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

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

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

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

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**

underwent various levels of deceleration and associated jerk in an instrumented vehicle while seated normally (forward facing); sideways (turned 90° counterclockwise from the direction of travel); and normally, but tilted backward (facing forward, but with the entire seat tilted 5° backward). The subjects also underwent various levels of jerk (seated normally only). Two groups of subjects were chosen to represent the anthropometric extremes of potential passengers: males larger than 95 percent of the male population and females smaller than all but 5 percent of the female population. Estimates based on these tests of the maximum permissible emergency deceleration are 0.47 *g* for forward-facing, seated passengers and 0.41 *g* for side-facing, seated passengers. Tilting the entire seat assembly back 5° increased the estimated maximum permissible deceleration to 0.52 *g*.

A major problem in the design of transit systems is the selection of the levels of deceleration and the associated rate of change of deceleration (jerk) used for emergency and service stops. These levels have an important effect on the headway (the time or distance maintained between vehicles) and, therefore, on the passenger-flow rate of the system. Shorter headways allow higher flow rates, but require greater decelerations and jerks. However, increasing the deceleration level increases the probability of injury to the passengers caused by dislodging them from their seats. This potential for injury becomes an even greater problem in conservatively designed systems because false-alarm stops will outnumber true emergencies. These false-alarm stops increase passenger exposure to excessive deceleration levels and, thereby, degrade safety.

The problem, therefore, is to determine the deceleration and jerk levels that will maximize the passenger-flow rate of the system while minimizing injuries to the passengers caused by decelerations.

## BACKGROUND

There has been very little experimental research on this topic, and of this limited research, only two previous studies have used live human subjects. In a study directed at developing specifications for street railways (trolley cars), Hirshfield (1) accelerated standing subjects at constant jerk rates of between 1 and 10 *g*/s. The participating subjects were 11 to 78 years old, weighed 39 to 107 kg (87 to 235 lb), and were 132 to 193 cm (4 ft 4 in to 6 ft 4 in) tall. In this study, the foot movement accompanying loss of balance resulted in the opening of a sensor switch. Loss of balance occurred at 0.16 *g* for both forward-facing, unsupported males wearing low-heeled shoes and forward-facing, unsupported females wearing high heels. Loss of balance occurred at 0.23 *g* for subjects holding an overhead strap and at 0.27 *g* for subjects holding a vertical stanchion.

The second study [Browning (2)] also measured only standees. Ninety subjects ranging from 15 to 65 years old participated. The subjects could face either forward or backward and use a handhold if they so desired. Observer ratings of movement indicated that the subjects reacted equally to acceleration (facing forward) or deceleration (facing backward). Ratings of slight relative movement occurred at 0.055 *g* for unsupported subjects, at 0.115 *g* for subjects holding the hand rail, and at 0.18 *g* for fit adults holding the hand rail. Safe emergency decelerations in excess of 0.2 *g* were postulated for seated subjects.

A more recent study (3) performed with seated anthropometric dummies used static test procedures. A 79.4-kg (175-lb) cloth-covered buttock form was pulled from a standard transit seat, and a spring scale was used to measure the force. Forces equivalent to 0.94 *g* acting on the buttock form were required to dislodge it from a forward-facing, contoured seat covered with barley-cloth vinyl. For the same seat facing sideways, forces equivalent to 0.97 *g* were required to dislodge the form. No attempt to validate these figures through dynamic testing was reported.

In an analytical study, Fox and Dryden (4), using a biomechanical computer model, found that 0.559 *g* would be required to dislodge a forward-facing 95th percentile [98.4 kg (215 lb), 186.2 cm (6 ft 1 in)] male model from its seat.

None of these investigations studied seated human subjects. However, some automated-guideway-transit (AGT) systems are projected to achieve high passenger-flow rates by using many small vehicles that have all passengers seated and short headways. Consequently, the design of these systems requires knowledge of the effects of deceleration and jerk on seated passengers to ensure that they are simultaneously safe and efficient. None of these studies provides such data.

## APPROACH

This study was designed to determine the deceleration levels required to dislodge potential passengers under typical conditions. These typical seating, passenger, and stopping conditions suggested the following choice of independent variables: seat orientation, seat tilt, level of jerk, and subject size. The relations among subject size, age, and sex were not considered.

