U. S. Department
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Administration

Study to Establish Ride Comfort Criteria for High Speed Magnetically Levitated Transportation Systems

National Maglev
Initiative Office
Washington DC, 20590

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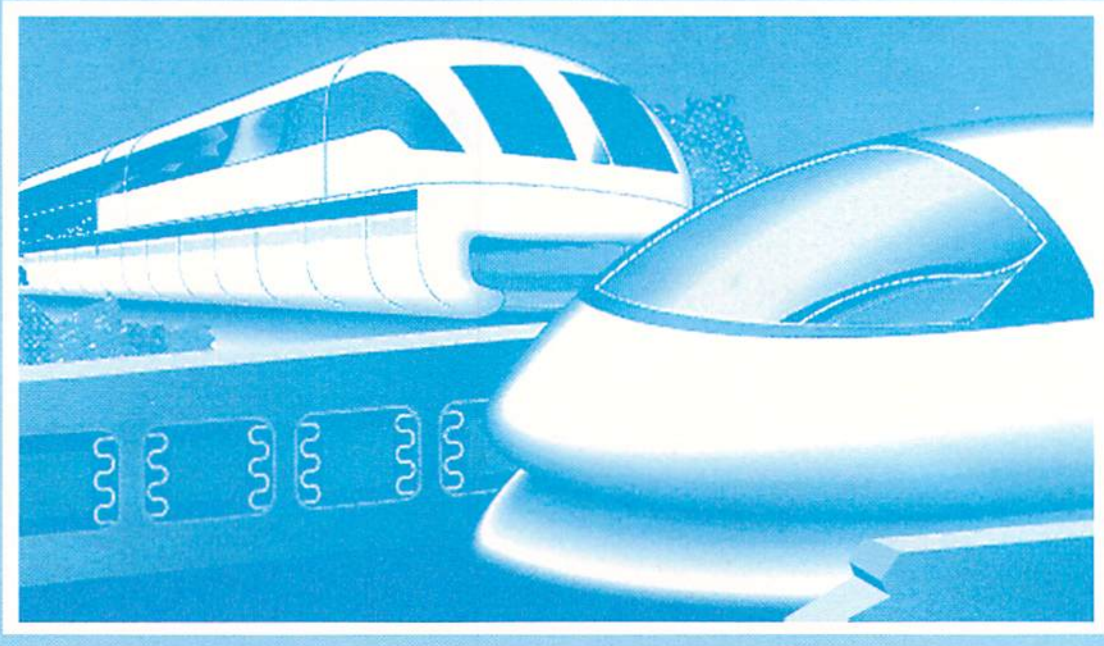

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13. ABSTRACT (Maximum 200 words)

Advanced high speed fixed guideway transportation systems such as magnetic levitation systems have speed, acceleration, and banking capabilities which present new guideway design issues. This increased performance results in new concerns for passenger comfort, particularly with regard to vertical and lateral motions. If existing highway and other rights of way are to be used to the fullest extent at the very high speeds of which these systems are capable, the ride comfort concerns translate into limitations on changes in grade, curve radii, and the transition spirals used to enter the curves. This report examines the effect of rolling, banking, and vertical motions on the ride comfort ratings of seated passengers. The motions were produced using specific maneuvers in a small executive jet aircraft. The ride comfort ratings were transformed to estimates of the probability that the passengers would ride again. Using a conservative rule, the motion environment should be such that 95 percent of passengers would not hesitate to ride again. This 95 percent criterion was met when positive vertical accelerations were less than .30 g and negative vertical accelerations were less than .20 g. In turning maneuvers, this occurred when roll rates were less than 7 degrees per second and bank angles were less than 37 degrees. The data were also used to estimate the percentage of passengers who would not hesitate to ride with roll rates up to 15 degrees per second, bank angles up to 40 degrees, and vertical accelerations up to .25 g.

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PREFACE

This report was prepared by the Operator Performance and Safety Analysis Division of the Office of Research and Analysis at the Volpe National Transportation Systems Center (VNTSC). The authors would like to thank all of the individuals who contributed to the study. Among these were John Harding, Chief Scientist of the National Maglev Initiative (NMI), and James Milner of the NMI staff, who served as Technical Monitor for this project.

Capt. John Turner of the Volpe Center's Unisys support staff selected the aircraft used for the experiments, which was brokered by Peter Torosian, President of Bird Air Fleet, Inc. We are especially grateful to chief pilot Ed Luppi and co-pilots Tom Duderewicz and Christine Latifi for their painstaking efforts in flying maneuvers to our specifications.

Carol Preusser and Bob Ulmer of Preusser Research Group recruited and selected subjects and flew with them, operating the data-collection system and keeping the subjects at ease.

Finally, we would like to thank our experimental subjects, whose responses form the basis of this entire effort.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m_2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (1)
1 pint (pt) = 0.47 liter (1)
1 quart (qt) = 0.96 liter (1)
1 gallon (gal) = 3.8 liters (1)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yeards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (1) = 1.06 quarts (qt)
1 liter (1) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0	1	2	3	4	5	6	7	8	9	10

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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EXECUTIVE SUMMARY

High speed fixed guideway transportation systems such as magnetic levitation systems present new concerns for passenger comfort particularly with regard to vertical and lateral motions. If existing highway right of ways are to be used to the fullest extent possible the ride comfort concerns translate into economic concerns since an important constraint on track placement will be whether a high speed vehicle traveling along the proposed guideway will subject passengers to forces in excess of what most people will tolerate.

