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Maximum Deceleration and Jerk Levels That Allow Retention of Unrestrained, Seated Transit Passengers

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Three experiments performed to determine the maximum deceleration and associated rate of change of deceleration (jerk) that will allow the majority of potential users of automated guideway transportation systems to remain securely in their seats are described. In each experiment subjects representative of three anthropometric classes underwent various levels of deceleration and jerk. These experiments were performed in an instrumented vehicle controlled by an automated braking system. Seat sensors, movies, and subject ratings were employed to determine the deceleration at which subjects began to move off the seat pan. Subjects were decelerated while seated normally, sideways, and forward facing but tilted backward (facing forward with the seat pan tilted back 3, 9, or 12°). Subjects underwent jerk levels of 0.25, 0.75, and 1.25 g/s while seated normally only. Jerk was found not to affect maximum deceleration levels. Modifications of features common to transit seating were found to increase retention. The maximum deceleration allowing retention was determined for both forward- and side-facing seated passengers. These results are discussed and presented in tabular and graphic form.

A major design goal of transit systems, particularly of automated guideway transit (AGT) systems, is high passenger flow rate. One technique employed to accomplish this goal is to minimize the headway between vehicles moving in the same direction along the guideway. However, a sufficient stopping distance between vehicles must be maintained for the safety of the passengers. The more closely one vehicle follows another, the more quickly it must

stop in order to avoid collision. High stopping rates and decelerations, however, do increase the risk of injury to passengers who may be dislodged from their seats. Therefore, it is important to determine the maximum deceleration levels that allow retention of unrestrained, seated transit passengers.

BACKGROUND

In a previous study, Abernethy and others (1) investigated the effects of seat position, anthropometry, and jerk on passenger retention. This study used a limited number of subjects, driver-controlled deceleration, and a seat-switch technique for sensing deceleration. Each of these elements could possibly have reduced the precision of the results. In particular, it was noted that the seat-pan switches required a small but finite time to activate as a subject came off the seat pan. Therefore the deceleration readings recorded were always higher than the actual deceleration at which the subject came off the seat, and the error in deceleration readings always increased as jerk increased, i.e., readings taken at higher jerk levels indicate higher decelerations than may have actually been encountered by the subjects. In addition, the vehicle driver could not always precisely apply the brakes to achieve target deceleration levels. Finally, a limited number of subjects were available for the 1977 study, which was a particular problem in the experiment to determine the effects of jerk.

A review of the previous experimental research on emergency deceleration and jerk in public transit vehicles has been made by Jacobs (2).

The study by Abernethy and others (1) revealed that the mean maximum deceleration level at which forward-facing subjects were dislodged was 0.55 g. When the seat was tilted 5° back, the mean value increased to 0.59 g. For the retention of 84 percent (mean minus one standard deviation) of the population, the permissible emergency deceleration level was estimated to be 0.47 g for passengers tilted back 5°. For side-facing subjects, the mean deceleration was 0.49 g for retaining 50 percent of the population and 0.41 g for 84 percent of the population. Estimates of emergency braking levels in existing AGT systems are found below.

System	Deceleration Level (g)
Tampa (3)	0.11
Fairlane (4)	0.19
King's Dominion (5)	0.20
Seattle-Tacoma Airport (6)	0.13
VAL (7)	0.18-0.25
Houston Tunnel Train (8)	0.15
AIRTrans (9)	0.16-0.22
WEDway (10)	0.16
Morgantown (11)	0.31-0.37

Previous research has indicated that jerk is a factor in determining the comfort aspects of deceleration. In terms of safety, the previous research of standees had differing findings on the effects of jerk. The only study directly applicable to the seated passenger in AGT systems is that by Abernethy and others (1), which did not find jerk to be a factor in passenger retention.

APPROACH

It was decided to measure the maximum deceleration and associated jerk that will allow the majority of passengers to remain securely in their seats by a method that combines seat-switch sensors,

photogrammetric data, and subject ratings. Vehicle decelerations and jerks were controlled by an automated braking system, and an increased number of subjects was used.

