	-3.79	1022	0.19
6	4	1000	0.00	868	-1.23	1024	0.20
7	5	1000	0.00	1001	0.01	1013	0.11
8	6.3	1000	0.00	1030	0.26	974	-0.23
9	8	1000	0.00	1001	0.01	891	-1.00
10	10	1000	0.00	952	-0.43	776	-2.20
11	12.5	1000	0.00	885	-1.06	647	-3.79
12	16	1000	0.00	791	-2.03	512	-5.82
13	20	999	-0.01	691	-3.21	409	-7.77
14	25	998	-0.02	586	-4.65	325	-9.76
15	31.5	995	-0.04	481	-6.36	256	-11.84
16	40	987	-0.11	384	-8.31	199	-14.02
17	50	970	-0.26	305	-10.31	156	-16.13
18	63	929	-0.64	234	-12.63	118	-18.53
19	80	842	-1.49	167	-15.52	84.4	-21.47
20	100	707	-3.01	113	-18.96	56.7	-24.94

[1] Index k is the frequency band number according to IEC 1260 for reference purposes only.

NOTE: For tolerances of the frequency weightings, see 5.3.3.1.2.

NOTE: The values have been calculated including frequency band limitation.

Table 2 - Human discomfort frequency weightings in one-third octaves (continued)

Frequency band number[1)] k	Frequency f Hz	W_d		W_e		W_{sl}	
		factor x 1000	dB	factor x 1000	dB	factor x 1000	dB
-10	0.1	62.4	-24.09	62.5	-24.08	62.4	-24.10
-9	0.125	97.3	-20.24	97.5	-20.22	97.2	-20.25
-8	0.16	158	-16.01	159	-15.98	158	-16.03
-7	0.2	243	-12.28	245	-12.23	243	-12.30
-6	0.25	365	-8.75	368	-8.67	364	-8.78
-5	0.315	530	-5.52	536	-5.41	527	-5.56
-4	0.4	713	-2.94	723	-2.81	708	-3.00
-3	0.5	853	-1.38	862	-1.29	844	-1.48
-2	0.63	944	-0.50	939	-0.55	930	-0.63
-1	0.8	992	-0.07	941	-0.53	974	-0.23
0	1	1011	0.10	880	-1.11	993	-0.06
1	1.25	1008	0.07	772	-2.25	1003	0.03
2	1.6	968	-0.28	632	-3.99	1011	0.09
3	2	890	-1.01	512	-5.82	1017	0.15
4	2.5	776	-2.20	409	-7.77	1022	0.19
5	3.15	642	-3.85	323	-9.81	1024	0.20
6	4	512	-5.82	253	-11.93	1011	0.10
7	5	409	-7.76	202	-13.91	972	-0.24
8	6.3	323	-9.81	160	-15.94	891	-1.00
9	8	253	-11.93	125	-18.03	767	-2.30
10	10	212	-13.91	100	-19.98	638	-3.91
11	12.5	161	-15.87	80.1	-21.93	516	-5.75
12	16	125	-18.03	62.5	-24.08	403	-7.90
13	20	100	-19.99	50.0	-26.02	320	-9.89
14	25	80.0	-21.94	39.9	-27.97	255	-11.88
15	31.5	63.2	-23.98	31.6	-30.01	201	-13.95
16	40	49.4	-26.13	24.7	-32.15	156	-16.12
17	50	38.8	-28.22	19.4	-34.24	123	-18.22
18	63	29.5	-30.60	14.8	-36.62	93.2	-20.62
19	80	21.1	-33.53	10.5	-39.55	66.4	-23.55
20	100	14.1	-36.99	7.07	-43.01	44.6	-27.02

[1)] Index k is the frequency band number according to IEC 1260 for reference purposes only.

NOTE: For tolerances of the frequency weightings, see 5.3.3.1.2.

NOTE: The values have been calculated including frequency band limitation.

5.3.2.2 Determination of the Domain-of-Validity

The RMS or RMQ values for each ride specimen should be tested to determine whether it is within the domain-of-validity of the respective ride metric. For each interface, compute the following.

$$z = T(x - x_0) \quad \text{(Eq. 3)}$$

where:

z is a p by 1 matrix of z-scores;

p is the number of interface axes (p =6 for the seat/buttock interface, p =3 otherwise);

x is a p by 1 matrix comprising the natural logarithm of the RMS or RMQ acceleration values;

x_0 is the mean value for x values in the original database used to develop the ride metric;

T is a p by p transformation matrix.

