Assessment of Ride Quality of AIRTRANS System

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The acquisition and analysis of ride-vibration data for the AIRTRANS automated-guideway-transit system at the Dallas-Fort Worth Regional Airport are discussed. The ride vibrations are measured as translational components of the vehicle floorboard accelerations in the three principal directions. The total record for a complete loop around the network was subdivided into sections of straight, gently curved, and sharply curved zones, and ensemble-averaged spectra for each type of zone were compared. The spectral-response characteristics between straight and gently curved zones are not very different, but the sharp turns increase the frequency, particularly in the 10 to 30-Hz range. The low-frequency behavior gives a multipeaked spectrum arising from the body and wheel modes as modified by kinematic resonances at frequencies corresponding to travel wavelengths that are multiples of the steering and main wheel bases. The ride quality was compared to a recent International Organization for Standardization standard, to a comfort criterion based on passenger satisfaction as found in small aircraft, and to ride ratings in a sedan automobile. All three predicted adequate ride satisfaction; the second method showed a 70 percent satisfaction level 94 percent of the time.

The ride quality of ground transportation systems is of current interest. While there is a good deal of knowledge about conventional systems using automotive, air, and rail vehicles, there is very little information about automated-guideway-transit systems. A recent example of such a system for group rapid-transit purposes is the AIRTRANS system at the Dallas-Fort Worth Regional Airport.

The AIRTRANS system consists of a network of U-shaped guideways, having both elevated and ground-level sections, inside which rubber-tired vehicles ride. The vehicle design is based on a modified truck chassis; individual vehicles are automatically controlled from a central computer for speed and location within the network. The vehicles have a passive steering system in which steering direction is given by rubber guide wheels that run on the guideway sidewall. There is provision for steering through bends and switches, including both merges and diverges. Each vehicle can accommodate up to 60 passengers. The system links approximately 14 stations with the Airport Marina Hotel and the north and south parking areas.

The route taken by a vehicle is controlled by the central computer control system, which gives signals to merge and diverge and switches rails appropriately, and the passive steering system, which guides the vehicle correctly through each switch point. Constant communication to and from the vehicle is maintained through signals transmitted through the signal rail; three-phase power is provided as the main driving source. A modified block control scheme is used. Each vehicle has a nominal route to take that depends on whether it is a passenger and employee or a utility vehicle. The nominal route will determine which station stops are made and which are bypassed.

Figure 1 shows the overall network schematic with its several interconnected loops. Figure 2 shows a typical AIRTRANS vehicle, which in its course around the network makes many turns, diverge and merge switches, and station stops.

From the point of view of ride quality, one of the important variables, known to be correlated with comfort (1), is that of vibration. For seated passengers, the vertical, longitudinal, and transverse components of low-frequency acceleration (0.1 to 40 Hz) are of direct concern (although the importance of the 20 to 40-Hz range has not been completely justified). In this work, the rotational degrees of motion have not been included. The sources of the vibration are primarily the on-board air compressor, excitation from unbalance and unevenness in the rolling stock, and roughness in the running surface and the sidewall steering surface. Because the AIRTRANS vehicle is laterally constrained with close tolerances, its vibration levels will be greater than are those of a typical sedan automobile that is relatively free to wander laterally.

This paper discusses the experimental techniques used to measure the floorboard acceleration levels found in an AIRTRANS vehicle and the data-reduction techniques used in their assessment. The results are given in terms of acceleration spectra, one-third-octave band analyses, and the variation of the root-mean-square (rms) acceleration levels around a typical transit loop. The idea of acceptability based on the percentage probability of achieving a given level of ride comfort is demonstrated.

EXPERIMENTAL METHOD

Instrumentation

The triaxial components of the linear acceleration were measured by using the battery-operated portable accelerometer set developed at Langley Research Center (2). This unit consists of three seismic-mass, strain-gauge type accelerometers, mounted in mutually perpendicular directions. The power supply is a 27-V source giving an output of approximately 5 V/g in each direction. Each axis is calibrated precisely before the field installation. The bandwidth of the accelerometer is from 0 to about 100 Hz.