Twelve subjects participated in each of three experiments designed to determine the maximum deceleration level under various conditions of jerk (0.25, 0.75, and 1.25 g/s; seat orientation (forward or side facing); seat-tilt angle (0, 3, 9, and 12° backward); and passenger assists (foot and arm rests).

METHOD

Subjects

Thirty-six subjects were recruited by newspaper advertisement. Subjects were selected to ensure that the male and female participants were representative of the smallest 15 percent, the middle 15 percent, and the largest 15 percent of the general population in both height and weight, as calculated from data in Damon, Stoudt, and McFarland (12). For males, the smallest 15 percent were less than 66 in (167.6 cm) tall and weighed less than 138 lb (62.6 kg), the middle 15 percent had a mean height of 68.5 in (174.0 cm) and a mean weight of 159.2 lb (72.2 kg), and the largest 15 percent were greater than 71 in (190.3 cm) and weighed more than 187 lb (83.9 kg). For females, the smallest 15 percent were less than 61 in (154.9 cm) tall and weighed less than 109 lb (49.5 kg), the middle 15 percent were between 128 lb (58.1 kg) and 138 lb (62.6 kg), and the largest 15 percent were greater than 66 in (167.6 cm) and weighed more than 157 lb (71.3 kg). Each subject was required to pass a physician's medical examination and to sign a statement of informed consent before participating. Each subject received $25.

Apparatus

1. A commercially available seat (American Seating Company model 6318A) was selected for use in these experiments because it was both readily adjustable and representative of the type of transit seat to be used in AGT systems (Figure 1). The seat back was always positioned to maintain an approximate angle of 97° with the seat pan. The seat pan was adjustable from a 0° (flat) position to tilts of 3, 9, and 12° back. The seat cushion was contoured by using one flat 1-in (2.54-cm) layer of 70-lb (31.8-kg) compression foam with a second layer contoured along the front and sides (see Figure 2). The compression foam was such that a 70-lb weight placed on a 9-in (22.9-cm) disc depressed the foam by 25 percent. This contoured foam was covered with a nylon and wool coarse-weave fabric (Craftex K12924N). Two switches were installed in the positions indicated in Figure 2 and connected to a light that indicated their open or depressed status. This light was attached to the side of the seat. The seat was equipped with fold-down armrests, and an adjustable footrest was bolted to the floor in front of the seat.

2. Vehicle: This test seat was mounted in the rear center of a 14-ft (4.3-m) van. The van had disc brakes on the front wheels and dual wheels with drum brakes in the rear. Approximately 150 lb (62.8 kg) of ballast was added to the rear bumper to increase the braking force.

3. Braking system: The brakes were controlled by an automated braking system (Lebow Associates model 7610-112 brake test instrument). This device consisted of a hydraulic power supply that drove a brake pedal actuator that physically depressed the brake pedal on command from an electronic

programmer-controller. This electronic package was always programmed to reach the maximum deceleration attainable by the vehicle. In operation, the driver initiated a programmed deceleration by means of a remote switch. The braking system depressed the brake pedal, and the programmer-controller monitored its built-in decelerometer (attached to the van floor next to the seat) to provide a uniformly increasing deceleration (constant jerk). If required, the driver could abort the deceleration at any time by releasing the switch. The accuracy of the built-in decelerometer was calibrated against an independent force balance decelerometer (Columbia Services SA-107) and also against deceleration levels calculated from velocity measurements of a fifth wheel (Laboratory Equipment Company, truck test fifth-wheel model DD-1) mounted at the rear of the vehicle.

4. Recording equipment: The deceleration data taken from the braking system's built-in decelerometer and the status of the two seat-switch sensors were continuously recorded at 0.98 in/s (25 mm/s) on a two-channel strip-chart recorder (Brush model 222). A movie camera aimed at the seat side recorded not only when the subjects began to move off the seat pan but also how they moved during deceleration. This camera also filmed the light that indicated the status of the seat-pan switches. The decelerations were filmed at a speed of 64 frames/s to produce slow-motion pictures. Later, frame-by-frame analysis determined the time at which initial buttock movement off the seat pan occurred and when the seat switches responded to this movement as indicated by the light. The number of intervening frames determined the instrument lag time, if any. This lag time was subtracted from the seat-switch sensor indication time on the two-channel strip chart to calculate the actual deceleration value at the time the seat-switch sensor should have indicated it.

