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/s² rms (summed weighted)	SD m/s² 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/s² rms (summed weighted acceleration); (b) case 2: vibration level increasing linearly along the vehicle from 0.5 to 1.1 m/s² rms (i.e., 0.8 m/s² mean value); and (c) case 3: vibration level 0.5 m/s² rms in the center of the vehicle, increasing to 1.1 m/s² rms each end (i.e., 0.8 m/s² 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/s²	93	69	31	11
Varying between 0.5 and 1.1 m/s²	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

D. SUSSMAN AND D.N. WORMLEY

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 quasipublic 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

(7-9) have specifically addressed the design requirements of guideway-vehicle systems and associated costs required to provide specified levels of ride quality. In this paper ride quality issues are discussed for advanced transportation systems, and recommendations are made for their specifications.

Ride Quality Definition

The quality of ride experienced by passengers in a vehicle is a function of many elements including the linear and angular acceleration of the car body, and the noise, temperature, humidity, and seating accommodations in the passenger compartment. This paper will consider primarily those aspects of ride quality influenced by vehicle motions. The ride environment is defined in terms of linear and angular accelerations (and angular velocities or rates) that result from vehicle motion. Car body motion is induced by guideway disturbances, wind disturbances, and the operational systems controlling the vehicle forward speed. Because wind disturbances are not easily characterized, they are not usually directly included in ride quality specifications for ground transport vehicles. Principal measures as a function of time have included linear acceleration and jerk (the rate of change of acceleration) along the vertical, lateral, and longitudinal vehicle axes as well as angular rate and acceleration about the roll (and pitch and yaw) axes (10,11). These measures of motion as a function of time may be processed in a variety of ways to yield the following:

1. The average value of the measure in a time period;
2. The rms value of the measure in a time period;
3. The peak or maximum value of the measure in a time period;
4. The number of times the measure exceeds a specified value in a time period;
5. From a record of the measures over a given time period, the power spectral density (psd) may be computed to yield the mean square amplitude of the measure as a function of frequency; and
6. From a record of the measure over a given time period, the rms acceleration in specified frequency bands may be computed (the computation can be performed directly from the psd by integrating the psd over the frequency band performing the square root).

Data-processing equipment is available to compute many of these measures as they are recorded in the field. Equipment is also available at many computation centers to process the data into an appropriate form directly from a magnetic tape record of the data (12).

RIDE QUALITY CRITERIA

The quantities computed from measured data may be compared with a number of criteria to evaluate the system ride quality. In discussing ride quality criteria, two types of vehicle motion are considered: (a) deterministic motions that result from programmed maneuvers and from operations along the general guideway topology, and (b) motions that result from local guideway surface profile irregularities including random roughness as well as dynamic motions.

Deterministic Criteria

Deterministic motions are established by the guideway general topology including grade, spiral curve entry, curve radius, superelevation, and switch geometry, and by acceleration and braking schedules. Criteria for the maximum levels of acceleration and jerk due to deterministic motion have been developed in a number of studies (13-15). On the basis of tests conducted at Transpo '72, acceptable ride quality for seated passengers was found to require that (a) longitudinal acceleration and jerk due to starting and braking be limited to 0.2 *g* and 0.2 *g*/s, respectively; and (b) lateral acceleration and jerk in curve negotiation and switch areas be limited to 0.12 *g* and 0.24 *g*/s, respectively (13).

A recent report recommends that if all passengers are standing, longitudinal accelerations be limited to less than 0.15 *g* (15). Other references have suggested limiting both longitudinal and lateral acceleration to the 0.1 *g* level. The constraints on guideway topology, including grade, curve radius, spiral entry, and superelevation required to meet prescribed levels of steady-state acceleration and jerk, are defined in Stevens and others (16) as a function of vehicle operating speed. The references cited provide strong guidelines for advanced system general guideway topology logical design to meet ride quality constraints.

Random Disturbance Criteria

The sensitivity of humans to vehicle motions that result from the local guideway surface profile, including irregularities and deflections, sets limits on allowable levels of guideway dynamic deflections and surface roughness. Ultimately, it directly influences vehicle suspension design. In advanced systems, the acceleration that results from these combined effects extends over relatively broad frequency bands. The most widely accepted ride quality criterion for vehicle broad-band motion is based on vehicle acceleration recorded over a time period and processed to yield the rms acceleration level in specified frequency bands as given by ISO 2631 (17). This criterion provides a specific quantitative measure of ride quality that can be used in the design and specification of vehicle/guideway systems.

ISO RIDE QUALITY SPECIFICATION

The ISO Guide for the Evaluation of Human Exposure to Whole-Body Vibration (ISO 2631) provides a conceptually straightforward method for ensuring that a planned system will not produce an unacceptably uncomfortable ride. The objective of ISO 2631 is to provide the system designer or system evaluator with provisional guidelines on acceptable levels of those vibrations to which humans may be exposed. Acceptability is defined in terms of safety, work efficiency, and comfort. Applicability of the standard is limited to vibration transmitted through a supporting surface to the entire body when it is in the standing or seated positions. There are four physical parameters that characterize human vibration exposure: direction, frequency, intensity, and duration.

Direction

The standard uses a coordinate system fixed with respect to the human body rather than based on external references. Therefore, axes must be evaluated relative to the passenger's position rather than the vehicle's axes.