A four-channel FM tape recorder was used to record the accelerometer output signals. The recorder is designed for a ±1.0-V range (±0.2 g) and has a 0 to 2000-Hz bandwidth, which is more than sufficient for this application. The first three channels were used to record the X, Y, and Z components of the acceleration, while the fourth channel was reserved for recording the vehicle speed. This latter signal was important because of the strong influence that vehicle speed has on vibration levels and was obtained by recording the output signal of the on-board tacho-pulser.

The instrumentation hardware was relatively simple because the method of data analysis was to record the raw data first and later process the records digitally.

Field Experiment

The accelerometer unit and tape recorder were installed in a single-car, passenger vehicle. The power for the tape recorder was supplied by a step-down transformer that picked up 440 V ac across two of the three phases that powered the vehicle and reduced it to 110-V 60-Hz power. An oscilloscope was used for signal monitoring to ensure that good quality data were obtained on the record. Generally, the 100-Hz bandwidth limitation

Figure 1. AIRTRANS guideway layout.

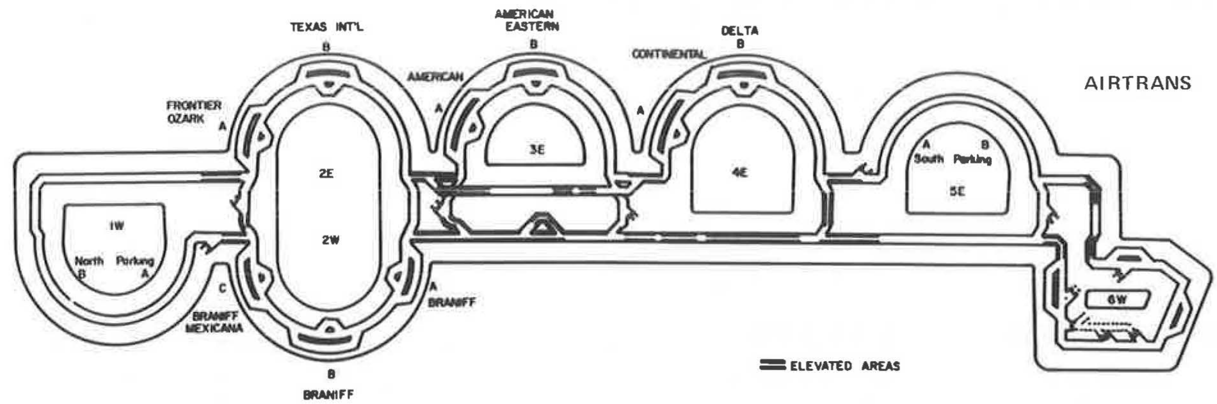


Figure 2. AIRTRANS vehicle.

of the triaxial accelerometer unit is adequate for eliminating unwanted high-frequency interference, and the signals obtained are relatively free from noise.

By careful selection and changing of designated routes, a special test route was designed that was a loop starting at the 5E south parking station, traveling through the 4E and 3E areas, crossing through the 3E bridge to the hotel station, and back along the long straight section to 5E; i.e., 5E to 4E to 3E to hotel to 5E. In this loop, the 3E bridge section has two sharp [46-m (150-ft) radius] curves and an assortment of gentle [242-m (800-ft) radius] curves in the semicircular terminal zones as well as a long straight section; thus, it encompasses all of the steering manuevers that the vehicles are required to accomplish.

Data Processing for Spectra and One-Third-Octave Band Analysis

The data processing technique used was based on digital methods and is described in detail elsewhere (4). The complete record for a loop illustrated that the nature of the vibration levels was highly variable because of vehicle-speed variations and effective-roughness input changes between straight and curved sections. There were only a few segments in which the results were approximately stationary. Because of this, segments of the total record were isolated corresponding to straight, gently curved, and sharply curved zones traveled at 0.25, 0.5, 0.75 and full speed. In the curved zones, the segments that exhibited nearly stationary results, i.e., a frequency resolution of 0.1 Hz, were of only 10-s duration.