Procedure

General

The experiments were conducted in clear weather on an unused, straight, dry airport runway at either Hanscom Field in Bedford or Otis Air Force Base, both in Massachusetts. Each subject was briefed on the purpose of the experiment and on the entire procedure. Each was asked to sit as if in an actual
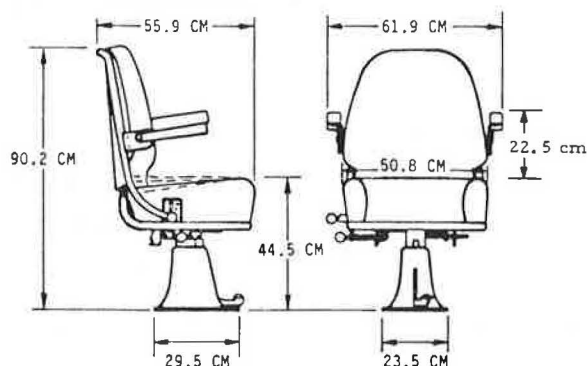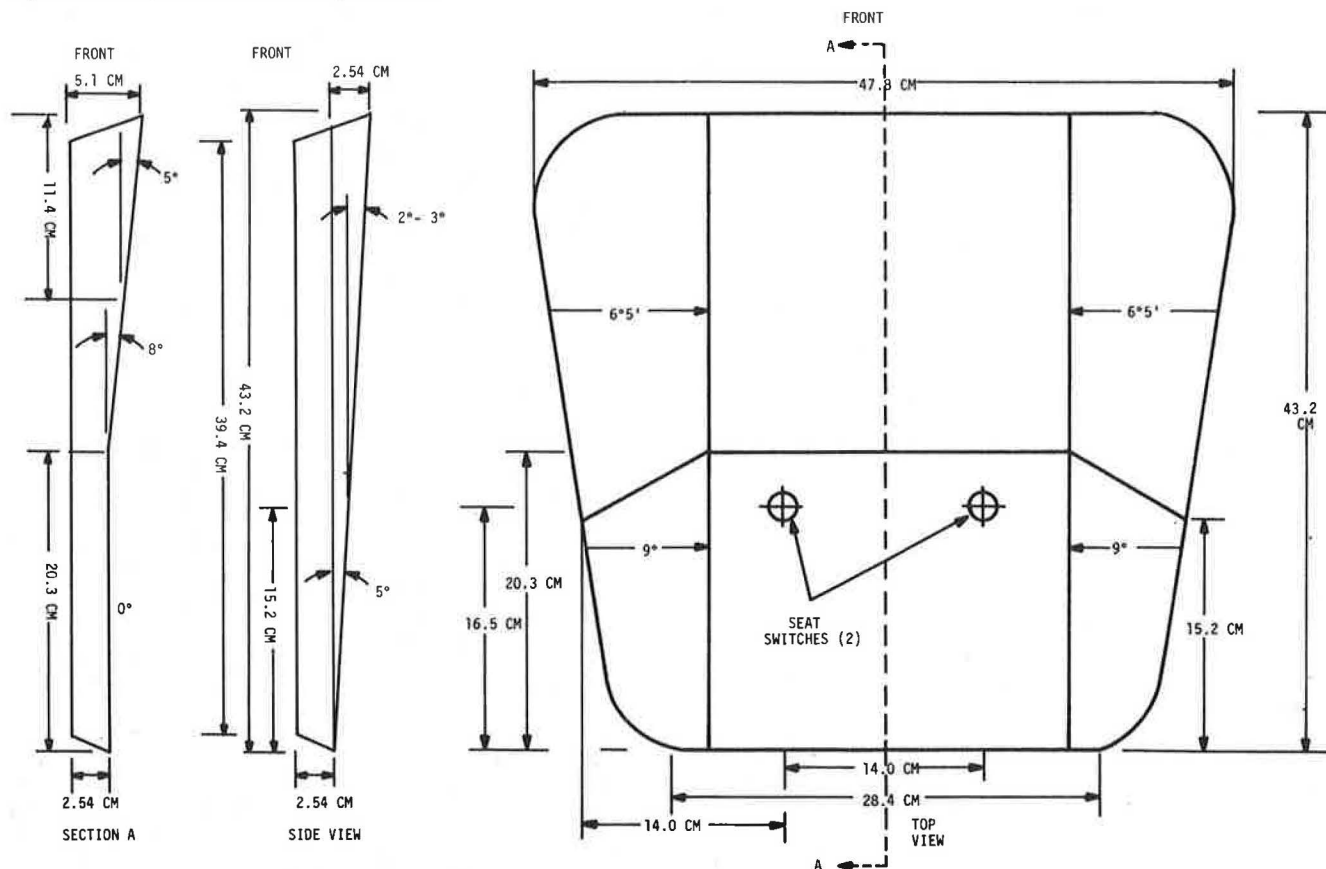
Figure 1. Experimental seat.