Under each set of conditions, large and small human subjects were subjected to controlled decelerations while seated in a standard transit seat. Switches placed in the seat pan indicated when the subject was dislodged from the seat.

The study was conducted in three segments or tests that were designed to determine the effects of seat orientation, seat tilt, and level of jerk on passenger dislodgment. The two seat orientations selected (forward facing and side facing) are those most commonly installed in transit systems. The seat tilt angle selected is the greatest degree of tilt possible commensurate with comfort and ease of egress. The jerk levels were chosen to represent an operational level and an emergency level. The methodology and results of these tests are described in the next two sections. The most sensitive dependent variable was found to be the level of deceleration at which the subjects left the seat pan.

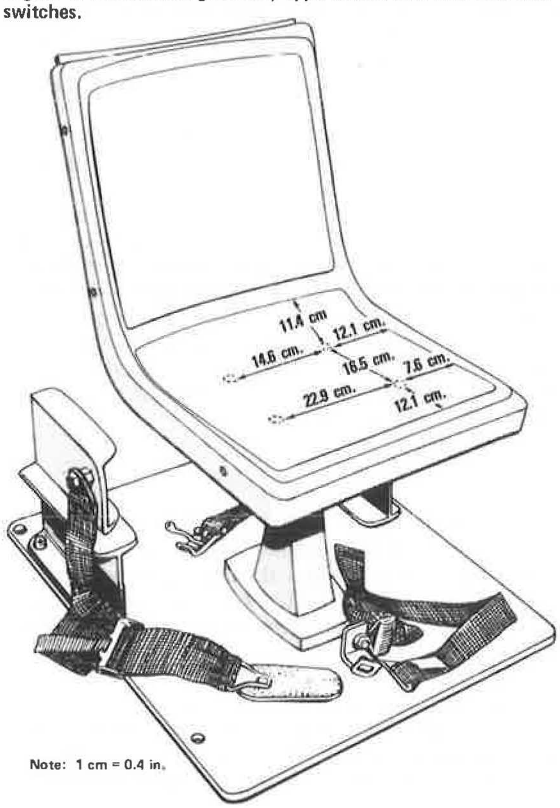
## METHOD

### Subjects

Twenty subjects were recruited by newspaper advertisement from the general population of Ayer, Massachusetts. Ten of the subjects were females below the 10th percentile of weight and height for females [i.e., less than 46.7 kg (103 lb) in weight and 155 cm (61 in) in height] and 10 were males above the 90th percentile of weight and height for males [i.e., more than 85.7 kg (189 lb) in weight and 183 cm (72 in) in height] (5). A summary of subject characteristics is given below (1 kg = 2.2 lb and 1 cm = 0.4 in).

| Characteristic | Small Females (N = 10) | Large Males (N = 10) |
|---|---|---|
| Age, years | | |
| Mean | 23.6 | 35.4 |
| Range | 18 to 32 | 25 to 50 |
| Weight, kg | | |
| Mean | 44.0 | 99.1 |
| Range | 41.5 to 46.7 | 85.7 to 113 |
| Height, cm | | |
| Mean | 152 | 188 |
| Range | 147 to 158 | 180 to 196 |

Figure 1. Automated-guideway type transit seat with installed switches.




Note: 1 cm = 0.4 in.

Before participating in the tests, the subjects were required to pass a medical examination administered at the Fort Devens Hospital. They also completed an informed-consent form.

## Apparatus

A commercially available seat was selected to be representative of the modern transit seat to be used in AGT systems. For these tests, it was mounted in the rear section of a large van. Switches were installed at the front and rear of the seat bottom so as to open when a subject was dislodged (Figure 1). A force-balance accelerometer mounted on the vehicle floor next to the transit seat was used to measure the deceleration of the vehicle, and a fifth wheel measured the vehicle velocity. The decelerations were initiated by the driver through the standard braking system of the vehicle. The driver controlled the deceleration level by monitoring a U-tube accelerometer attached to the front windshield. The following analog data were recorded on a 14-channel magnetic tape recorder: velocity, switch openings, and actual decelerations.

Each subject was fitted with a pair of denim trousers to eliminate frictional differences caused by clothing design and material. A five-point racing-type safety harness was loosely fastened about the subject and adjusted to allow him or her to slide to the front edge of the seat, but no further. All subjects were fitted with motorcycle helmets to prevent accidental head injuries.