Frequency

The range of application is limited to those frequencies that have primarily mechanical effects on the human body; frequencies within the auditory range are excluded. Therefore, the standard covers only these basic frequencies that extend from 1.0 through 80.0 Hz. [Geoffrey Allen of the Royal Aircraft Establishment, Farnsborough, United Kingdom, has developed an addendum to ISO 2631 that extends the frequency range covered in the document below 1.0 Hz. This addendum was recently incorporated into ISO Document 2631. If significant levels of vibration below 1.0 Hz are expected on vehicles, this addendum should provide useful guidance.]

Intensity

The standard describes the conditions under which differing intensities of vibration are acceptable. Three conditions are discussed.

1. The exposure limit is the highest intensity of vibration to which humans may be safely exposed. Exposure to vibrations of a higher intensity-duration combination than specified in the guideline may lead to severe risk of physical damage, physiological injury, and possible permanent aftereffects.
2. The fatigue decreased proficiency boundary indicates the range of vibration amplitude and duration combinations that can be expected to decrease work performance. This boundary is often considered as the maximum permissible for occupational exposure.
3. The reduced comfort boundary was developed with the intent of defining minimum specifications for human comfort. Activities such as reading, writing, or eating are considered to be possible at the vibration levels encompassed by this boundary. The values of the three boundaries can be computed from one another. The reduced comfort boundary is derived by reducing the fatigue decreased boundary by 1 dB, or dividing by a factor of 3.15.

Duration

Duration is defined as a time period for human body exposure to vibration. The ISO standard limits the allowable combination of vibration intensity and exposure time. Exposure duration extends from 1 min to 24 h of uninterrupted exposure; it is, however, considered in terms of a daily "dose" (more than 24 h). Therefore, for a commuter who makes two daily 30-min trips, the 1-h criterion is appropriate.

In the event that vibration intensity varies during exposure, the ISO standard provides a formula to compute "equivalent exposure time," which may then be used to establish the particular exposure limit needed. In addition to defining the various exposure boundaries, the standard gives guidance to measurement techniques, the location and mounting of transducers, and methodology for evaluation of frequency spectra for narrow and broad-band vibration inputs. Specific ISO criteria are applied in the following manner:

1. Determine the rms acceleration in each one-third octave frequency band and compare this number with the appropriate reduced comfort ISO curve at the center frequency of each one-third octave band to determine what duration level is satisfied for all frequencies (see Figures 1 and 2).
2. In order to achieve a single number (index) representing ride quality, compute the weighted rms acceleration by multiplying the rms acceleration value in a frequency band by a weighting factor (derived from Figure 3), and then sum all weighted components to yield a single effective rms acceleration (a_e):

$$a_e = \left[\sum_{i=1}^{n} (a_i W_i)^2 \right]^{1/2} \tag{1}$$

where a_i is the rms acceleration in a specified frequency band and W_i is the general weighting factor.

The resulting weighted rms acceleration (a_e) is compared with the approximate reduced comfort ISO curves to determine the duration level satisfied. For the toe-to-head direction acceleration, the weighted rms acceleration is compared with the ISO curve values in the 4 to 8 Hz range, while for transverse acceleration it is compared with the ISO curves in the 1 to 2 Hz range.

A recent change in ISO 2631 has recommended, as specified in item 2 above, that a single quantity of "overall weighted vibration value" be used to characterize a vibration environment instead of using a complete one-third octave band analysis as specified in item 1. This more recent technique is called a weighting method of measurement; it is recognized in the standard that this technique provides a conservative assessment of the effects of vibration.

Guidance for evaluation of multiaxis vibration is also provided if vibrations occur in more than one direction simultaneously. The 1974 ISO standard suggests that for multiaxis vibration the corresponding limits should be applied separately to each vectorial component along the three axes: x (lateral), y (longitudinal), and z (vertical). However, a pending 1977 amendment to the standard by Griffen recommends the following combined ISO weighting formula for evaluation of multiaxis vibration (15):

$$a_{eff} = (1.4 a_{x_w})^2 + (1.4 a_{y_w})^2 + a_{z_w}^2 \tag{2}$$

where

a_{x_w} = transverse weighted rms acceleration,
a_{y_w} = longitudinal weighted rms acceleration, and
a_{z_w} = toe-head weighted rms acceleration.

To determine the net effective comfort in terms of duration level, the quantity a_{eff} is compared with values of the effective weighted acceleration of the ISO head-to-toe axis reduced comfort curve.

The above formula requires weighting of the vibration by using the frequency weighting network provided in the guide, or measurement of the vibration in each of the one-third octave bands for all three degrees of freedom and the subsequent weighting of each one-third frequency octave band as per the guide.

In actual use, however, the electronic weighting network is far less cumbersome. As an example, a commuting trip consisting of two daily exposures can be evaluated by first summing the individual trip lengths of a typical user. Therefore, for each 10-min leg of a commuting trip, the value for the 25-min reduced comfort boundary should be used as the standard for evaluating the weighted vibration values. For the z-axis, this value is 0.059 *g*.

The ISO standard does not currently define boundaries for rotational (angular) modes of vibration. The standard does, however, recommend that when it can be assumed that the center of rotation is far enough from the point of application of the vibration to the body, the resulting motion can be represented by translatory (linear) vibration alone and the appropriate boundaries apply.

RIDE ACCEPTANCE MEASURES

The ISO reduced comfort boundaries and the rms acceleration levels are useful in comparing the ride quality of transportation systems but give little indication of relative passenger satisfaction with (or acceptance of) the system ride quality. Pas-

Figure 1. ISO acceleration/frequency curves for vertical axis.