Figure 2. Fabric-covered contoured seat-pan cushion.

transit vehicle, to remain relaxed but not limp, and to not anticipate the decelerations. Each subject was fitted with a pair of denim overalls and a pair of rubber-soled shoes to eliminate the effects of frictional differences in personal clothing design or material. Each also wore a baseball catcher's chest protector and a motorcycle helmet approved for safety by the U.S. Department of Transportation. A five-point racing-type safety harness was loosely fastened about each subject and adjusted to allow the subject to slide up to the front edge of the seat but no further. The subject was cautioned not to grab the seat or seat belts during decelerations. The subject, when seated, could see through the front window of the vehicle. However, the automatic braking system could not be seen, so that the subject could not determine when the driver initiated a deceleration. The hydraulics of the automated braking system made a loud sound during warmup and activation. This sound was explained to the subject as being normal. To prevent the sound from serving as a cue to initiation of a deceleration, the braking system was kept on.

For each deceleration the driver would accelerate the vehicle to a predetermined velocity and then trigger the automated braking system with the remote switch for a preprogrammed constant deceleration until just prior to an abrupt stop. At this point the braking system was released, allowing the vehicle to coast to a stop. This procedure provided the required deceleration data at the onset of the stop; at the same time it avoided throwing the subject against the seat back as a result of the final jerk.

Specific

1. Experiment 1--effects of jerk: This study was designed to investigate the effects of level of jerk on passenger retention. Because of previous anomalous research findings, no assumptions about the effects of jerk on retention were made. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced three decelerations at each of three levels of jerk (0.25, 0.75, and 1.25 g/s. These decelerations were given in a counterbalanced order for a total of nine decelerations per subject. The subject sat in a forward-facing, untilted (0°) position on the fabric-covered contoured seat. The vehicle was decelerated from a velocity of 40 mph (64 km/h). Subject movement was filmed as described above. Each subject rated the last five decelerations on a scale from 1 to 7, where 1 = very comfortable and 7 = very uncomfortable.

2. Experiment 2--forward facing, seat tilt, and footrest: This study was designed to determine the maximum deceleration that will allow retention of passengers and to investigate the retention effects of increasing the seat-pan tilt and providing a footrest. The seat-pan tilt angles studied were 0 (flat), 3, 9, and 12°. It was assumed that passenger retention would increase with increasing seat tilt. The presence or absence of a footrest was also investigated. It was assumed that use of a footrest would enhance retention. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced decelerations at each tilt angle four times. Half of these 4 decelerations were with a footrest, half without, for a total of .16 decelerations per subject. The subject sat in a forward-facing position on the fabric-covered contoured seat. The footrest was adjusted so that both shoe heels rested on the floor and both shoe soles rested fully against the footrest. The vehicle was decelerated

from a velocity of 30 mph (48 km/h) at a jerk of 0.5 g/s. Subject movement was filmed, but no ratings were taken.