Spectral densities were calculated by computing the discrete Fourier transform, extracting the mean value, and smoothing the resultant raw spectral estimates. The measure of statistical confidence in estimating the spectral-density values is the number of statistical degrees of freedom used in the averaging. In the results that follow, 6, 10, and 18 degrees of freedom were used respectively in the 0 to 1, 1 to 10, and above 10-Hz ranges for the individual section analyses. Better estimates of the spectra in specific zones [such as a 46-m (150-ft) radius turn] were later found by ensemble averaging each spectral-density value across sets of data taken from sections having the same characteristics, but obtained either at another location in the network or from the other run around the primary test loop.

The total mean-squared acceleration (σ^2) of a section is given by the sum of the spectral-density estimates [P(m)] divided by the record length (T). Thus

$$\sigma^2 = (1/T) \sum_{m=0}^{N/2} P(m) \tag{1}$$

To find the rms acceleration in band intervals of one-third octave, Equation 1 is applied over a frequency interval of $[\hat{f} - (B/2)]$ to $[\hat{f} + (B/2)]$, where $\hat{f}$ is the band-center frequency and B is the bandwidth. For a one-third-octave bandwidth, B = 0.230 02$\hat{f}$, and the rms acceleration in the band is

$$\sigma^2_{1/3}(\hat{f}) = (1/T) \sum_{\hat{f}-(B/2)}^{\hat{f}+(B/2)} P(f) \tag{2}$$

Because values of P(m) occur only at multiples of the digitizing frequency 1/T, where $(\hat{f} \pm B/2)$ is not an integer multiple of 1/T, allowance must be made to include the power that would otherwise be lost.

Probability Density and Cumulative Probability

The measures of the amplitude content, as opposed to those of the frequency content, of random vibrations are the probability density and the cumulative probability function of the signal. The probability density is the fraction of total samples lying within the band, i.e., $\bar{x} < x_i < (\bar{x} + dx)$, so that

$$p(\bar{x}) = [1/N(dx)] \sum_{i=0}^{N-1} x_i \qquad [\bar{x} < x_i < (\bar{x} + dx)] \tag{3}$$

and the cumulative probability [cp $(\bar{x})$] is a function of the acceleration level that gives the total fractional probability of having acceleration amplitudes less than some value $\bar{x}$.

$$cp(\bar{x}) = (1/N)\sum_{i=0}^{N-1} x_i \qquad (-\infty < x_i < \bar{x}) \tag{4}$$

Many processes for which enough samples are taken exhibit probability functions described by the Gaussian normal distribution and are thus described by a mean and a variance only.

In the examination of the experimental digitized records, probability functions have been obtained both for the probability of exceeding a given value of acceleration within a section and for the probability of exceeding a given rms level in any section for the total ride around the test loop.

RESULTS

By using the procedures described above and outlined in more detail by Healey and others (3), a series of test sections were isolated for detailed study. These sections were grouped in the general categories of

1. Full speed along the straight section between the hotel and 6W,
2. Full speed in the gently curved turns around the 4E and 3E terminals, and
3. Full speed in the sharply curved turns in the 3E bridge zone.

The effect of speed variation is complex and will be discussed in a later report.

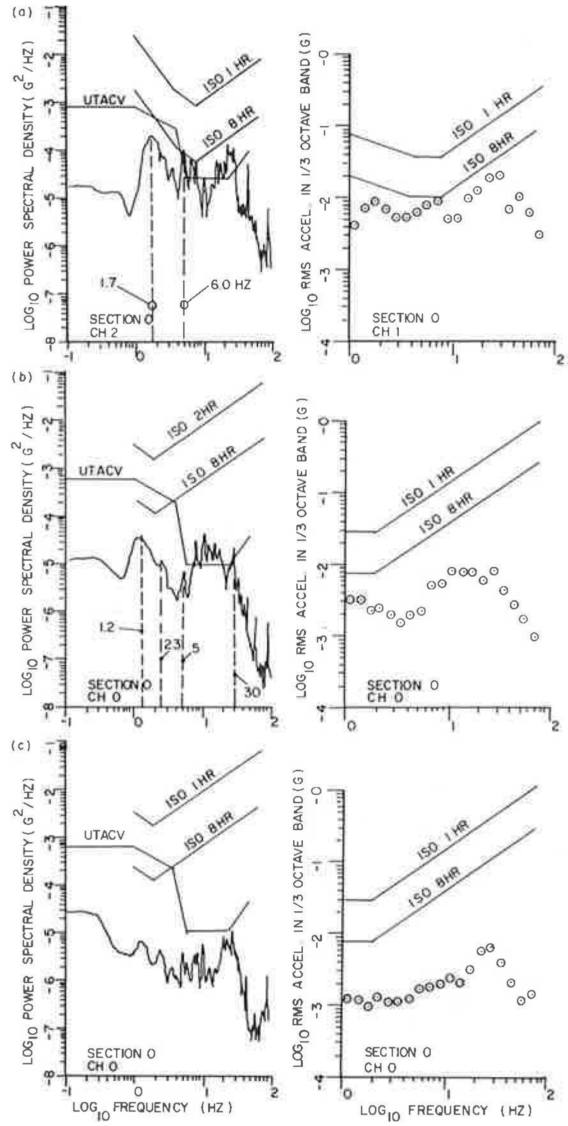
Spectra and One-Third-Octave Band Analysis