The values for x_0 and T should be determined according to 5.5.3.1.

If $z_{min} < z < z_{max}$ is satisfied, where:

z_{min} and z_{max} are p by 1 matrices that specify the range of z values in the original database used to develop the ride metric;

then the ride specimen given by x is within the domain-of-validity of the ride metric.

The values for z_{min} and z_{max} should be determined according to 5.5.3.2. The results of this test should be reported for each ride specimen along with the ride discomfort value calculated in 5.4.

5.3.3 Frequency Weighting

5.3.3.1 Frequency Weighting of Acceleration Time History

For integration of the frequency-weighted acceleration time history, the frequency weighting shall be determined from Tables 1 and 2, as applicable.

The frequency weightings listed in Table 1 for each of the applicable axes and locations of vibration shall be used.

The human discomfort frequency weightings listed in Table 2 for the respective axes shall be used. The corresponding frequency weighting curves are shown in Figures 3 and 4, respectively.

The frequency weightings may be implemented by either analog or digital methods. They are defined in a mathematical form familiar to filter designers, in Appendix A.

The frequency weightings given in Table 2 and illustrated in Figures 3 and 4 include the frequency band limitations. In Appendix A the equations for the frequency band limitation are expressed separately.

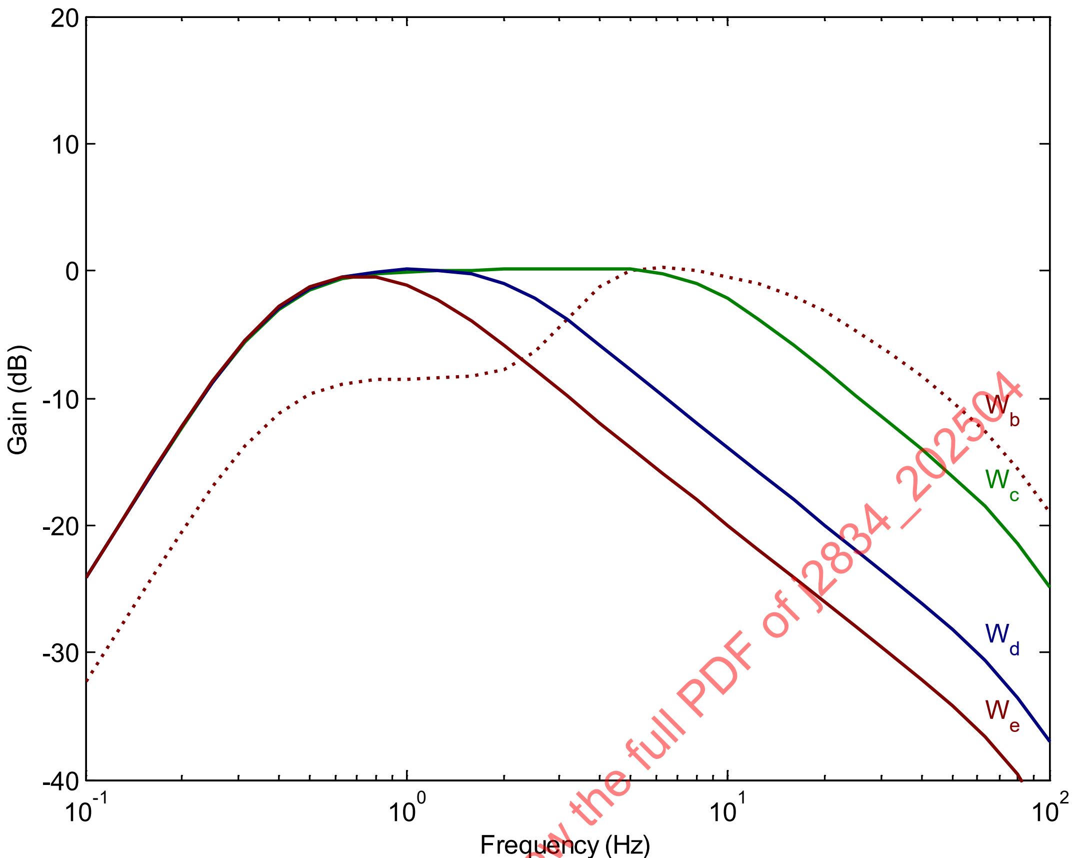

Figure 3 - Frequency weighting curves for human discomfort weightings

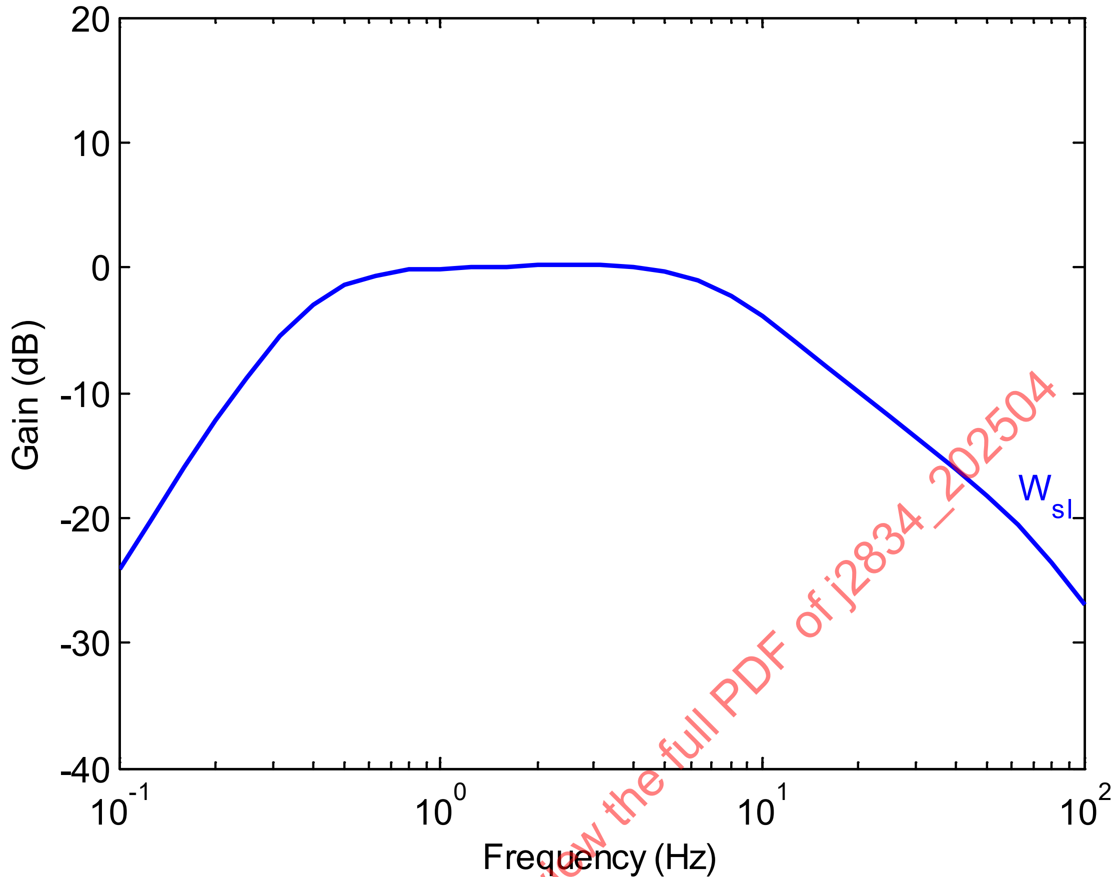

Figure 4 - Frequency weighting curve for steering wheel/hands discomfort weighting

5.3.3.1.1 Frequency Band Limitation

Lower and upper frequency band limitation shall be achieved by two-pole high-pass and low-pass filters, respectively, with Butterworth characteristics having an asymptotic slope of -12 dB per octave. The corner frequencies of the band-limiting filters shall be one-third octave outside the nominal frequency range of the relevant band.

Frequency weightings defined in Appendix A include the band-limiting filters (high pass at 0.4 Hz and low pass at 100 Hz) which shall be used with weightings W_b, W_c, W_d, W_e, and W_{sl}.