3. Experiment 3--side facing, armrests: This study was designed to determine the maximum deceleration that allowed retention of side-facing passengers and to investigate the retention effects of armrests. It was assumed that armrests would enhance retention. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced three decelerations with armrests and three without for a total of six decelerations per subject. The subject sat in a side-facing, 3° seat-pan tilt position on the fabric-covered contoured seat. The armrest was fixed at 13.5 in (34.3 cm) above the seat pan. The vehicle was decelerated from a velocity of 30 mph at a jerk of 0.5 g/s. Subject movement was filmed, but no ratings were taken.

RESULTS

Experiment 1--Effects of Jerk

This experiment was conducted to determine the magnitude of any instrumentation lag and to establish the effects of levels of jerk. Several measures of subject responses to three levels of jerk (0.25, 0.75, and 1.25 g/s) were recorded: (a) the deceleration at which the seat-pan switch opened, which indicated initial buttock movement off the seat pan; (b) movies of actual subject movement; and (c) subject ratings of comfort level on a seven-point scale.

The first measure was the same as that employed by Abernethy and others ($\underline{1}$). The results of this measure are reported below as the mean uncorrected deceleration as a function of level of jerk. The deceleration readings taken at the time of the seat-switch opening increase as a function of increasing jerk levels. However, film analysis did, in fact, reveal that the seat sensor lagged behind actual subject buttock movement from the seat pan. Correction of each deceleration reading removed the experimental error introduced by this instrumentation lag. The mean of these corrected decelerations is also reported as a function of jerk level, and these mean corrected decelerations do not increase with increasing levels of jerk.

Jerk Level	Mean Deceleration Level (g)	
(g/s)	Uncorrected	Corrected
Low (0.25)	0.383	0.29
Medium (0.75)	0.429	0.29
High (1.25)	0.491	0.30

An analysis of variance (Table 1) indicated that there were no significant differences in mean corrected decelerations among the three jerk levels, i.e., there was a high probability (0.73) that the measured differences were due to random variations in the data. Further, there was no significant interaction of jerk level with subject size.

The maximum deceleration for retention of 84 percent of the potential passengers is 0.30 g, regardless of level of jerk within the extended range employed. Thus, lower jerk levels do not contribute to increased retention.

Although they were physically unaffected by jerk level, subjects did report significant differences in terms of comfort level. Mean subjective comfort ratings were 3.5 or "somewhat comfortable" for the low jerk condition, 4.6 or "somewhat uncomfortable" for the medium, and 5.2 or "very uncomfortable" for the high jerk level. Film analysis to determine how

Table 1. Analysis of variance of forward-facing corrected decelerations as a function of levels of jerk and subject size.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Jerk (J)	2	0.0032	0.0016	0.31	0.73
Subject size (S)	5	0.0678	0.0136	2.65	0.03
J × S	10	0.0898	0.0090	1.75	0.08
Error	90	0.4608	0.0051		

Table 2. Analysis of variance of forward-facing corrected decelerations as a function of levels of seat-pan tilt, footrest, and subject size.

| Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Between					
Subject size (S)	5	0.4715	0.0943	4.97	0.005
Error (S × R)	18	0.3417	0.0190		
Within					
Seat tilt (T)	3	0.1252	0.0417	5.94	0.001
T × S	15	0.0648	0.0043	0.62	0.846
Error (T × S × R)	54	0.3793	0.0070		
Footrest (F)	1	0.2022	0.2022	11.24	0.004
F × S	5	0.1599	0.0320	1.78	0.168
Error (F × S × R)	18	0.3237	0.0180		
F × T	3	0.0164	0.0055	1.10	0.357
F × T × S	15	0.0658	0.0044	0.88	0.589
Error	54	0.2687	0.0050		

subjects came off the seat indicated that, in most cases, the subject's shoulders moved forward, followed by a forward sliding of the buttocks.

Experiment 2--Forward Facing, Seat Tilt, and Footrest

The corrected deceleration level obtained for retention of 50 percent and 84 percent of potential passengers facing forward is presented in the text table below for each seat-pan tilt (0, 3, 9, and 12° back) with and without a footrest. Both increased seat-pan tilt and use of a footrest increased passenger retention.