For the first category—travel along the back straight at full speed—five different sections of 10.4-s duration for each section were analyzed separately and the spectral-density values then ensemble averaged for each of the three acceleration components. The results for the ensemble-averaged spectra and the resulting one-third-octave band values are summarized in Figure 3. Figure 3 also shows lines corresponding to the 1 and 8-h reduced comfort guides (5) for comparison. For the spectral-density results, the reduced comfort guides have been converted into spectral-density levels on the basis of the one-third-octave bandwidth. Figures 4 and 5 show results similar to those of Figure 3; Figure 4 presents the results for full-speed travel around the gently curved turns, for which nine cases were averaged, and Figure 5 presents the results for sharply curved turns, for which seven cases were averaged.

Relationships Between Measured Spectra and Vehicle Dynamics

Figures 3, 4, and 5 show that the body-acceleration response spectra are generally multipeaked. This is expected because of the nature of the steering and suspension systems and the guideway inputs. The guideway inputs excite the vehicle through the front and rear wheel sets. The sidewall inputs act to steer the vehicle, both front and rear. The general nature of guideway roughness would be expected to follow that of highway roughness and, because of the time delay between inputs acting at the front and rear of the vehicle,

Figure 3. Ensemble-averaged spectral densities and one-third-octave band values—full speed along the back straight: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.



kinematic resonances (3) in the body heave, pitch, yaw, roll, and transverse motions are anticipated at frequencies of

$$f = kV/W \qquad (k = 1, 2, 3, \ldots) \tag{5}$$

where V = vehicle speed and W = wheel base.

For the AIRTRANS vehicle, W = 5.5 m (18 ft) between guide wheels and 4.3 m (14 ft) between drive wheels; at the full speed of 7.6 m/s (25 ft/s), peaks are expected at intervals of about 1.4 Hz in the lateral acceleration and 1.78 Hz in the vertical. These kinematic resonances are apparent in the experimental results.

In some frequency ranges, these kinematic resonances coincide with the vehicle dynamic modes. The primary vertical modes derived on the basis of mass and stiffness data obtained from the vehicle manufacturer are given below (1 kg = 2.2 lb and 1 kg/m = 0.0560 lb/in).

Figure 4. Ensemble-averaged spectra and one-third-octave band values—full speed around 242-m (800-ft) radius turn: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.