NOTE: The ISO 2631-1 (1997) weighting W_k is within 3 dB the W_b weighting in the 0.4 to 100 Hz frequency range.

5.3.3.1.2 Tolerances

Within the nominal frequency bands and one-third octave from the frequency limits, the tolerance of the combined frequency weighting and band limiting shall be ±1 dB. Outside this range, the tolerance shall be ±2 dB. One octave outside the nominal frequency bands, the attenuation may extend towards infinity.

NOTE: Also refer to ISO 8041 concerning tolerances.

5.3.3.2 Frequency Weighting of Acceleration Spectra

The acceleration signal of RMS weighted rough road accelerations may be analyzed and reported as either constant bandwidth or proportional bandwidth (e.g., as one-third octave band) spectra of unweighted acceleration. In the case of one-third octave bands the center frequencies shall be as stated in Table 2. Any form of frequency analysis, analog or digital, direct one-third octave band or summation of narrow band data may be used. The data analysis method shall be consistent with the one-third octave band filter specification given in IEC 1260.

The frequency-weighted RMS acceleration shall be determined by weighting and appropriate addition of narrow band or one-third octave band data.

For the conversion of one-third octave band data, the weighting factors given in Table 2 shall be used. The overall weighted acceleration shall be determined in accordance with the following equation or its digital equivalent in the time or frequency domain:

$$a_w = \left[\sum_k \left(W_k a_k \right)^2 \right]^{\frac{1}{2}} \quad \text{(Eq. 4)}$$

where:

a_w is the frequency-weighted acceleration;

W_k is the weighting factor for the k th one-third octave band given in Table 2;

a_i is the RMS acceleration for the k th one-third octave band.

5.4 Prediction of Discomfort Ratings

5.4.1 Rough Road Ride Specimens

The predicted numerical discomfort rating of an occupant interface shall be calculated for a rough road ride specimen as follows:

$$DR_{int} = b_{r,int,0} + \sum_i b_{r,int,i} RMS\left(a_{w,i}\right) \quad \text{(Eq. 5)}$$

where:

$a_{w,i}$ is a frequency weighted translational or rotational acceleration with respect to axis i, (e.g., $i=x, y, z$);

$b_{r,int,0}$ and $b_{r,int,i}$ are rough road ride interface discomfort model coefficients.

The overall motion and vibration discomfort rating for an occupant shall be calculated for a rough road ride specimen as follows:

$$DR_{omv} = b_{r,omv,0} + \sum_{int} b_{r,omv,int} DR_{int} \quad \text{(Eq. 6)}$$

where:

$b_{r,omv,0}$ and $b_{r,omv,int}$ are rough road overall motion and vibration discomfort model coefficients.

The rough road ride discomfort model coefficients in Equations 5 and 6 shall be determined based on data collected from suitable human psychometric experiments as described in 5.1 and 5.2 and the statistical methods as described in 5.5. These coefficients may have different values depending on the occupant type (i.e., driver or passenger), occupant physical characteristics (e.g., age and sex), vehicle market segment and road specimen sample.

NOTE: Sound may influence the perception of motion and vibration discomfort, therefore terms for noise discomfort or sound indices may also be included in Equation 5 (refer to SAE 980585).

5.4.2 Transient Ride Specimens

The discomfort rating of an occupant interface shall be calculated for a transient ride specimen as follows:

$$DR_{int} = b_{t,int,0} + \sum_{i} b_{t,int,i} RMQ\left(a_{w,i}\right) \quad \text{(Eq. 7)}$$

where:

$a_{w,i}$ is a frequency weighted translational or rotational acceleration with respect to axis i, (e.g., $i = x, y, z$);

$b_{t,int,0}$ and $b_{t,int,i}$ are transient ride interface discomfort model coefficients.

The overall motion and vibration discomfort rating for an occupant shall be calculated for a transient ride specimen as follows:

$$DR_{omv} = b_{t,omv,0} + \sum_{int} b_{t,omv,int} DR_{int} \quad \text{(Eq. 8)}$$

The transient ride discomfort model coefficients in Equations 7 and 8 shall be determined based on data collected from suitable human psychometric experiments as described in 5.1 and statistical methods as described in 5.5. These factors may have different values depending on the occupant type (i.e., driver or passenger), occupant physical characteristics (e.g., age and sex), vehicle market segment, and road specimen sample.