	Corrected Deceleration Level (g)			
Seat-	Without Footrest		With Footrest	
Pan Tilt	50%	84%	50%	84%
(°)	Retention	Retention	Retention	Retention
0	0.35	0.30	0.38	0.33
3	0.34	0.28	0.41	0.31
9	0.38	0.31	0.41	0.36
12	0.43	0.33	0.46	0.36

An analysis of variance (Table 2) of the corrected decelerations indicated that there were significant differences among the four seat-pan tilts, i.e., there was a probability of less than 0.001 that their differences were due to random variation. Tukey's honestly significant difference (HSD) test [cited by Kirk (13)] of these differences among seat tilts indicated that there were only random differences among the data taken at 0, 3, and 9° tilts but that the differences between the data at 12° and those at the other tilt angles were significant, i.e., there was less than a 0.05 chance that these differences were due to random variation. The analysis of variance also indicated that there was a significant difference between data taken in the footrest and no-footrest conditions, i.e., there was a probability of less than 0.004 that these differences were due to random chance. There were no significant interactions.

Figure 3. Percentage of passengers retained in a typical transit-seat configuration compared with a seat configuration for increased retention.
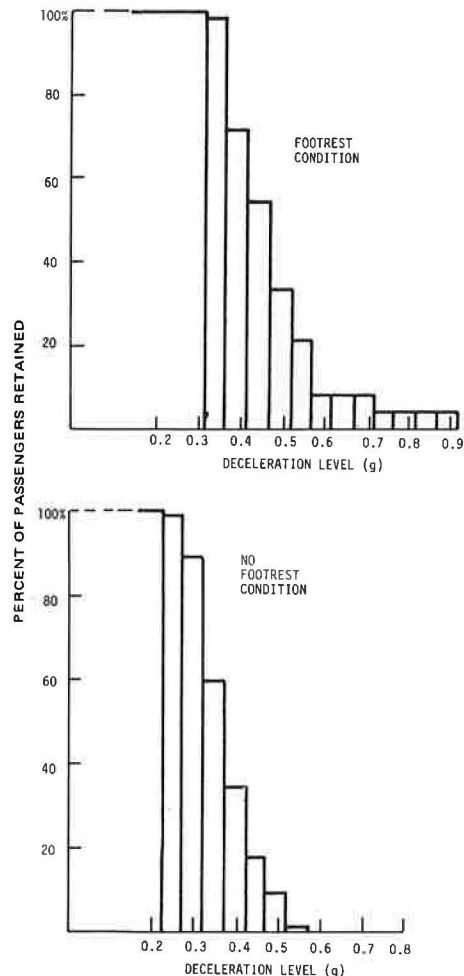
The increased retention attained by simply tilting a typical transit seat pan back 12° and adding a footrest (provided it is used) is illustrated in Figure 3. The distribution of corrected decelerations for the typical transit installation (forward facing; combined 0, 3, and 9°; without footrests) is presented in the top graph, and the distribution for an increased-retention configuration (forward facing, tilted 12°, with footrests) is presented in the bottom graph. The maximum deceleration for retention of 84 percent of the potential passengers is 0.30 g for the typical transit installation, compared with 0.36 g for the increased-retention configuration.

Experiment 3--Side Facing, Armrests

The uncorrected deceleration levels for retention of 50 percent and 84 percent of potential passengers facing sideways (turned 90° counterclockwise from the direction of travel) with and without armrests is shown below.

	Deceleration Level (g)	
Condition	50% Retention	84% Retention
Without armrests	0.367	0.261
With armrests	0.367	0.244

The presence of armrests does not increase retention as measured by initial body movement, although the movies showed that the armrests did act as a

Table 3. Analysis of variance of side-facing uncorrected decelerations as a function of armrests and subject size.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Between					
Subject size (S)	5	0.2650	0.0530	2.31	0.072
Error (S × R)	27	0.6207	0.0230		
Within					
Armrests (A)	1	0.0050	0.0050	1.32	0.261
A × S	5	0.0130	0.0026	0.68	0.642
Error (A × S × R)	27	0.1030	0.0038		