## Procedure

Ten of the subjects recruited for the tests were used in the studies designed to evaluate the effect of seat orientation, and the remaining 10 were used in the studies designed to evaluate the effect of seat tilt. From the total group of 20, 6 subjects were later drawn to participate in the studies designed to evaluate the effect of jerk. Within each experiment, the effect of passenger size was evaluated by selecting half the subjects to be 10th and lower percentile females and half to be 90th and higher percentile males.

The tests were conducted in clear weather on a straight, dry macadam road at Fort Devens in Ayer, Massachusetts. Up to 4 subjects/d were tested with up to 10 decelerations per subject, 5 for each experimental condition in the first two tests and 3 each for the third test. Each subject was briefed on the entire procedure before the testing. They were asked to sit as they would normally sit in a transit vehicle such as a bus, remain relaxed, and not anticipate the decelerations. The five-point safety harness was fastened and adjusted. The subject, when seated, could see through the front windshield of the passenger's side of the vehicle, but was prevented from viewing the driver's activities by a curtain. Each subject was tested individually; the other subjects were able to view the tests from a distance.

In each test, the driver would accelerate the vehicle to 64 km/h (40 mph) and then brake it at a constant deceleration until it stopped. Each subject experienced 10 predetermined deceleration levels.

The experimental conditions for the effects of the independent variables (passenger size, seat position, seat tilt, and jerk) on the dependent variable (deceleration at which the subjects were unseated) are summarized below:

1. Ten subjects (5 large and 5 small) were exposed to 10 decelerations at high jerk. For 5 of the decelerations, the subjects were seated facing forward in a normally mounted seat. For the other 5, they were seated facing sideways.
2. A second set of subjects (5 large and 5 small) were exposed to 10 decelerations each at high jerk. For 5 of these decelerations, the subjects were seated facing forward in a normally mounted transit seat. For the other 5, they were seated tilted 5° back.
3. Six of the previous subjects (3 large and 3 small) were exposed to 6 decelerations seated facing forward in a normally mounted seat. The onset of 3 of these decelerations was rapid (high level of jerk), and the onset of the other 3 decelerations was gradual (low level of jerk).

## Design of Tests

All three tests were designed to be analyzed by using two-way, fixed-effects analyses of variance with repeated measures on the second factor. The first factor in all three analyses was subject size (S) (small versus large). The second factor was the experimental condition: seat orientation (O) in the first test, seat tilt (A) in the second, and jerk level (J) in the third. To ensure that any obtained significant differences in the repeated variable were interpretable as due to the variable tested and not to procedural or subject differences, the order of presentation of treatments was arranged according to the following three constraints:

1. Subjects were not to experience either the forward or reverse order of any two adjacent deceleration levels (to reduce subject anticipation),
2. Both subject groups were to experience the same order of treatment in each experimental condition (to allow proper comparison of their responses), and
3. The deceleration levels used in each experimental condition (up to five in some cases) were to be counterbalanced over the five subjects within each group.

Because it was disruptive and time-consuming to change the seat position or tilt after each run, all five decelerations for one seat arrangement were presented sequentially.

RESULTS

Analysis

Examination of the data showed that the left rear switch provided a common and sensitive measure of subject displacement in all phases of the experiment, and therefore only the data for this switch were used in the analysis. The dependent variable reported and analyzed is the actual deceleration at the time of the opening of the switch, for all trials in which the switch opened. Because the subjects were exposed to predetermined decelerations, rather than to deceleration until the switch opened, there were cases in which the switch did not open, and no value of deceleration that caused dislodgement was obtained. This occurred only at the lowest deceleration levels (0.3 *g* in test 1 and 0.4 *g* in tests 2 and 3) and was a problem only with the small subjects. Because of the failure to obtain reliable and consistent measures at these low deceleration levels, the data were considered anomalous and excluded from the analysis.

To determine whether there was any difference in the deceleration level at which the passenger seat switch opened under the control conditions (forward facing and untilted), a t-test was used to compare the data taken under these conditions for tests 1 and 2. No significant difference was identified ($t = 0.14$, degrees of freedom = 77), indicating that the slight differences associated with subject or order variables can be attributed to chance.

Because there was no statistically significant difference, the data from the control conditions were pooled. Tests for skewness and kurtosis were performed on the 20 forward-facing, untilted subjects of tests 1 and 2. The results of these two tests indicate that the data were distributed normally, which permits the use of statistical parametric techniques. Figure 2a represents these pooled data.