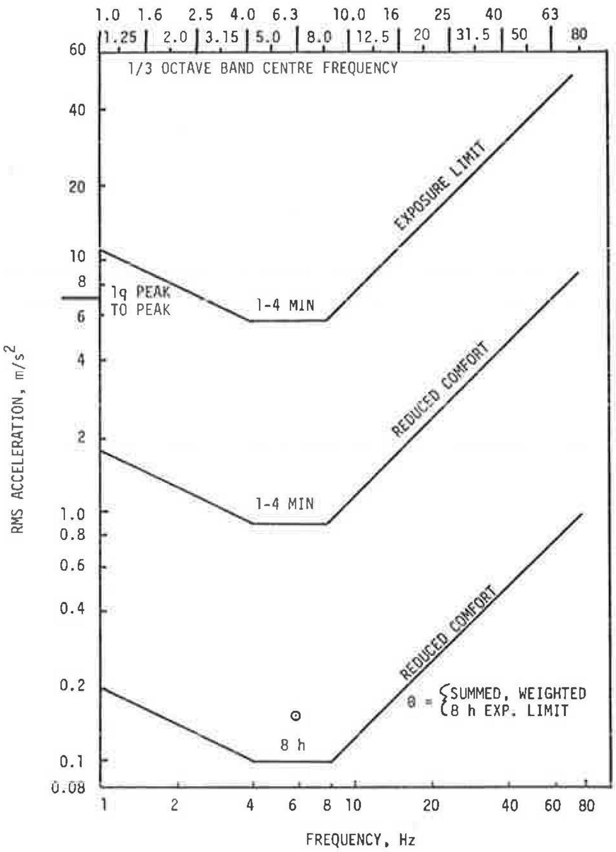
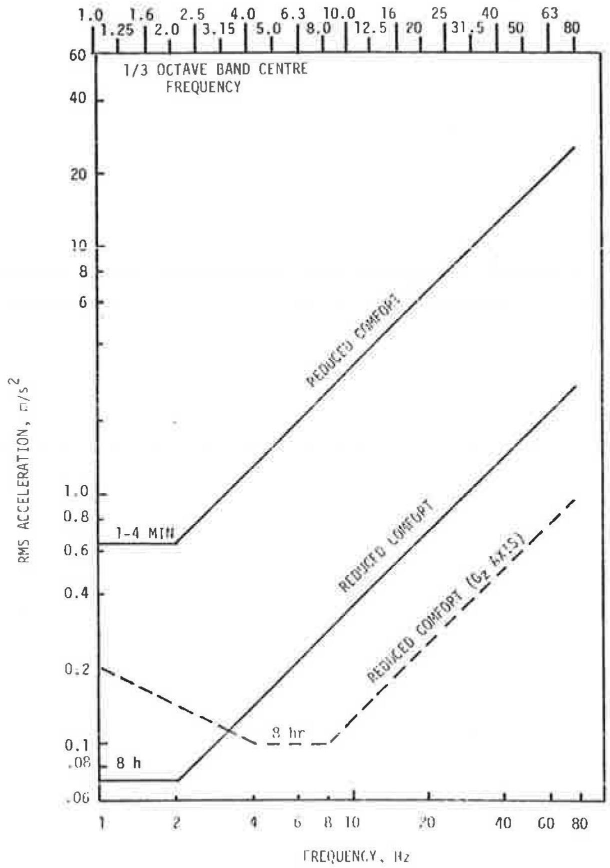


Figure 2. ISO acceleration/frequency curves for lateral and longitudinal axes.



senger satisfaction has been shown to depend on factors other than vertical and horizontal linear accelerations, most notable of which are roll rate, noise, and passenger expectations (18). The relative importance of the various factors is a function of the transportation mode. Ride acceptability is based on the aggregate willingness to reuse a vehicle and is usually expressed as a percentage of the potential passenger market.

The aggregate response of a group of passengers to the physical characteristics of a vehicle may be predicted through the use of recently developed mathematical models (11,19). In such a process ride quality is usually represented by a scale factor. The scale may be either bipolar or unipolar, but for the purposes of this paper we will refer to the following seven-point bipolar scale: 1, very comfortable; 2, comfortable; 3, slightly comfortable; 4, neutral; 5, slightly uncomfortable; 6, uncomfortable; and 7, very uncomfortable.

Because it is mostly a function of physical sensations, the level of ride quality is a stable factor with relatively little variation between the scale responses of different individuals exposed simultaneously to the same conditions and even less variation within individuals exposed to identical conditions at different times. This is not the case with ride acceptability because an individual's acceptance of a ride is a function not only of physical sensations but also of expectations about the system, cost of the ride, and other considerations. For this reason, while the same physical accelerations, temperature, and acoustic noise environment will generally give the same ride comfort rating for a given vehicle, the ride acceptability of two vehicles with similar ride environments but different service characteristics may be very different. For example, the ride motions that passengers find acceptable in an urban bus are unlikely to be acceptable in an aircraft vehicle.

Figure 3. ISO prescribed frequency bands and weighting factors.

