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EFFECTS OF DECELERATION AND RATE OF DECELERATION ON LIVE SEATED HUMAN SUBJECTS

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16. Abstract

This report describes the testing of live, 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 (AGT) systems can remain securely in their seats. In this study, subjects underwent various levels of deceleration and associated jerk in an instrumented vehicle. Subjects were decelerated while seated normally (forward-facing), sideward (turned 90 degrees counterclockwise from the direction of travel), and normally, but tilted backward (facing forward but with the entire seat tilted 5 degrees backward). Subjects also underwent various levels of jerk while seated normally only. Two groups of subjects were chosen to represent anthropometric extremes of potential passengers: males larger than 90 percent of the male population, and females smaller than all but 10 percent of the female population. Based on these tests, an estimate of the maximum permissible emergency deceleration for forward-facing, seated AGT passengers is 0.47 g, and for side-facing passengers, 0.41 g. The tests also indicated that tilting the entire seat assembly backward 5 degrees increased the estimated maximum permissible deceleration to 0.52 g.

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PREFACE

A major problem in the design of transit systems is the selection of the levels of deceleration and associated rate of change of deceleration (jerk) used for emergency and service stops. These levels have a profound effect on the headway (time or distance maintained between vehicles) and, therefore, on the passenger flow rate of the system. It is clear that shorter headways, allowing higher flow rates, 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 since "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 optimum deceleration and jerk levels which will maximize the passenger flow rate of the system while minimizing injuries to the passengers caused by decelerations.

This report is based on research supported under DOT-TSC's Advanced Automated Urban Systems, sponsored by UMTA's New System and Automation Division.

We wish to thank H.H. Jacobs of Dunlap and Associates of Darien, Connecticut, for his assistance in the conduct of these experiments.

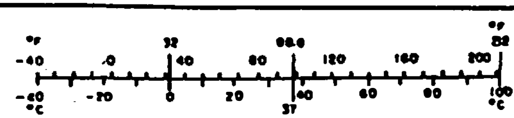
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

Very little experimental research has been performed on the effects of deceleration on seated users of ground transportation. Of this limited research, only two previous studies have used live human subjects.[1,2] In studies aimed at developing specifications for street railways (trolley cars), Hirshfield accelerated standing subjects at constant jerk rates of between 1 and 10 g/sec. Participating subjects ranged from 11 to 78 years, 39 (87) to 107 g (235 lb), and 132 (4 ft. 4 in.) to 193 cm (6 ft. 4 in.) in height. In the 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 in 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, by Browning,[2] also measured only standees. Ninety subjects ranging from 15 to 65 years participated. Subjects could face either forward or backward and use a handrail if they so desired. Observer ratings of movement indicated that subjects reacted equally to acceleration (facing forward) or deceleration (facing backward). Ratings of "slight relative movement" occurred at 0.055 g for unsupported subjects and at 0.115 g for subjects holding the handrail. Safe emergency decelerations in excees of 0.2 g were postulated for seated subjects.

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

Dryden and Fox in an analytical study,[4] utilizing a biomechanical computer model, reported that 0.559 g would be required to dislodge a forward-facing 95th percentile (98.4 Kg, 186.2 cm) male model from his seat.

None of the previous investigations have studied seated human subjects. However, some AGT systems are projected to achieve high passenger flow rates by using many small vehicles with all passengers seated and short vehicle headways. Consequently, the design of these AGT systems requires knowledge of the effects of deceleration and jerk upon seated passengers to assure a simultaneously safe and efficient transit system. None of these studies provide such data.

2. APPROACH

The present study was designed to determine deceleration levels necessary to dislodge potential passengers under typical seating conditions. These typical seating, passenger, and stopping conditions suggested the choice of independent variables for study. The following independent variables were identified: seat orientation (forward-facing, side-facing), seat tilt (normal, 5 degrees back), jerk level (low, high), and subject size (small, large). Note that subject size, age, and sex remain confounded in this study.