To estimate a conservative level of deceleration that would allow the great majority of passengers to remain securely in their seats, the standard deviation was computed and subtracted from the mean. This value represents the deceleration level at which 84 percent of the occupants would remain securely in their seats. In a similar manner, a second estimate obtained by subtracting two standard deviations represents the deceleration level at which 95 percent of the occupants would remain securely in their seats. The deceleration levels at which 50, 84, and 95 percent of the subjects will remain securely in their seats are indicated in Figure 2a for the control condition. Similarly, Figure 2b represents the data obtained when the seat was oriented to the side, and Figure 2c represents the data obtained when it was tilted back 5°. (The small number of these data points precluded vigorous tests for normality.) A discussion of these tests follows.

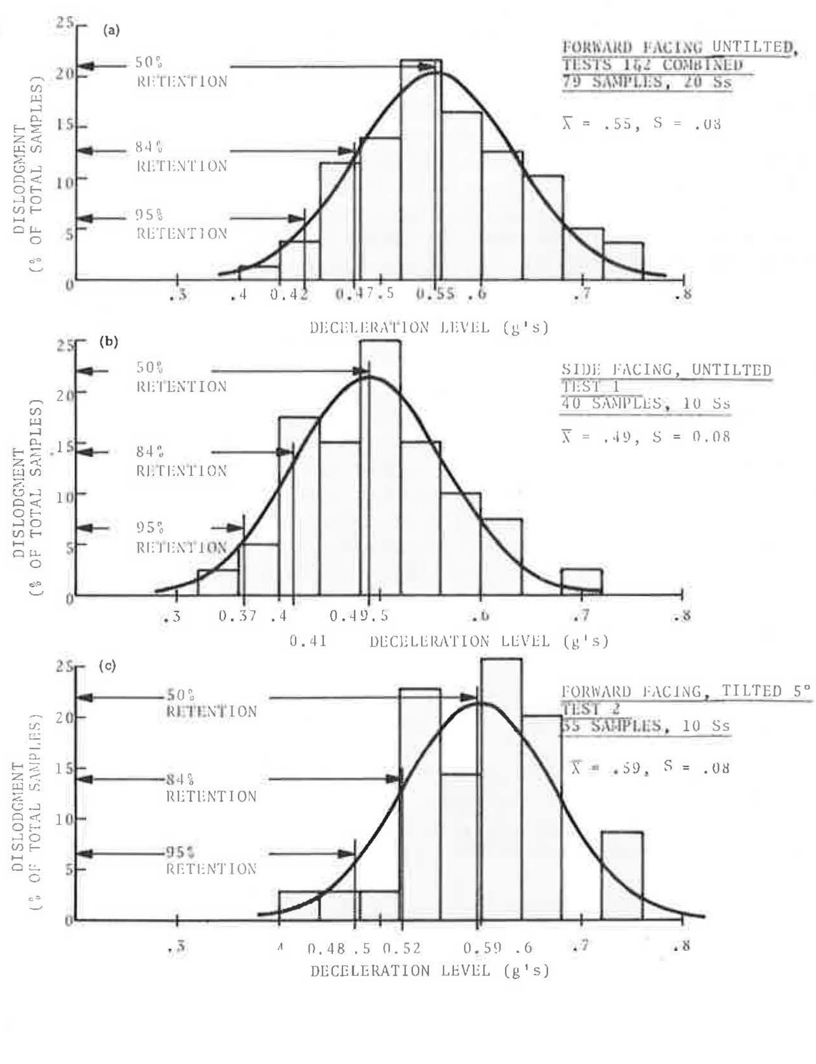



Figure 2. Comparison of distributions of observed data with the normal (results of tests 1 and 2).

## Test 1: Seat Orientation

Five large and five small subjects seated in the standard transit seat, facing forward or facing sideward toward the driver's side, were decelerated at levels of up to 0.3, 0.4, 0.5, 0.6, and 0.7.