CENTER FREQUENCY OF ONE-THIRD OCTAVE BAND, Hz	WEIGHTING FACTOR	
	LONGITUDINAL VIBRATIONS	TRANSVERSE VIBRATIONS
1.0	0.50	1.00
1.25	0.56	1.00
1.6	0.63	1.00
2.0	0.71	1.00
2.5	0.80	0.80
3.15	0.90	0.63
4.0	1.00	0.5
5.0	1.00	0.4
6.3	1.00	0.315
8.0	1.00	0.25

Mathematical models of human comfort responses to vibration have been developed at the NASA Langley Research Center (LRC) (20). These models were obtained in carefully controlled laboratory experiments by using the LRC passenger ride quality apparatus (PRQA). The models provide the direct psychophysical scaling of the discomfort attributable to whole body vibration. By using a magnitude estimation technique, a scale factor (the "Disc") was developed that varies monotonically with vibration magnitude. By using this scale it is possible to establish the relative discomfort levels attributable to vibrations with differing frequencies and evaluate vibratory masking. The scale can also be used to compare the relative discomfort caused by vibrations with those caused by other environmental factors such as acoustic noise, and to compare the relative levels of comfort produced by vehicles intended for use in the same transit system.

A somewhat different approach to human comfort responses was undertaken by Jacobson and his coworkers (19) at the University of Virginia and at Dunlap and Associates. They used a statistical technique known as multiple regression to develop models of the comfort responses of passengers actually experiencing rides in revenue service vehicles. In practice, they recorded the ride environment of the test vehicle over selected guideway segments (acceleration along the X, Y, and Z axes; the rotational rates about the X, Y, and Z axes; and the levels of acoustic noise, temperature, and humidity), while simultaneously obtaining comfort ratings of the vehicle's ride from selected subjects by using the seven-point bipolar comfort scale described above.

By using a stepwise regression analysis, Jacobson and others (18) first derived the equations that best fit the data sources and then validated these data against independent data samples. In general it was found that ride comfort responses could be predicted based on only a few terms, provided that the ride motions of the system to be evaluated were within the dynamic range of those measured during the development of the model. The restriction of the number of terms, usually to no more than two or three, is believed to stem from the high level of correlation between the levels of motion along and about the different axes of surface vehicles. Therefore, in order to apply these models, it is usually sufficient to perform measurements on all six degrees of freedom to ensure that the vehicle motion is within the range of the model and then perform detailed measurements only on those identified by the model as the best predictors of comfort. A detailed discussion of the procedures and the research that they are based on can be found in a report by the American Iron and Steel Institute (9), whereas the following example illustrates the methodology used.

To develop a set of performance specifications to ensure that 90 percent of the potential passengers of a proposed short-haul bus route consider the ride acceptable, Pepler and others (11) indicate that a mean comfort response of 3.0 on the seven-point scale is required. By using the formula for urban buses operating on straight roads, $C' = 0.87 + 1.05\ W_r$, where C' is the comfort rating and W_r is the roll rate (degrees per second), a maximum roll rate of 2 degrees/s would be permitted. The values of the other major variables would be limited to the range encountered in the experiments from which the formula was developed: pitch less than 2.6 degrees/s and yaw less than 2.7 degrees/s for the rotational rates; X less than 0.059 *g*, Y less than 0.103 *g*, and Z less than 0.099 *g* for the linear accelerations.

At this time the joint research effort by Jacobson, Pepler, and others has resulted in the development of ride quality models and limiting values for the following vehicle types: compact automobiles, subcompact automobiles, rapid-rail coaches, intercity rail coaches, urban buses, commuter buses, intercity buses, rubber-tired automated guideway vehicles, and various types of passenger aircraft. In addition, composite ride acceptance equations have been prepared for vehicles that combine the characteristics of one or more vehicle types, for instance, a linear induction motor-powered, steel-wheel rail vehicle. Such equations should be used with great caution when applied to new vehicle systems unless the ride dynamics and the system applications are clearly similar to the vehicles for which the equations were originally developed.

MEASURING, RECORDING, AND PROCESSING OF DATA

The quantitative evaluation of ride quality or ride acceptance in an existing system requires some care in measurement, recording, and processing of primary physical variables. Several reports describe experimental data acquisition techniques for several advanced systems (12,21,22).

Primary measuring instruments usually include linear accelerometers arranged, for example, in a three-axis package to measure the three linear accelerations, or a six-axis package to measure three linear and three angular accelerations. When angular rate (angular velocity) is included in a specification, then instrument rate gyroscopes are required. Data from primary instruments are usually low pass filtered at a break frequency of 100 Hz to remove high-frequency noise, and then either recorded on FM tape, digitized and stored on digital tape or a disk for subsequent data processing, or directly processed on-line.

Processing of a specific data record measured over a time interval to compute average values and the number of signal values that exceed a given threshold is relatively straightforward. Processing of data to compare measured data with an ISO type specification requires the computation of the power spectral density (12), followed by integration of the power spectral density to compute rms accelerations in one-third octave frequency bands (21,22). Good statistical accuracy in this computation requires data records of a minimum time duration and may require recording data for a number of trips. Guidelines for these types of specifications are given in Bendat and Piersol (12).

In a 1979 study of AGT ride quality (21), data records of 10 s in duration were used to compute accelerations in frequency bands of 0.1 Hz each from 0.1 Hz to 50 Hz. Approximately 20 such records were analyzed and averaged together so that a good level of statistical accuracy was achieved. Thus, 200 s of total data for a designated section of the trip were required to achieve reliable estimates of rms acceleration in one-third octave bands. For many DPM and AGT systems, 200 s of consistent data can only be obtained by recording data for several trips in a consistent manner.