NOTE: Sound may influence the perception of motion and vibration discomfort, therefore terms for noise discomfort or sound indices may also be included in Equation 7 (refer to SAE 980585).

5.5 Statistical Method for Determining the Ride Discomfort Models

Determine the rough road and transient ride discomfort model coefficients from experimental data using multi-variable linear regression methods (e.g., Draper and Smith, 1981).

Determine models representing a jury, comprised of several subjects, by combining the regression models for individual subjects. The terms in the models shall be selected to maximize the fit and predictive capability, on average, of the subject models, as quantified by the linear regression RPRED statistic described in 5.5.2.

5.5.1 Jury Model

Given the following set of linear regression models for individual (driver or passenger) subjects,

$$y_j = b_{j,0} + \sum_{i=1}^{p} b_{j,i} x_i \text{, for } j = 1, m \quad \text{(Eq. 9)}$$

where:

y_j is the discomfort rating reported by the jth subject,

x_i are the model inputs (either frequency weighted accelerations or interface discomfort ratings),

p is the number of model inputs,

$b_{j,0}$ and $b_{j,i}$ are the subject model coefficients, and

m is the number of subjects,

calculate the jury model coefficients as follows:

$$b_0 = \frac{1}{m}\sum_{j}^{m} b_{j,0} \quad \text{(Eq. 10)}$$

$$b_i = \frac{1}{m}\sum_{j}^{m} b_{j,i} \quad \text{(Eq. 11)}$$

5.5.2 RPRED Statistic

Calculate the RPRED statistic of a candidate linear regression model according to the equation:

$$RPRED_j = 1 - \frac{PRESS_j}{SS_{TOT,j}} \quad \text{(Eq. 12)}$$

$$PRESS_j = \sum_{k=1}^{n_j}\left(y_{j,k} - \hat{y}_{j,k,-k}\right)^2 \quad \text{(Eq. 13)}$$

$$SS_{TOT,j} = \sum_{k=1}^{n_j}\left(y_{j,k} - \bar{y}_j\right)^2 \quad \text{(Eq. 14)}$$

$$\bar{y}_j = \frac{1}{n_j}\sum_{k=1}^{n_j} y_{j,k} \quad \text{(Eq. 15)}$$

where:

$y_{j,k}$ is the reported discomfort rating value of the k th data observation for the j th subject,

$\hat{y}_{j,k,-k}$ is the discomfort rating value predicted by the candidate model estimated with the k th data observation removed, and

n_j is the number of observations for the j th subject.

The jury average RPRED statistic shall be calculated as follows:

$$RPRED_{jury} = \frac{1}{m}\sum_{j}^{m} RPRED_j \quad \text{(Eq. 16)}$$

The ride discomfort ratings shall be predicted by jury models with large values for $RPRED_{jury}$.

5.5.3 Domain-of-Validity

Determine the magnitude domain-of-validity of each interface discomfort model comprising the ride metric as follows:

5.5.3.1 Z-Score Transformation Parameters

Compute the following for each ride specimen in the database used to estimate the interface discomfort model:

$$\mathbf{x}_k = \begin{bmatrix} \ln(\text{RMS or RMQ acceleration of axis 1}) \\ \ln(\text{RMS or RMQ acceleration of axis 2}) \\ \vdots \\ \ln(\text{RMS or RMQ acceleration of axis } p) \end{bmatrix} \quad \text{(Eq. 17)}$$

where:

$\mathbf{x}_k$ is a p by 1 matrix,

k is the index of the ride specimen,

p is the number of interface axes (p =6 for the seat/buttock interface, p =3 otherwise).

Compute the mean value for $\mathbf{x}_k$ in the database according to the equation:

$$\mathbf{x}_0 = \frac{1}{n}\sum_{k=1}^{n}\mathbf{x}_k \quad \text{(Eq. 18)}$$

where:

n is the number of ride specimen used to estimate the ride metric model coefficients.