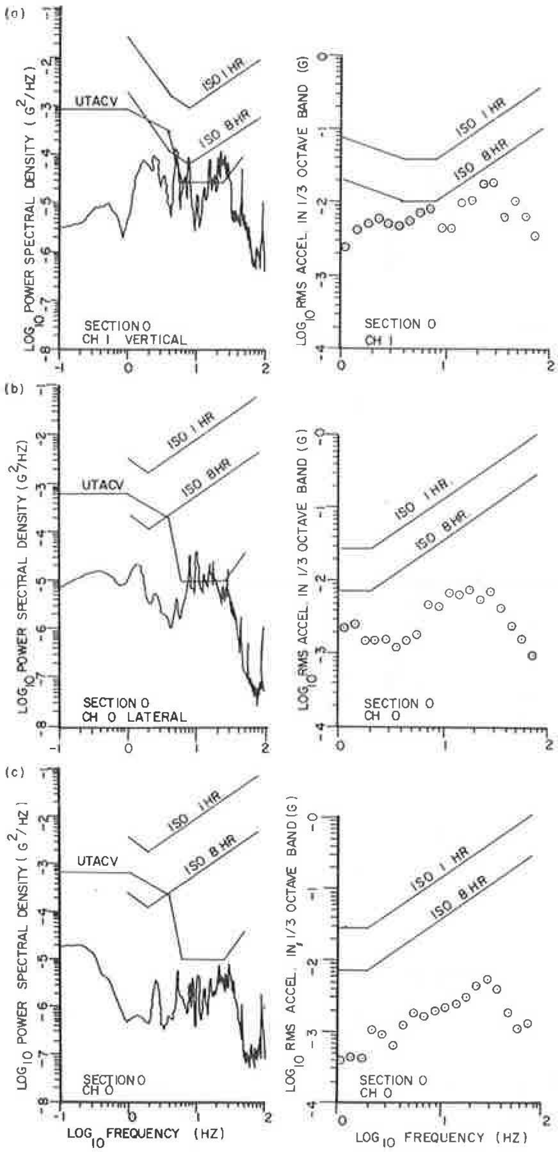
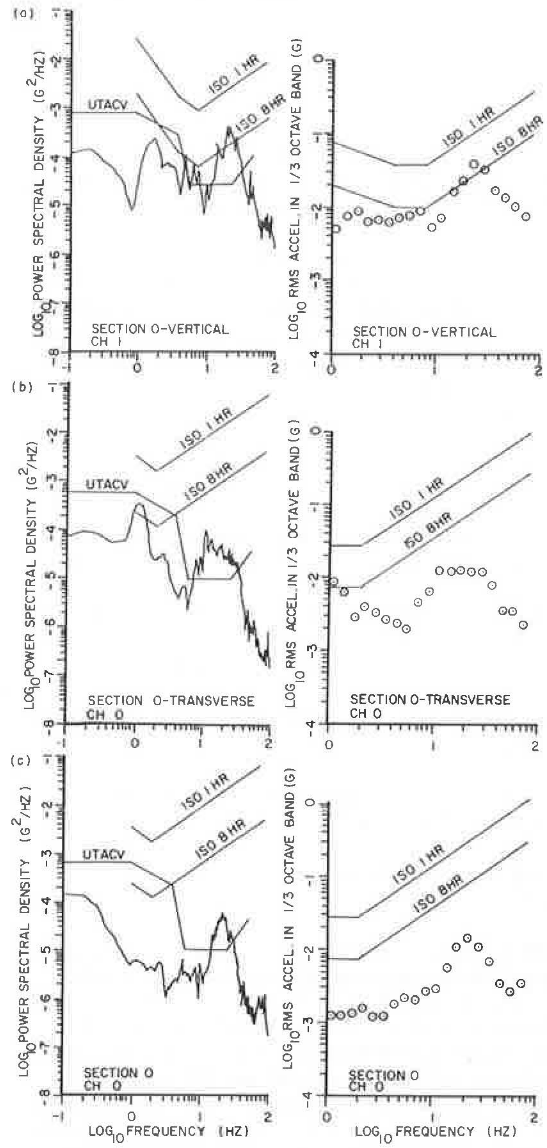


Figure 5. Ensemble-averaged spectra and one-third-octave band values—full speed around 46-m (150-ft) radius turn: (a) vertical acceleration, (b) transverse acceleration, and (c) longitudinal acceleration.



Parameter	Value
Sprung mass, kg	3960
Load with 10 passengers, kg	772
Unsprung masses (each axle), kg	1250
Air-bag springs (total), kg/m	3144
Tire stiffness (total), kg/m	328 000
Body-bounce frequency, Hz	1.25
Wheel-hop frequency, Hz	6.0

Figure 3a shows that the body-bounce mode at 1.25 Hz does not stand out strongly, but that there is a general peak in the acceleration response at about 2 Hz that arises because of the proximity of the bounce mode to the fundamental vertical kinematic resonance. Other peaks at approximately 3.5 Hz and 5.0 Hz are identified. The 5.0-Hz peak is heightened because of its proximity to the natural frequency of the wheel-hop mode. The peaks in the spectrum at 30 and 60 Hz are caused by excitation from the on-board air-compressors required to run the air-bag secondary suspension.