RIDE QUALITY DATA FOR ADVANCED SYSTEMS

Ride quality data have been measured for a number of advanced systems. The most extensive data exist for AGT systems employing rubber-tired vehicles operating on concrete guideways and include data processed to compare with ISO specifications, as well as total rms accelerations (13,21,22). Very few data, however, exist for TLV systems. The AGT systems tested have ride comfort levels generally comparable to those of other transportation modes (see Figure 4). The Fairlane vehicle with ISO specifications meets and ISO level corresponding to the 8-h reduced comfort boundary (see Figure 5).

In ride acceptance studies conducted at Transpo '72 (15) and in Germany (23) on AGT systems, passenger surveys of ride acceptance were correlated with ISO ride criteria that specify the computation of a weighted sum of rms acceleration in discrete frequency bands. The system tested at Transpo '72 provided a ride with a better vertical vibration acceleration than an ISO criteria corresponding to a 1-h reduced comfort boundary. The ride ratings ranged between "noticeable" and "clearly noticeable-strong." Thus, those rides of the Fairlane and Airtrans systems that meet the 4-h ISO reduced comfort criteria would approach the "noticeable" level, whereas the Morgantown ride at the highest speed would approach the "clearly noticeable-strong" level.

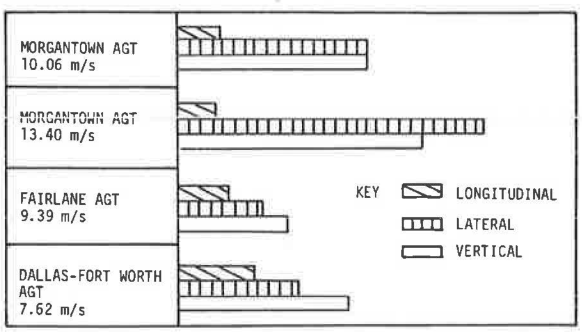
A German study recommends that a ride acceptance index be adopted, based first on determining the sum of ISO weighted rms accelerations over the specified frequency bands for each linear acceleration, i.e., vertical, lateral, and longitudinal, and then computing the vector sum of weighted accelerations from each axis to yield a single ride index. This equivalent ride index, based on the hypothesis that typical AGT passenger trips are 10-30 min in duration, equates subjective indices with the vector sum of weighted rms accelerations. Cabinlift, Cabintaxi (with 12 persons), and the various subway railway, all have "good" to "satisfactory" rides while bus and Cabintaxi (with three people) have "adequate" rides (see Figure 6). By using this type of index, the Fairlane, Airtrans, and Morgantown systems would have rides judged to be "good," with the Fairlane system approaching a rating of "very good."

Additional ride acceptance data for AGT systems are provided in Richardson and others (19) and Healy and Smith (22).

DEVELOPMENT OF DESIGN SPECIFICATIONS FOR A PROPOSED ADVANCED TRANSPORTATION VEHICLE

Sometimes it is necessary to perform "clean sheet" design studies for a novel vehicle system with ride dynamics that has not been previously studied and/or that has an application significantly different from systems previously studied. In such an effort, vehicle costs, guideway costs, and operating costs are traded off against operating requirements. In order to establish the values of the trade-off parameters, simulation studies can be used. In such studies the critical aspects of the proposed vehicle's ride environment are simulated at the levels under consideration, and the comfort and acceptability ratings of selected subjects are assessed. The following example of such an effort conducted as part of a joint United States/Federal Republic of Germany study of non-contact suspension vehicles illustrates this process.

Figure 4. Comparison of AGT vehicle ride comfort with other modes.



Development of Guideway-Vehicle Models

The basic guideway configuration for the system was based on the configuration required for an attractive magnetically levitated vehicle operating over an elevated guideway at speeds of up to 400 kmh. The guideway variables that affected ride in the model were span camber, pier misalignment, and surface configuration; the non-guideway factors were velocity, wind loadings, and secondary suspension design. By using values that represent these factors in mathematical models of guideway/vehicle system dynamics behavior, it was possible to develop values simulating the linear accelerations and rotational rates that would be exhibited by the vehicle under the specified conditions. These values representing the vehicle's Y acceleration, Z acceleration, and rotational acceleration about the X axis (roll) were then recorded as analog signals on a control tape. An acoustic noise signal was also provided in addition to the associated timing and calibration signals. The values for this signal were derived from measurement of the cabin noise level of an acoustically similar system--a rear engine jet passenger aircraft operating in the 250- to 400-km/h speed range.

Selection of Critical Operating Conditions

In any laboratory study, the number of possible operating conditions to be simulated and studied are limited by the funds, labor, and time available. Although a full factorial experimental design will yield the most precise predictions, program limitations often preclude such an effort. In such situations, the number of experimental combinations of different operating conditions can be reduced by eliminating those that are not expected to be of interest in the design process. For instance, an

Figure 5. Fairlane vehicle ISO RMS acceleration plot at 9.39 m/s.