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

The study was conducted in three segments or tests, which were designed to determined the effects of seat orientation, seat tilt, and jerk on passenger dislodgment. The two orientations most commonly installed in transit systems, forward-facing and side-facing, were selected for study. The seat-tilt angle was selected as being 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 three tests are described in the next two sections. It was determined that the most sensitive dependent variable is the level of deceleration at which the subjects left the seat pan.

3. METHOD

3.1 SUBJECTS

In September 1976, 20 human subjects were recruited by newspaper advertisement from the general population at Ayer MA. Ten of the subjects were females below the 10th percentile of weight and height for females (i.e., weighing less than 46.7 Kg (103 lb) and less than 155 cm (61 in.) tall, and ten were males above the 90th percentile of weight and height for males (i.e., weighing more than 85.7 Kg (189 lb) and more than 183 cm (72 in.) tall).[5] A summary of subject characteristics is presented in Table 1. Before participating in the tests, subjects were required to pass a medical examination administered by physicians of the U.S. Army at the Fort Devens Lovell General Hospital. The subjects also completed an "informed consent" form.

TABLE 1. SUMMARY OF SUBJECT CHARACTERISTICS

Subject	Number	Age (yr)		Height (cm)		Weight (Kg)	
Type		Mean	Range	Mean	Range	Mean	Range
Small (10 percentile Females)	10	23.6	18-32	152	147-158	44.0	41.5-46.7
Large (90 percentile Males)	10	35.4	25-50	188	180-196	99.1	85.7-113.4

[5] The populations from which these weight and height values were obtained came from the Harvard study.

3.2 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 (Figure 1) installed at the front and rear of the seat bottom were located to open when a subject was dislodged from the seat. A force-balance accelerometer mounted on the vehicle floor next to the transit seat measured the deceleration of the vehicle. A fifth wheel measured the vehicle velocity. Deceleration levels 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, presence of switch openings, and actual deceleration in g.