Compute a p by p matrix $\mathbf{C}$ (representing the covariance of x_k) according to the equation:

$$\mathbf{C} = \frac{1}{n-1}\sum_{k=1}^{n}(\mathbf{x}_k - \mathbf{x}_0)(\mathbf{x}_k - \mathbf{x}_0)^T \quad \text{(Eq. 19)}$$

Compute the eigenvalues and eigenvectors of $\mathbf{C}$ such that:

$$\mathbf{CV} = \mathbf{VD} \quad \text{(Eq. 20)}$$

where:

$\mathbf{D}$ is a p by p diagonal matrix comprising the eigenvalues of $\mathbf{C}$, ordered such that:

$$D_{1,1} \geq D_{2,2} \geq \cdots > 0$$

$\mathbf{V}$ is a p by p matrix comprising the corresponding eigenvectors of $\mathbf{C}$.

NOTE: The eigenvalues and eigenvectors of $\mathbf{C}$ can be computed using the EISPACK routine RS (Smith et al., 1976), LAPACK routine DSYEVR (Anderson et al., 1999) or other equivalent computer software.

Compute the p by p transformation matrix $\mathbf{T}$ according to the equation:

$$\mathbf{T} = \mathbf{D}^{-1/2}\mathbf{V}^{-1} \quad \text{(Eq. 21)}$$

5.5.3.2 Z-Score Domain-of-Validity

Compute the z-scores for each ride specimen in the original database according to the equation:

$$\mathbf{z}_k = \mathbf{T}(\mathbf{x}_k - \mathbf{x}_0) \quad \text{(Eq. 22)}$$

The method in 5.3.3.3 may be used to compute $\mathbf{z}_{min}$ and $\mathbf{z}_{max}$ if the z-scores are normally distributed; otherwise, use the method in 5.3.3.4.

5.5.3.3 Normally Distributed Z-Score Limits

Compute the standard deviation of each element of the z-scores as follows:

$$s_i = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n} z_{k,i}^2} \quad \text{(Eq. 23)}$$

Determine $t_{0.005,n-1}$, the critical value for the 0.005 tail area probability of t-distribution with $n-1$ degrees-of-freedom.

If $n > 120$ use the following approximation,

$$t_{0.005,n-1} = 2.576$$

NOTE: The value for $t_{0.005,n-1}$ can be found in Table B1 of Box (1978) or other equivalent table.

Then, compute z_{min} and z_{max} according to the equation:

$$\begin{aligned} z_{\min,i} &= t_{0.005,n-1} s_i \\ z_{\max,i} &= t_{0.995,n-1} s_i \end{aligned} \quad \text{(Eq. 24)}$$

5.5.3.4 Not Normally Distributed Z-Score Limits

If the distribution of z-scores is not normally distributed, then the following method may be used to calculate $\mathbf{z}_{min}$ and $\mathbf{z}_{max}$. For each element of $\mathbf{z}$ sort the n values for $z_{k,i}$ from the smallest to the largest value. Then determine the 0.5th and 99.5th percentile values as follows:

$$\begin{aligned} z_{min,i} &= z_{k_{min,i}} \\ z_{max,i} &= z_{k_{max,i}} \end{aligned} \quad \text{(Eq. 25)}$$

where:

$$\begin{aligned} k_{min,i} &= \text{nearest integer}\,(0.005(\mathrm{n}+1)) \\ k_{max,i} &= \text{nearest integer}\,(0.995(\mathrm{n}+1)) \end{aligned} \quad \text{(Eq. 26)}$$

where nearest integer(x) indicates to round *x* to the nearest integer value.

6. NOTES

6.1 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE SAE VEHICLE DYNAMICS STANDARDS COMMITTEE

APPENDIX A - MATHEMATICAL DEFINITION OF THE FREQUENCY WEIGHTINGS

A.1 PARAMETERS OF THE TRANSFER FUNCTIONS

The parameters of the transfer functions are given in Table A1.