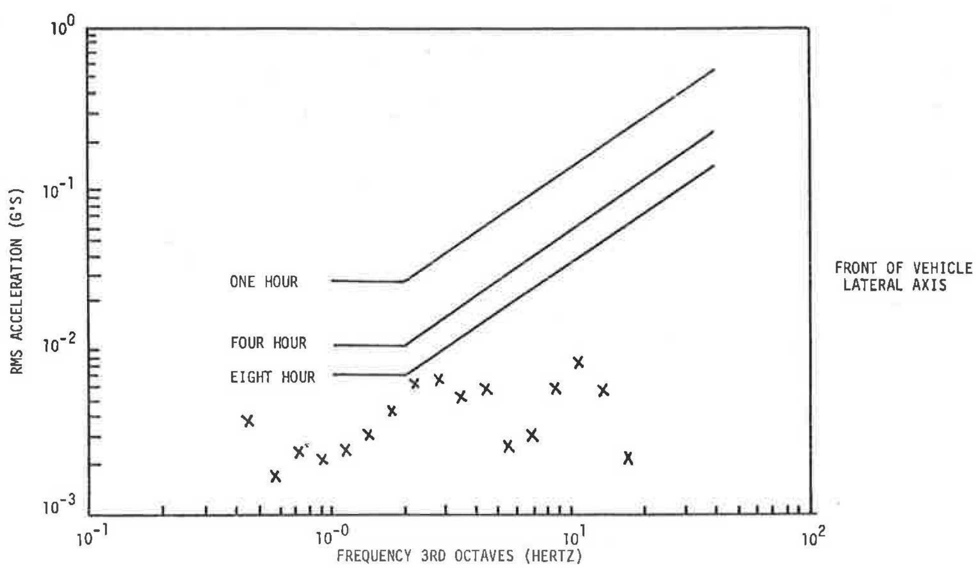


Figure 6. Ride comfort of several systems in Germany.

SYSTEM DESCRIPTION	RIDE INDEX[a]
CABINTAXI IN HAGEN WITH 3 PERSONS	13
CABINTAXI IN HAGEN WITH 12 PERSONS	6
CABINLIFT IN SCHWALNSTADT	4
SUBWAY IN HAMBURG	5
SUBWAY IN BERLIN	5
EXPRESS RAILWAY	6
INTERCITY RAILWAY	3
BUS IN HAMBURG	12

experimental combination of a vehicle at its slowest possible speed traversing the smoothest possible guideway configuration in calm air will probably not reveal much about the necessary design process and can, therefore, be eliminated. Alternatively, conditions that are not expected to occur can be eliminated. An example might be a vehicle traversing the roughest possible guideway configuration at the maximum possible speed under maximum possible wind gust conditions.

Selection of Simulation Facility

Studies of ride comfort or acceptance require that the simulation facility be capable of accommodating passenger transit seats, couches or beds of the type proposed for the system under study, and also have sufficient headroom (where the proposed system is to carry standing passengers). The simulator must also be able to (a) simulate motion in a minimum of three degrees of freedom (one of which should be rotational), (b) simulate the rotational motion in such a manner that the center of rotation is roughly in the same location as it would be in the system being simulated, (c) simulate complex motion wave forms, and (d) simulate the acoustic and temperature environments of the proposed system. The simulator facility must be instrumented for the recording of both the motion and acoustic signals produced in the cabin during the simulation, as these will often vary significantly from the programmed input levels. Finally, any simulation facility must be "man-rated." That is, it should have been systematically tested and judged not to present any safety risks by a panel of experts familiar with both simulation and safety requirements.

There are few motion simulators that are both suitable and generally available for passenger ride quality research. The NASA LRC PRQA mentioned above is a good example of such a facility for the following reasons: (a) its interior configuration simulates a six-seat section of a passenger aircraft cabin, (b) it can be operated directly for analog signals or from prerecorded magnetic control tapes, and (c) it can provide linear accelerations along the Y and Z axis and rotational accelerations about a simulated roll axis, or by turning the cab 90° it can provide acceleration along the X and Z axis and rotational acceleration about a pitch axis. The PRQA also provides various temperature and acoustic noise environments; simulation of visual scenes can be accomplished by the projection of motion pictures on screens outside the cabin windows.

Preparation of Experimental Design

The development of an experimental design that ensures that the data collected in the simulation study can be analyzed in a meaningful fashion is critical. Such a design must ensure that all of the important possible combinations of operating conditions are measured, that sufficient statistical degrees of freedom are available for precision, and that no artifacts are introduced due to treatment order effects.

In such a design the independent variables (factors whose influences are to be measured in the study) must be clearly identified with particular combinations of operating conditions. The design must be such that there is no statistical confounding between the main effects representing the independent variables. Examples of independent variables in ride quality studies might include the level of simulated guideway roughness, vehicle speed, or suspension stiffness. In certain instances, due to limitations in the time or funds available for the study, it may be necessary to confound some of the interaction effects with minor factors such as the presentation order of different operating conditions. This should only be attempted when there is a clear a priori understanding of the impact of such a confounding and only by using statistical designs intended for this purpose such as "partially incomplete block designs," as described by Cochran and Cox (24).

Preparation of Stimulus Material

Control Tapes

The magnetic motion and acoustic control tapes may be produced through the use of computer models of the predicted ride dynamics or processing of data taken in field tests. Either analog or digital tapes may be used to control a simulator depending on the equipment available at the facility.

Visual Simulation

Representations of the visual scene outside the simulated vehicle are often valuable in increasing the involvement of the subject with the study. These may be of particular importance in studies of long-distance surface transportation systems where the passenger normally spends a great deal of time looking out the window. In such cases system acceptance may be influenced by the content and complexity of the visual scene. In studies where the subject is a passive observer of the scene, 16-mm color motion pictures are usually sufficient. These are generally taken from a vehicle moving at a constant speed and later processed to provide synchronized simulations of the scene as it would appear at the speeds used in the study. In studies where the subject must actively respond to events depicted in the visual part of the simulation, computer-generated display systems programmed to respond to subject and system inputs are recommended. For such simulations the complexity and update rate of the visual simulation must be carefully matched to the requirements of the study in order to ensure validity while at the same time controlling study costs.