Turning to the transverse response case, in a mathematical model described by Healey (6), the prime transverse body mode occurs near 1.5 Hz and the lateral guidebar bounce mode occurs around 4 Hz. Figure 3b shows peaks at the 1.5-Hz primary natural frequency and multiple resonances at intervals close to the 1.4-Hz interval predicted for the lateral steering kinematic resonances. Further comparison between four-degree-of-freedom lateral models and the data in Figure 3b is given by Smith and others (6).

Figure 4 shows that there is little difference between travel on large-radius turns and along straight sections. Apparently, little steering action is taking place. Data given by Murray (7), which consider the measurement of guideway sidewall roughness, showed that in these areas, only light steering motions occur.

Comparison between Figures 3 and 5 shows that the action of positive steering around the sharp turns increases the vertical-acceleration levels, particularly in the 20 to 25-Hz range, and also the low-frequency transverse-acceleration levels. The increase in low-

frequency transverse content comes from long-wavelength irregularities in the sidewall profile.

Probability Distributions

Figure 6 shows that the probability of exceeding a given level of vertical acceleration within a 10-s record is very close to the Gaussian normal. This may be expected. In these records, there are only small amounts of low-frequency acceleration and, in a selection of 4096 data points, many samples of higher frequency. For data with significant linear trends, such as for guideway roughness measurement, this happy result may not be true.

If each 10-s record is assigned its rms acceleration values, then it is possible to calculate the probability of experiencing a ride of less than, for example, 0.05*g* by extracting the percentage of 10-s sections having rms accelerations less than 0.05. Over the total ride around the loop, approximately 120 such sections were found; their corresponding cumulative probability functions were calculated.

Figures 7 and 8 show the cumulative probability for exceeding the rms acceleration taken over the whole test loop where the 10-s interval was taken as the time for calculation of the rms accelerations. Here, the Gaussian distribution function is not followed; the nature and design of the test loop has contributed some sections of sharply curved turns on which higher acceleration levels are inevitable and many sections with levels close to average. There are also some sections having low rms accelerations. Many of these occur in sections where the vehicle speed is slow because of system control command.

Ride Quality and Comfort Levels

The question of relating data on ride motion to anticipated comfort levels for passengers has been a perplexing one for many years. Early work dealt with the evaluation of simple harmonic motions, but the AIRTRANS motions are of a broad-band random nature. It has been suggested (5) that such ride motions be evaluated from the point of view of passenger safety in terms of a one-third-octave band analysis and compared with reduced comfort limits for various exposure times. Such comparisons give rise to the one-third-octave band results as given in Figures 3, 4, and 5. This approach is insufficient, however, because the degree of acceptability of a ride meeting the 1-h exposure guide, but not the 8-h exposure guide, is not given. As a general observation, the 1-h exposure reduced-comfort guideline (5) would allow far larger vertical accelerations than were found in AIRTRANS.

A more appropriate approach has recently been suggested by Jacobson, Kaulthau, and Richards (8). After many correlation studies working with small aircraft (and more recently buses, as discussed in a paper in this Record), they suggest comfort equations that link the combined axial accelerations to a comfort level and finally to the percentage of satisfied passengers. Their comfort equation (8), given for the case in which transverse accelerations are greater than 62 percent of the vertical, is

$$C = 2 + a_{vert} + 25a_{trans} \quad (2 < C < 5) \tag{6}$$

where

a_{vert} = rms vertical acceleration;
a_{trans} = rms transverse acceleration; and

Figure 6. Probability density and cumulative probability distributions for a typical section.