Figure 4. Percentage of passengers showing no significant body movement on side-facing seats, with and without armrests.
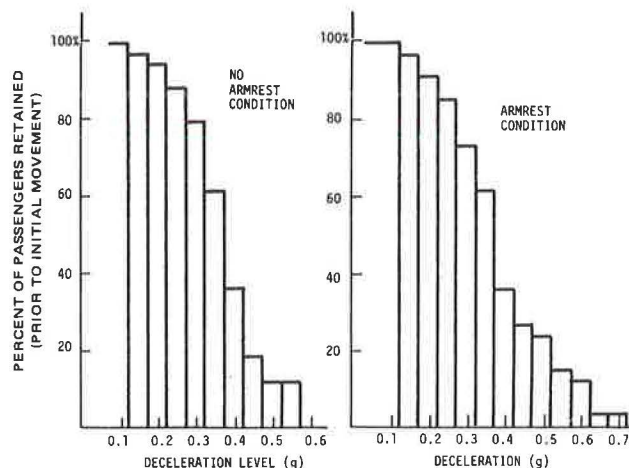
physical barrier to prevent actual dislodgement. Film analysis of this experiment showed that the seat-switch opening occurred at the same time as significant body movements; therefore, there was no instrumentation error and no correction for instrumentation lag required.

An analysis of variance (Table 3) of the uncorrected decelerations indicated that the difference between having and not having armrests had a high probability (0.261) of being due to random variations.

The distribution of uncorrected decelerations for a side-facing seat without armrests is presented in the left graph of Figure 4 and for a side-facing seat with armrests in the right graph. The maximum deceleration for retention of 84 percent of the potential passengers is 0.261 g for the side-facing seat without armrests and 0.244 g with armrests. Both of these deceleration values are considerably less than those for the forward-facing configuration.

Film analysis to determine when subjects came off the side-facing seat indicated that, in most cases, the subject's upper torso moved until it was physically stopped by the leading armrest. Although actual dislodgement was prevented by this armrest, the subject's buttocks did lift off the trailing seat sensor.

DISCUSSION

This study was designed to establish, measure, and correct for the measurement errors presumed to have biased the results of previous deceleration studies, particularly those reported by Abernethy and others (1). The method employed not only seat-switch sensors but also movies and subject ratings, vehicle

decelerations and jerk levels controlled by an automated braking system, and an increased number of subjects. The results of this investigation indicated that instrumentation problems had biased the data toward higher deceleration levels in previous studies. Correction of this bias resulted in the resolution of the previous anomalous results about the effects of jerk on passenger retention.

The maximum deceleration that allows retention of 84 percent of the potential passengers is 0.30 g for a typical transit seat installation (forward facing; tilted at 0, 3, or 9°; fabric-covered contoured seat pan) and 0.36 g for an increased retention configuration (forward facing, tilted back 12°, fabric-covered contoured seat pan, with footrest). These results are considerably lower than those obtained by Abernethy and others in 1977: 0.47 g for a forward-facing, untilted transit seat and 0.52 g for a forward-facing seat tilted back 5° (1).

The maximum deceleration that allows retention of 84 percent of the occupants of a side-facing transit seat is 0.25 g with or without armrests. Again, these results are considerably lower than the 0.41 g obtained by Abernethy and others (1) for a side-facing seat without armrests.

Jerk level was not found to be a factor in passenger retention, only in passenger perception of comfort. It was found that the effects of instrumentation lag increased with increasing levels of jerk.

The results of this investigation indicate that increased retention levels are obtainable through changes in seat installation (tilting back) and the presence of passenger assists (footrests). Further increases may be obtainable by providing warnings prior to deceleration.

Two cautions must be raised concerning the results of this study.

1. All subjects expected to be decelerated. Some degree of preparedness should be assumed. This preparedness implies even lower actual deceleration levels for unprepared passengers.

2. Only seated, able-bodied passengers participated in this study. These results, therefore, may not be applicable to children, the elderly, or the handicapped. Accommodation of these potential passengers again may imply that lower actual deceleration levels must be incorporated into AGT transit design.

A more comprehensive discussion of the work presented in this paper has been made by Jacobs (2).

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