Selection of Subjects

It is generally best to recruit paid subjects for such studies. The subjects should be representative of the population of interest in terms of their demographic characteristics (age, sex, income level, and educational level), should have had some prior experience with the transportation mode being studied, and should have no personal or professional interest in the proposed vehicle system being investigated. Prior to acceptance all subjects must undergo both a medical screening and a "prior consent" procedure. This last procedure has two purposes; first, it protects the rights of the subject, and second, it acquaints the subject with the details of the system and thereby establishes an appropriate mindset. Establishment of the proper mindset can be critical to the success of the study. For instance, individuals who are familiar with and anticipate the ride of a long-distance passenger aircraft vehicle are unlikely to rate the ride motions of any STOL aircraft as comfortable.

Preparation of Rating and Performance Test Material

The comfort and acceptability characteristics of the system under study are obtained by scoring the subjects' responses on forms rating the system. In general, subjects are quite capable of providing stable ratings of overall ride comfort and acceptability. With proper instruction subjects can even differentiate between the discomfort caused by the different motions of the vehicle.

Performance testing is often used in simulation studies to determine the effects of ride quality on the subjects. Appropriate testing activities are first selected and then standardized test procedures are obtained from commercial sources or specifically developed for the study. These tests can range from paper-and-pencil reading comprehension tests for simulations of systems such as commuter trains, to computer-scored tests of "man-in-the-loop" control dynamics for tests involving simulations of passenger automobile ride quality.

A word of caution, however, must be said about performance testing. Humans have great ability to compensate for the effects of adverse environments and, therefore, systematic performance decrements of mental tasks are rarely detected except under the most extreme environmental stress. In studies of passenger ride quality, changes in the performance of cognitive tasks will not often be directly detected in the scores of motivated subjects due to the limited range of environmental stresses.

However, the subjects are aware of the impact of the environment and are generally capable of estimating the increased difficulty imposed by the environmental stresses on the performance of the required tasks. This information can be readily elicited through use of a properly designed rating form.

Analysis and Interpretation of Results

Assuming an appropriate experimental design has been followed, analysis will be straightforward since the subjects' scores will generally meet the assumptions required for use of parametric statistical techniques such as the analysis of variance. This analysis will permit the investigator to determine which of the dependent variables affected comfort and the extent to which the subjects differentiated among the levels of the variables presented. Subsequent to such an analysis, the mean scores attributable to those effects found to be statistically significant can be displayed in tabular or graphic form.

Interpretation of the results must be approached carefully. If a sufficiently comprehensive simulation was conducted (one that provided not only the motion variables but also simulated the ambience, visual, social, temporal, and other situational factors), the ratings obtained may be considered "absolute" estimates for the comfort of the system under study. If a limited set of the most critical factors were used in the study, the ratings will represent only the relative comfort attributable to the variables used.

In order to determine whether the ratings are absolute or merely relative, the scores obtained should be compared, whenever possible, to ratings for similar revenue service systems. When comparable revenue service scores are not available the rating scores may be compared with the scores predicted through the use of the mathematical models developed by Pepler and others (11) and by Richards and Jacobson (19). These models were developed from actual ratings taken from passengers on revenue service vehicles; therefore, the measured scores obtained by entering acceleration and acoustic noise levels into the simulation models should correlate well with the scores provided by the subjects in the simulation.

If the ratings obtained in the simulation are sufficiently correlated with ratings obtained in field studies or with the scores predicted by the field study-based mathematical models, passenger acceptance of the various ride conditions may be predicted through the use of the binomial expansion technique described in Pepler and others (11). This technique gives a percentage estimate of passengers likely to find the ride of the system sufficiently comfortable so as not to preclude reuse. Selection of the percentage to be used as a "cut-off" value can thereby be used to determine the ride dynamics, guideway configuration, system operating characteristics, and, ultimately, the amount of money needed to improve ride quality, as a function of the total cost of the system.

CONCLUSIONS AND RECOMMENDATIONS

The evaluation and specification of ride quality for advanced ground transport systems may be based strongly on data and procedures developed for other transportation modes. For example, specification of ride quality for the DPM system in Los Angeles (3) has included requirements for (a) sustained steady accelerations, (b) vibration induced accelerations in terms of total rms levels and one-third octave frequency bands for comparison with ISO specifications, and (c) angular rates for straight and curved guideway sections. It is recommended that future specifications for advanced systems include these three basic types of specifications. In addition, while current specifications do not limit maximum peak values of acceleration that may occur due to guideway anomalies, it is recommended that development of such a specification be considered.

The establishment of acceptable values of ride quality measurements depends on the length and type of trip. For short rides characteristic of DPM systems, where activities such as writing and reading may not be important, relatively high values may be acceptable, whereas for intercity advanced systems lower values are required to provide passengers the opportunity to read and write and walk about the passenger compartment. The establishment of these values will have a strong influence not only on passenger comfort but also on the development of guideway specifications and maintenance, vehicle suspension, and, thus, the cost of the system.