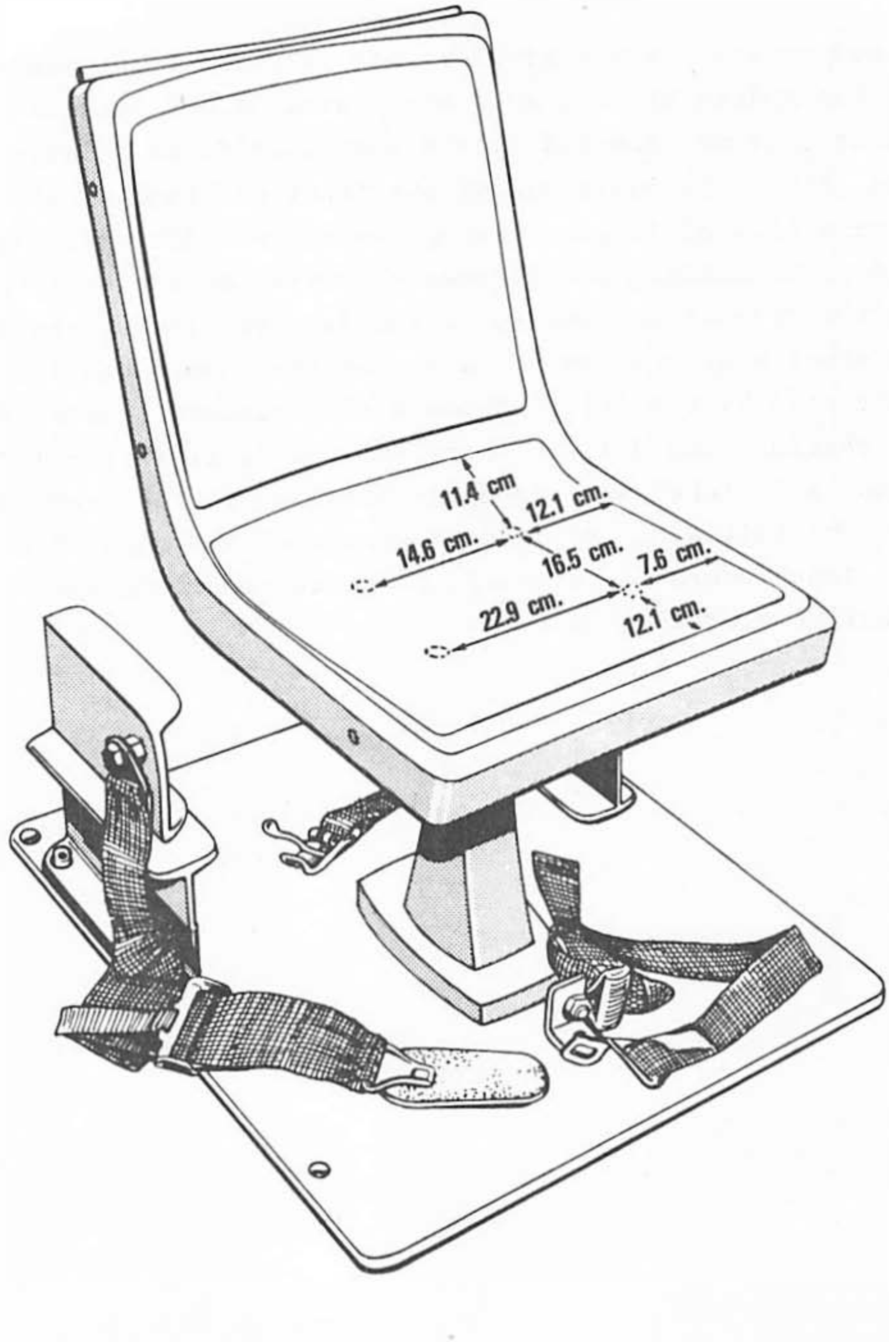

FIGURE 1. AGT TYPE TRANSIT SEAT WITH INSTALLED SWITCHES AS USED IN THESE TESTS

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 the subject to slide up to the front edge of the seat but not farther. All subjects were fitted with motorcycle helmets to prevent accidental head injury.

3.3 PROCEDURE

To explore the effects of the independent variables of passenger size, seat position, seat tilt, and jerk on the dependent variable, level of deceleration at which subjects became unseated, various controlled levels of deceleration and jerk from an initial velocity of 64 kph (40 mph) were presented under the three sets of experimental conditions listed below:

In the first test, 10 subjects (5 large and 5 small) were exposed to 10 decelerations at high jerk. For five of the decelerations, they were seated forward-facing in a normally mounted seat. For the other five, they were seated side-facing.

In the second test, a second set of subjects (5 large and 5 small) were exposed to 10 decelerations each at high jerk. For five of these decelerations, they were seated facing forward in a normally mounted transit seat. For the other five, they were seated tilted 5 degrees back.

In the third test, 6 of the previous subjects (3 large and 3 small) were exposed to six decelerations seated facing forward in a normally mounted seat. The onset of three of these decelerations was rapid (high jerk). The onset of the other three decelerations was gradual (low jerk).

Twenty subjects were recruited for these tests. Ten subjects were used in the studies designed to evaluate the effect of seat orientation, and the remaining subjects were used in the studies to evaluate the effect of seat tilt. Six subjects were later drawn from the total group to participate in the evaluation of the effect of jerk. Within each experiment, the effect of passenger size was evaluated by testing two groups: one group equal to or less than 10th percentile females, and the other equal to or greater than 90th percentile males.

The tests were conducted in clear weather on a straight, dry macadam road at Fort Devens in Ayer MA. Up to 4 subjects were tested per day with up to 10 decelerations per subject, 5 for each experimental condition in tests 1 and 2, and 3 each for test 3. Each subject was briefed on the entire procedure prior to 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, was able to 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 while the other subjects were able to view the tests from a distance.

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

3.4 DESIGN

All three tests were designed to be analyzed 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 (small versus large). The second factor was the experimental condition: seat orientation in the first test, seat tilt in the second, and jerk level in the third. To assure 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:

a. Subjects were not to experience either the forward or reverse order of any two adjacent deceleration levels (to reduce subject anticipation).

b. Both subject groups were to experience the same treatment order in each experimental condition (to allow proper comparison of their responses).

c. 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.