As anticipated, the subjects seated facing forward sustained higher decelerations without dislodgment than did those facing sideways. The mean deceleration (±1 standard deviation) required to displace the subjects from the seat was 0.55 (±0.08) *g* in the forward position and 0.49 (±0.08) *g* in the side position for the same subjects. The analysis of variance shown below indicates that this difference had a probability of less than 0.001 of being due to random variation rather than to seat orientation (Ss = number of subjects).

| Source of Variation | Degrees of Freedom | Sums of Squares | Mean Squares | F | P |
|---|---|---|---|---|---|
| Between subjects | | | | | |
| S | 1 | 0.000 82 | 0.000 82 | 0.034 92 | NS |
| S x Ss | 8 | 0.018 77 | 0.002 35 | – | – |
| Within subjects | | | | | |
| O | 1 | 0.021 00 | 0.021 00 | 26.948 88 | 0.001 |
| O x S | 1 | 0.000 30 | 0.000 30 | 0.390 46 | NS |
| O x Ss | 8 | 0.006 23 | 0.000 78 | – | – |
| Total | 19 | 0.047 12 | – | – | – |

There was no difference due to subject size or the interaction of subject size with seat orientation.

Observations made during the deceleration tests indicate that, generally, for subjects in the forward-facing seat position, the higher decelerations resulted in the torso pitching forward and rotating about the hips, followed by the buttocks sliding forward in the seat until the entire body reached the maximum excursion allowed by the restraint system. The reaction to lower decelerations was primarily rotational with little sliding.

In the side-facing seat position, the reaction to all deceleration levels was a rotation of the upper torso about the right buttock. At higher deceleration levels, this rotation resulted in the maximum excursion allowed by the restraint system. The pure rotation was, in all likelihood, due to the deep contour of the seat in the side position.

## Test 2: Seat Tilt

It was anticipated that tilting the entire transit seat back 5° from the standard mounting position would permit subjects to sustain higher decelerations without dislodgment than they could with the seat in the standard position. The 5° tilt was chosen as a compromise between increased retention and comfort. Five large and five small subjects seated facing forward in the standard transit seat, normally mounted (i.e., untilted) or tilted 5° back, were decelerated at levels of up to 0.4, 0.5, 0.6, 0.7, and 0.8 *g*.

The mean deceleration (±1 standard deviation) required to displace the subjects from the seat as measured by the opening of the left rear switch was 0.56 (±0.08) *g* in the normally mounted position and 0.59 (±0.08) *g* in the tilted (5°) backward position for the same subjects. The analysis of variance shown below indicates that this difference has a probability of less than 0.04 of being due to random variation rather than to seat tilt.

| Source of Variation | Degrees of Freedom | Sums of Squares | Mean Squares | F | P |
|---|---|---|---|---|---|
| Between subjects | | | | | |
| S | 1 | 0.005 02 | 0.005 02 | 1.677 15 | NS |
| S x Ss | 8 | 0.023 97 | 0.003 00 | – | – |
| Within subjects | | | | | |
| A | 1 | 0.011 38 | 0.011 38 | 5.806 31 | 0.041 |
| A x S | 1 | 0.001 75 | 0.001 75 | 0.892 37 | NS |
| A x Ss | 8 | 0.015 67 | – | – | – |
| Total | 19 | 0.057 79 | – | – | – |

There was no evidence of a difference due to subject size or the interaction of subject size with seat tilt.

Observations made during the deceleration tests indicated that, for subjects in the forward-facing seat position, for both tilt angles, the reaction to the higher deceleration levels was as follows: The upper torso pitched forward and rotated about the hips, and this was followed by the buttocks sliding forward in the seat. The reaction to lower deceleration levels was a rotation with less violent sliding.

## Test 3: Jerk

Three large and three small subjects were selected for this test from those participating in the previous two tests. These subjects were exposed to decelerations applied with high (1.5 to 2.0 *g*/s) or low (0.1 to 0.5 *g*/s) levels of jerk. The deceleration levels were up to 0.4, 0.5, and 0.6 *g*. All subjects were exposed to all six combinations of jerk and deceleration while seated facing forward in a standard transit seat mounted in the normal position.