REFERENCES

1. Automated Guideway Transit--An Assessment of PRT and Other New Systems. U.S. Office of Technology Assessment, 1975.
2. System Specification: The Los Angeles Downtown People Mover. U.S. Department of Transportation, Tech. Specification, 1980.
3. Proc., International Symposium of Traffic and Transportation Technology, Vols. B-1, B-2. Bundesministerium für Forschung und Technologie, Hamburg, West Germany, June 18-20, 1979.

4. G. Anagnostopoules. Assessment of Operational Automated Guideway Systems--Jetrail. U.S. Department of Transportation, Tech. Rept. UMTA-MA-0067-77-1, 1977.
5. Development/Deployment Investigation of Cabintaxi-Cabinlift Systems. U.S. Department of Transportation, Tech. Rept. UMTA-MA-06-0067-02, Dec. 1977.
6. G.R. Slemon. Development of Electric Propulsion Systems for Canada. Proc., International Symposium on Traffic and Transportation Technologies, Bundesministerium für Forshung und Technologie, Hamburg, West Germany, June 18-20, 1979.
7. D.N. Wormley, J.K. Hedrick, L. Eglitis, and D. Costanza. Elevated Guideway Cost-Ride Quality Studies for Group Rapid Transit Systems. U.S. Department of Transportation, Tech. Rept. DOT-TSC-OST-77-54, 1977.
8. P.W. Birkeland and others. Investigation of Reduced Cost Guideway Design for Tracked Air Cushion Research Vehicle. Federal Railroad Administration, FRA ORD/D 7445, Dec. 1972.
9. Steel Structures for Mass Transit. American Iron and Steel Institute, 1976.
10. Summary Report: Workshop on Vehicle Ride Quality. U.S. Department of Transportation, Tech. Rept. DOT-TSC-OST-7744, Aug. 1977.
11. R.D. Pepler, L.I. Vallerie, I.D. Jacobson, R.W. Barber, and L.G. Richards. Development of Techniques and Data for Evaluating Ride Quality. U.S. Department of Transportation, Tech. Rept. DOT-TSC-RSPD-77-1, 1977.
12. J.S. Bendat and A.G. Piersol. Random Data: Analysis and Measurement Procedures. Wiley-Interscience, New York, 1971.
13. W.L. Caywood, H.L. Donnelly, and N. Rubenstein. Guideline for Ride Quality Specifications Based on Transpo '72 Test Data. APL/JHU CP060/TPR039, Oct. 1977.
14. J.W. Gebhard. Acceleration and Comfort in Public Ground Transportation. APL/JHU TPR-022, Feb. 1970.
15. A.M. Wichansky and E.D. Sussman. Guidelines for the Design and Evaluation of Human Factors Aspects of AGT Systems. Transportation Systems Center, U.S. Department of Transportation, Tech. Rept. UMTA-MA-06-0081-79-1, 1979.
16. R.D. Stevens and others. AGT Guideway and Station Technology: Vol. 4, Design Guidelines. U.S. Department of Transportation, Rept. UMTA-IT-06-0152-79-3, March 1979.
17. ISO/TC108: Guide for Evaluation of Human Exposure to Whole-Body Vibrations. International Organization for Standardization, International Standard ISO 2631-1978, 1978 (E).
18. I.D. Jacobson and others. Comparison of Passenger Comfort Models is Buses, Trains and Airplanes. TRB, Transportation Research Record 646, 1977.
19. L.G. Richards and I.D. Jacobson. Ride Quality Models for Diverse Transportation Systems. U.S. Department of Transportation, 1980.
20. J.D. Leatherwood and T.K. Dempsey. A Model for Prediction of Ride Quality in a Multifactor Environment. NASA, TMX-72842, 1976.
21. R.D. Stevens, C.W. Dolan, R.J. Pour, E. Fernandez, and J.A. Vanek. AGT Guideway and Station Technology: Vol. 6, Dynamic Model. U.S. Department of Transportation, Tech. Rept. UMTA-IT-06-0152-79-5, 1979.
22. A.J. Healey and C.C. Smith. Ride Quality Studies in the Airtrans Automated Guideway Transit System. U.S Department of Transportation, DOT-OS-50126, July, 1977.
23. P.W. Birkeland, C.W. Friends, and S.M. Easley. Investigation of Reduced Cost Guideway Design for Tracked Air Cushion Research Vehicles. Federal Railroad Administration, FRA ORD/D 7455, Dec. 1972.
24. W. Cochran and G. Cox. Experimental Designs. John Wiley and Sons, New York, 1954.

Marine Vehicle Ride Quality: A State-of-the-Art Assessment

D.R. STARK

The riding characteristics of marine vehicles are affected mostly by low-frequency random accelerations. Specific examples of acceleration spectra illustrate the nature and variability of the motions encountered, and the human response data base is discussed in light of the riding characteristics shown. Ride quality evaluation methods are identified and correlated with subjective ride scales. Standard evaluation methodology that uses frequency weighting is recommended.

In a broad sense, vehicular ride quality technology encompasses human response/human tolerance to the vehicle environment, vehicle responses to the external environment as well as vehicle-induced environments, and the subjective value function that passengers and operators place on the overall ride. (See Figure 1.)

Marine vehicles, due to the nature of the sea environment in which they operate, have riding properties dominated by low-frequency random motions, with most of the energy occurring below 1 Hz. Although marine vehicles subject the passengers to the other physical environments, noise, temperature, seating, leg space, and such, these environmental factors are generally less important to the state of the art than the motion environment. Also, solutions for these environmental influences derive directly from a broader technology base. This assessment of the

Figure 1. Overall ride-quality system.