4. RESULTS

4.1 ANALYSIS

After examination of the data, it was determined that the left rear switch provided a common and sensitive measure of subject displacement in all phases of the experiment, and therefore, data for this switch only are used in the analysis. The dependent variable reported and analyzed is the actual deceleration, in g, at the time of the opening of the left rear switch, for all trials in which the switch opened. Because subjects were exposed to predetermined decelerations rather than decelerated until the switch opened, there were cases in which the switch did not open, and no value of deceleration which caused dislodgment was obtained. This occurred only at the lowest target 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, these data were considered anomalous and excluded from the analysis.

To determine if there were any differences in the deceleration level at which the passenger-seat switch opened under the forward-facing, untilted conditions, 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 are attributable 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 permitting the use of statistical parametric techniques. Figure 2a represents these pooled data.

To estimate a conservative level of deceleration which would allow the great majority of passengers to remain securely in their seats, the standard deviation was computed and subtracted from the

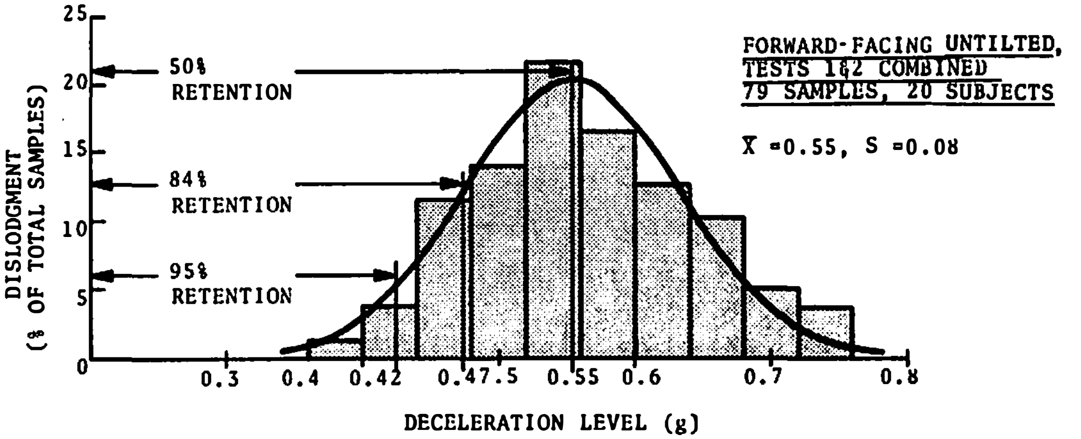

Figure 2a

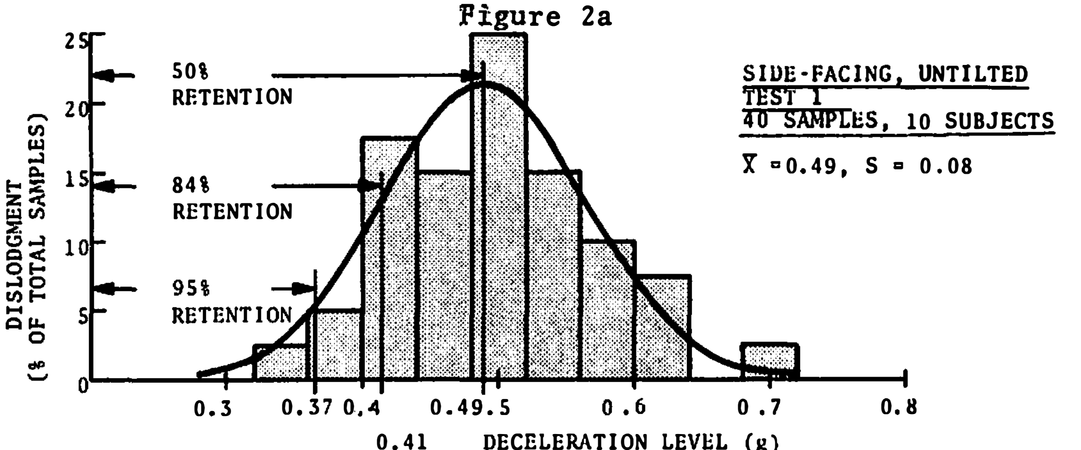

Figure 2b

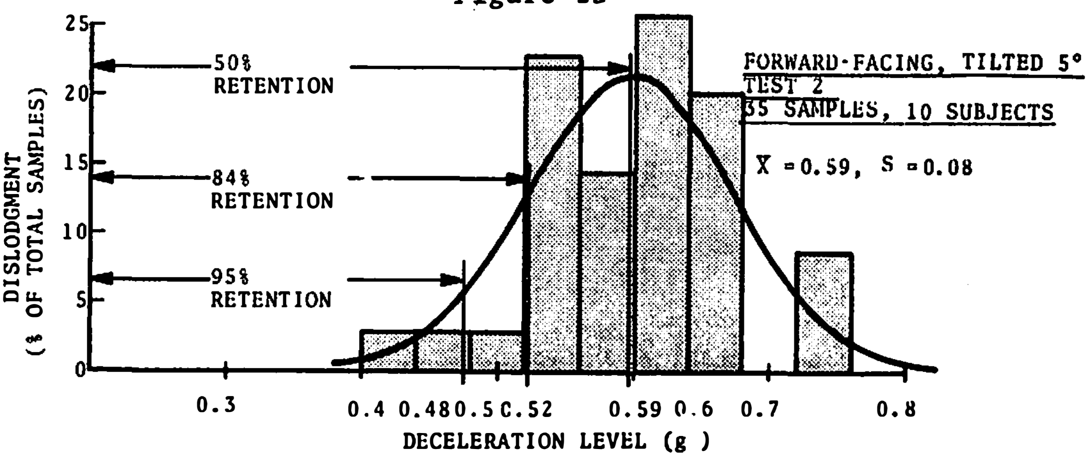

Figure 2c

FIGURE 2. COMPARISON OF DISTRIBUTIONS OF OBSERVED DATA WITH THE NORMAL FOR THE RESULTS OF TESTS 1 AND 2