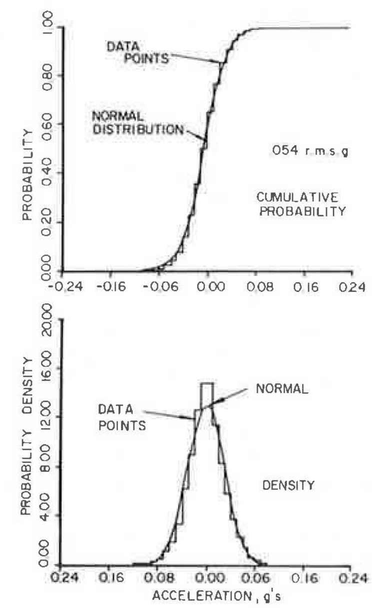


Figure 7. Cumulative probability for exceeding transverse acceleration taken over the complete test loop.

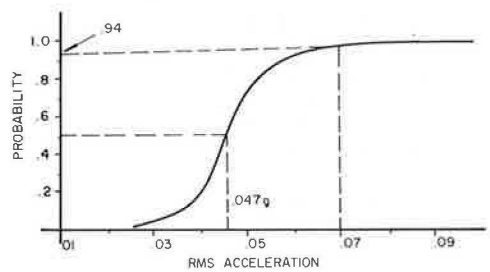
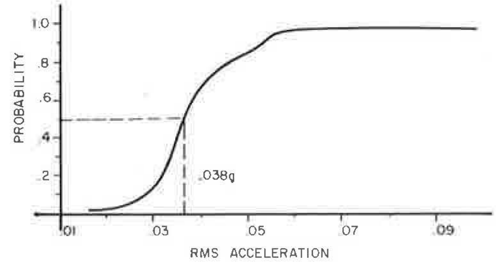


Figure 8. Cumulative probability for exceeding vertical acceleration taken over the complete test loop.



C = 2 (comfortable), 3 (neutral), 4 (uncomfortable), or 5 (very uncomfortable).

At the 70 percent passenger satisfaction level, C = 3.4 (8).

Because AIRTRANS passengers face the side of the vehicle, the transverse direction for passenger comfort is the longitudinal vehicle direction. However, in most of the sections examined, the rms longitudinal acceleration was the smaller of the horizontal plane motions (Figures 3b and 3c) and, by following identical procedures for evaluating horizontal plane motions (5), it seems appropriate to use the vertical and transverse accelerations in computing a comfort-level number.

Finally, under the assumption that the AIRTRANS transverse and vertical accelerations are always correlated and that a_{trans} is related to a_{vert} by

$$a_{trans} = 0.8a_{vert} \quad (7)$$

(which has been found to be the case over many individual sections analyzed), it follows that

$$C = 2 + 21a_{vert} \quad (8)$$

and for a 70 percent satisfaction level, $a_{vert} \cong 0.07\ g$. Figure 7 shows that this level of satisfaction is expected over 94 percent of the network loop.

A previous study (9) of rides in automobiles showed that the vertical acceleration correlated strongly with the ride rating; ratings for 80-km/h (50-mph) travel over a U.S. highway in an American sedan were between three and four (9). The corresponding vertical-acceleration-level band was between 0.035 and 0.055 g. The AIRTRANS rms vertical-acceleration levels average 0.047 g, which is within the bound of the automobile comfort.

CONCLUSIONS

It would appear that the ride quality of the AIRTRANS vehicle, as measured in terms of the vertical and transverse components of body acceleration, will yield a 70 percent satisfaction level 94 percent of the time. This conclusion is based on the assumption of a comfort equation developed for small aircraft that may not be precisely applicable. However, it is also supported by a favorable comparison of the vertical-acceleration levels with those measured in an American sedan traveling at 80 km/h (50 mph) over a U.S. highway.

The probability distribution of the acceleration level within a 10-s section of record is closely modeled by a Gaussian distribution. The spectra as measured at the floor of an AIRTRANS vehicle show that vertical, transverse, and longitudinal accelerations are multipeaked with the major peaks in the 1.0 to 6.0-Hz range. These peaks can be explained in terms of the primary vehicle resonances and the kinematic resonances induced by the delays between the guideway inputs at the front and rear of the vehicle.

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Effects of Deceleration and Rate of Deceleration on Live Seated Human Subjects

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This paper describes the testing of seated human subjects to determine the maximum deceleration and associated rate of change of deceleration (jerk) at which the majority of potential users of automated-guideway-transportation systems will remain securely in their seats. The subjects