Table A1 - Parameters of the transfer functions of the human discomfort frequency weightings

Weighting	Band-limiting		Acceleration-velocity transition (a-v transition)			Upward step			
	f_1 Hz	f_2 Hz	f_3 Hz	f_4 Hz	Q_4	f_5 Hz	Q_5	f_6 Hz	Q_6
W_0	0.4	100	-	-	-	-	-	-	-
W_b	0.4	100	16.0	16.0	0.55	2.5	0.90	4	0.95
W_c	0.4	100	8.0	8.0	0.63	-	-	-	-
W_d	0.4	100	2.0	2.0	0.63	-	-	-	-
W_e	0.4	100	1.0	1.0	0.63	-	-	-	-
W_{sl}	0.4	100	6.3	6.3	0.63	-	-	-	-

NOTE: The W_{sl} weighting specified by the parameters in Table A1 is a realizable analytic approximation for the asymptotic W_s weighting reported by Giacomin et al. (2004) within the 0.5 to 80 Hz frequency range.

A.2 TRANSFER FUNCTIONS

The frequencies f_1, ..., f_6 and the resonant quality factors Q_4, ..., Q_6 are parameters of the transfer function which determine the overall frequency weighting (referred to acceleration as the input quantity). The transfer function is expressed as a product of several factors as follows.

Band-limiting (two-pole filter with Butterworth characteristic).

High pass:

$$|H_h(s)| = \left| \frac{s^2}{s^2 + \sqrt{2}\omega_1 s + \omega_1^2} \right| = \sqrt{\frac{f^4}{f^4 + f_1^4}} \quad \text{(Eq. A1)}$$

where:

$s = j2\pi f$ is the imaginary angular frequency where $j = \sqrt{-1}$;

f is the frequency in Hz;

$\omega_1 = 2\pi f_1$;

f_1 is the corner frequency in Hz (intersection of asymptotes).

Low pass:

$$|H_l(s)| = \left| \frac{\omega_2^2}{s^2 + \sqrt{2}\omega_2 s + \omega_2^2} \right| = \sqrt{\frac{f_2^4}{f^4 + f_2^4}} \quad \text{(Eq. A2)}$$

where:

$\omega_2 = 2\pi f_2$;

f_2 is the corner frequency in Hz.

Acceleration-velocity transition (proportionality to acceleration at lower frequencies, proportionality to velocity at higher frequencies):

$$|H_t(s)| = \left| \left(\frac{s + \omega_3}{s^2 + \frac{\omega_4}{Q_4} s + \omega_4^2} \right) \cdot \left(\frac{\omega_4^2}{\omega_3} \right) \right| = \sqrt{\frac{f^2 + f_3^2}{f_3^2}} \cdot \sqrt{\frac{f_4^4 \cdot Q_4^2}{f^4 \cdot Q_4^2 + f^2 \cdot f_4^2 \left(1 - 2Q_4^2\right) + f_4^4 \cdot Q_4^2}} \quad \text{(Eq. A3)}$$

where:

$\omega_3 = 2\pi f_3$;

$\omega_4 = 2\pi f_4$.

Upward step (steepness approximately 6 dB per octave, proportionality to jerk):

$$|H_s(s)| = \left| \frac{s^2 + \frac{\omega_5}{Q_5} s + \omega_5^2}{s^2 + \frac{\omega_6}{Q_6} s + \omega_6^2} \right| = \frac{Q_6}{Q_5} \cdot \sqrt{\frac{f^4 \cdot Q_5^2 + f^2 \cdot f_5^2 \left(1 - 2Q_5^2\right) + f_5^4 \cdot Q_5^2}{f^4 \cdot Q_6^2 + f^2 \cdot f_6^2 \left(1 - 2Q_6^2\right) + f_6^4 \cdot Q_6^2}} \quad \text{(Eq. A4)}$$

where:

$\omega_5 = 2\pi f_5$;

$\omega_6 = 2\pi f_6$.

The product $H_h(s) \cdot H_l(s)$ represents the band-limiting transfer function; it is the same for all weightings.

The product $H_t(s) \cdot H_s(s)$ represents the actual weighting transfer function for a certain application.

$H_t(s) = 1$ for weighting W_0;

$H_s(s) = 1$ for weightings W_0, W_c, W_d and W_e.

This is indicated by the absence of quality factors in the tables.

The total weighting function is:

$$H(s) = H_h(s) \cdot H_l(s) \cdot H_t(s) \cdot H_s(s) \quad \text{(Eq. A5)}$$