mean. This value represents the deceleration level at which approximately 84 percent of the occupants would remain securely in their seats. In a similar manner, a second estimate obtained by subtracting two standard deviations was made for the 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 forward-facing, untilted condition. Similarly, bargraphs of the data obtained when the seat was oriented to the side (2b), and when it was tilted back 5 degrees (2c), have been plotted although the small number of data points precluded vigorous tests for normality. A discussion of these tests follows.

4.2 TEST 1. SEAT ORIENTATION

Test 1 was conducted to measure the effects of seat orientation. Five large and five small subjects seated in the standard transit seat, facing forward (F), and facing sideward (S) toward the driver's side were decelerated at levels of up to 0.3, 0.4, 0.5, 0.6, and 0.7 g.

As anticipated, subjects seated facing forward sustained higher decelerations without dislodgment than those facing sideward. The mean deceleration ($\pm$ 1 standard deviation) required to displace subjects from the seat was 0.55 ($\pm$0.08) g in the forward position and 0.49 ($\pm$0.08) g in the side position for the same subjects. An analysis of variance (Table 2) indicates that this difference had a probability of less than 0.001 of being due to random variation rather than seat orientation. There was no difference due to subject size, or the interaction of subject size with seat orientation.

Examination of movies taken during the deceleration tests indicate that, generally, for subjects in the forward-facing seat position, the higher decelerations resulted in the torso pitching forward, 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.

TABLE 2. ANALYSIS OF VARIANCE ON DECELERATION FOR TEST 1. SEAT ORIENTATION.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F-test	Probability
Between					
Subjects	9				
Size	1	0.00082	0.00082	0.03492	not significant
(S X Ss)	8	0.01877	0.00235		
Within					
Subjects	10				
Orientation	1	0.02100	0.02100	26.94888	0.001
O X S	1	0.00030	0.00030	0.39046	not significant
(O X Ss)	8	0.00623	0.00078		
Total	19	0.04712			

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.