The mean deceleration (±1 standard deviation) required to displace the subjects from the seat was 0.45 (±0.11) *g* for the low levels of jerk and 0.49 (±0.09) *g* for the high levels of jerk. The analysis of variance shown below indicates that there are no significant differences due to the high and low levels of jerk, the two subject sizes, or the interaction of subject size with level of jerk.

| Source of Variation | Degrees of Freedom | Sums of Squares | Mean Squares | F | P |
|---|---|---|---|---|---|
| Between subjects | | | | | |
| S | 1 | 0.017 40 | 0.017 40 | 1.178 03 | NS |
| S x Ss | 4 | 0.059 10 | 0.014 77 | – | – |
| Within subjects | | | | | |
| J | 1 | 0.004 45 | 0.004 45 | 2.772 86 | NS |
| J x S | 1 | 0.001 90 | 0.001 90 | 1.184 84 | NS |
| J x Ss | 4 | 0.006 41 | 0.001 60 | – | – |
| Total | 11 | 0.089 26 | – | – | – |

Observations made during these tests indicated that, in most cases, the higher level of jerk induced a torso rotation that was followed by sliding of the buttocks on the seat, and the result of the lower jerk was primarily sliding, with little rotation of the torso.

## DISCUSSION OF RESULTS

The goals of this study were to provide data to help understand the influences of various parameters on seated passengers during emergency stops and to obtain estimates of the emergency decelerations to be specified for transit systems.

These data indicate that seated passengers can safely experience deceleration levels about twice those reported for standees (1, 2). A conservative estimate of the emergency deceleration to be specified in the design of tran-

sit systems on which 84 percent of the occupants of an untilted forward-facing standard transit seat will remain securely within their seats is 0.47 *g*. To ensure retention of 84 percent of the occupants at a side-facing seat, the best estimate is 0.41 *g*; for the occupants of a facing-forward seat tilted back 5°, the best estimate is 0.52 *g*.

Consequently, these data support the use of forward-facing, back-tilted seating to permit high decelerations with a low incidence of passenger dislodgment. (Obviously, backward-facing seating permits higher decelerations; however, many AGT systems operate bidirectionally, and many users prefer facing the direction of movement.)

The small observed differences in the data obtained under different rates of change of deceleration are not attributable to treatment effects, nor are the small differences observed between the two different sizes of subjects.

The results of this study should be applied cautiously; no attempt was made to distinguish independently among the effects, if any, of subject age, sex, and size. Although no significant effects of jerk were found, further studies of jerk should not be precluded because only six subjects participated and only a limited, poorly controlled range of jerk levels was possible in this study.

ACKNOWLEDGMENTS

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# Passenger Perceptions of the Helicopter: Ride-Quality Considerations

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**A summary of the National Aeronautics and Space Administration civil helicopter ride-quality research is presented. Three components of the ride-quality problem are discussed: passenger preconditioning; in-flight cabin conditions, such as noise and motion; and flight duration. Passenger anxiety and motivation for flying were studied as potentially important factors influencing perceptions of ride quality. In addition, the relation between these factors and previous flight experience is examined. The relative importance of cabin noise and vibration is determined for a range of noise and vibration combinations, and changes in passenger comfort due to ride improvements are evaluated. The importance of flight duration on ride satisfaction is discussed.**

In the highly competitive field of public transportation, consideration of the needs of the user is essential. Accordingly, to make the helicopter a feasible transportation alternative, one must, among other things, understand how to design the system to be attractive to potential users. It is important to identify the relations between the attributes of the helicopter and the passenger's evaluation of the effects of these attributes as they relate to his or her satisfaction. One source of this information is passenger evaluation based on actual experience of these attributes.

One of the more important attributes of a transportation system, and especially of the helicopter, is the ride environment. The multiharmonic nature of helicopter vibration presents a special problem in evaluating subjective responses to this environment. Previous studies of subjective evaluation of this type of environment have shown that the levels of each of the component rotor harmonics can be well within acceptable limits and still combine to produce an unacceptable ride (1). An equally important part of the helicopter environment is the noise level. Thus far, there have been few investigations of the interactive effects of different combinations of noise and vibration on a passenger's satisfaction with the ride. Therefore, it is important to extend ride-quality research into these areas and to identify and evaluate passenger responses to the helicopter environment. Also requiring attention are the modifying effects of other ride-quality variables, such as flight duration, low-frequency motion, temperature, and visual cues, as well as such passenger psychological variables as anxiety, attitude toward flying, and flight experience.

The passenger-acceptance flight-research phase of the National Aeronautics and Space Administration (NASA) Civil Helicopter Technology Program is designed to investigate all of these variables through controlled experiments that use a large transport helicopter configured to commercial-type specifications. The experiments are designed to simulate real-world conditions as closely as possible. This paper discusses the objectives and results of the first phase of the program. An overview of other flight research activities of the program can be found elsewhere (2).