4.3 TEST 2. SEAT TILT

Test 2 was conducted to determine the effect of tilting the entire transit seat back 5 degrees from the standard mounting position. It was anticipated that this position would permit subjects to sustain higher decelerations without dislodgment than they could with the seat in the standard position. A 5-degree tilt was chosen as a compromise between increased retention and comfort. Five large and five small subjects seated in the normally mounted transit seat (i.e., untilted), and tilted 5 degrees back (in both cases facing forward), were decelerated at levels of up to 0.4, 0.5, 0.6, 0.7, and 0.8 g.

The mean deceleration ($\pm$ 1 standard deviation) required to displace subjects from the seat as measured by the opening of the left rear switch was 0.56 ($\pm$ 0.08) g in the normally mounted position and 0.59 ($\pm$ 0.08) g in the tilted (5 degrees) backward-mounted position for the same subjects. The analysis of variance (Table 3) shows that this difference has a probability of less than 0.04 of being due to random variation rather than seat tilt. 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, in the forward-facing seat position, for both tilt angles, the subject's reaction to the higher deceleration levels was as follows: The upper torso pitched forward, rotating about the hips, followed by the buttocks sliding forward in the seat. The reaction to lower deceleration levels was a rotation with less violent sliding.

TABLE 3. ANALYSIS OF VARIANCE ON DECELERATION FOR TEST 2. SEAT TILT.

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F-test	Probability
Between					
Subjects	9				
Size	1	0.00502	0.00502	1.67715	not significant
(S X Ss)	8	0.02397	0.00300		
Within					
Subjects	10				
Angle	1	0.01138	0.01138	5.80631	0.041
A X S	1	0.00175	0.00175	0.89237	not significant
(A X Ss)	8	0.01567			
TOTAL	19	0.05779			

4.4 TEST 3. JERK

Test 3 was conducted to measure the effects of rate of change of deceleration (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 jerks of high levels (H, 1.5 to 2.0 g/sec) or low levels (L, 0.1 to 0.5 g/sec). The deceleration levels in these tests reached 0.4, 0.5, and 0.6 g. All subjects were exposed to all six combinations of jerk and deceleration while seated in a standard transit seat facing forward in the normally mounted position.

The mean deceleration (± 1 standard deviation) required to displace subjects from the seat, as measured by the opening of the left rear switch, was 0.45 (± 0.11) g for low-level jerks and 0.49 (± 0.09) g for high-level jerks. The analysis of variance (Table 4) indicates that no significant difference exists between the results obtained at the high and low jerk levels, between the two subject sizes, or the interaction of subject size with jerk.

Observations made during these tests indicated that, in most cases, the high jerk levels induced a torso rotation followed by sliding of the buttocks on the seat, while the result of the slow jerk was primarily sliding with little rotation of the torso.

TABLE 4. ANALYSIS OF VARIANCE ON DECELERATION FOR TEST 3.

JERK

Source of Variation	Degrees of Freedom	Sums of Squares	Mean Squares	F-test	Probability
Between					
Subjects	5				
Size	1	0.01740	0.01740	1.17803	not significant
(S X Ss)	4	0.05910	0.01477		
Within					
Subjects	6				
Jerk	1	0.00445	0.00445	2.77286	not significant
J X S	1	0.00190	0.00190	1.8484	not significant
(J X Ss)	4	0.00641	0.00160		
TOTAL	11	0.08026			

5. DISCUSSION

The goals of this study were both to provide data to understand the influences of various parameters on seated passengers during emergency stops, and to obtain initial 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 transit systems at which 84 percent of the occupants of an untilted forward-facing standard transit seat will remain securely in the seat is 0.47 g. To insure retention of 84 percent of the occupants of a side-facing seat, the best estimate is 0.41 g. And, for a seat tilted back 5 degrees (facing forward), 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 may 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 cautiously applied as 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 were possible in this study.

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