The ride motions addressed in this study are relatively long duration, vertical accelerations imposed on passengers during vehicle climbing and descending as well as rolling and banking motions imposed by a vehicle traversing a curved section of guideway. Other possible determinants of comfort, such as high frequency vibration, noise or temperature were at levels sufficiently low as to be unlikely to influence comfort ratings.

The ride motions of a maglev system were simulated by performing specific vertical and roll maneuvers in a small executive jet aircraft (Cessna Citation). After each maneuver the passenger subjects (4 per flight, 10 flights) recorded a comfort rating on a 7-point scale from very comfortable to very uncomfortable. The vertical accelerations of the jet were measured with an accelerometer and recorded in a computer data file.

In addition to analyzing the subject responses on the original 7-point comfort scale an attempt was made to relate these comfort ratings to an estimate of the percent of passengers that would use the system. This was accomplished by using the results of a study (Richards and Jacobson, 1977) which examined the relationship between passengers' ride comfort ratings and the likelihood that they would ride again.

The results showed that passenger discomfort increased with bank angle and roll rate in the case of roll maneuvers and with the magnitude of the vertical g forces in the case of vertical maneuvers. Based on the assumed relationship between ride comfort ratings and willingness to ride again, it is estimated that fewer than 5 percent of the passengers would "hesitate to ride again" if bank angle were less than 37 degrees and roll rate were less than 7 degrees per second for roll maneuvers; and if vertical accelerations were of magnitudes less than .30 g for positive accelerations (into the seat) and magnitudes less than .20 g for negative accelerations (out of the seat) (1 g is approximately 1^2 equal to 9.8 m/sec^2).

The data were also used to estimate the percentage of passengers who would not hesitate to ride with roll rates up to 15 degrees per second, bank angles up to 40 degrees, and vertical accelerations up to .25 g.

Roll rate is of particular interest because it dictates the length of the transition spirals between tangent and curved sections of the guideway. In this study, roll rates of 11 degrees per second resulted in estimates that no more than 8 percent of our subjects would hesitate to ride again, roll rates of 15 degrees per second resulted in estimates that no more than 10 percent would hesitate to ride again if banks were restricted to less than 37 degrees.

While these results suggest useful guidelines for design considerations, they are based on ratings for individual maneuvers. Further study is planned to determine the cumulative effects, if any, of presenting the sequence of forces likely to be present in a complete trip on a maglev system.

1.0 INTRODUCTION

Both the costs and the ridership of proposed maglev systems will be strongly impacted by the level of ride quality provided to the passenger. In determining ride specifications for any fixed guideway system, the two major factors which must be considered are: the minimum level of ride quality which will be acceptable to the great majority of the passengers, and the construction and maintenance costs which will be required to achieve and maintain this minimum level.

1.1 COSTS

The costs associated with guideway structure will be influenced by ride smoothness requirements as well as the maximum vertical accelerations the passengers will accept when traversing vertical obstacles.

The costs associated with right-of-way acquisition will be impacted by the minimum curve radii and lengths of transition segments, which are functions of the maximum accelerations, bank angles, and roll rates the passengers will accept.

1.2 RIDERSHIP

Ridership will be affected by the trip duration and the number of intermediate station stops. Trip duration is also influenced by the maximum acceptable acceleration, and the maximum rate of change of acceleration (jerk).

Ridership will also be impacted by the proportion of the passengers who find the ride acceptable. Ride acceptance is not simply a function of perceived comfort but in large part a function of the extent to which the ride interferes with passenger activities such as reading, sleeping, writing or moving through the car.

2.0 BACKGROUND

2.1 SPECIFYING RIDE QUALITY

One method of specifying the ride quality of a system is called *as-good-as*. Here we ensure that the ride of a new vehicle is no worse than an existing vehicle in the same service. This methodology is not appropriate when developing specifications for an entirely new system. As an example, limiting the ride movements and accelerations of proposed maglev systems to those found in today's rail system will incur significant performance limitations which may be unnecessary.

Estimates of the acceptability, to the passenger, of the ride should be based on the physical characteristics of the ride:

- Linear accelerations, rotational rates, and possibly rates of change of these motions.
- Acoustic noise.
- Temperature and humidity.
- Potential interference with passengers activities.

2.2 VIBRATION - COMFORT

Information on the effects of vibration in the 1 to 20 Hz range, (such as that produced in transportation vehicles) on human comfort is available through the International Organization for Standardization's *Guide for Evaluation of Human Exposure to Whole Body Vibrations* (ISO-2631).

2.3 VIBRATION - ACCEPTABILITY

Methodology for the evaluation of the acceptability to passengers of ride motions in the same frequency ranges is provided by Pepler, Vallerie, Jacobson, Barber, Richards (1978). This methodology provides comfort and acceptability models which not only use linear and rotational vibrations but also use factors such as temperature and acoustic noise level. Guidance is provided by Sussman and Wormley (1982) on the application of the Pepler and ISO models to new transportation systems. Guidance to the impact on system cost of ride quality specifications may be found in Wormley, Hedrick, Eglitis and Costanza (1977).

It should be noted the motion parameters described in ISO 2631 are not appropriate for evaluating most sustained or low-frequency accelerations. The exception is long duration vertical movements in the 0.1 to 0.5 Hz range which are associated with motion sickness. No useful ride comfort or acceptability data exists for sustained acceleration of the type which might be encountered in a magnetically levitated vehicle negotiating a curve or traversing a vertical obstacle. Short of *as-good-as* data which will limit the performance of the system to that of steel-wheel-on-steel-rail, there exists no usable data by which we could systematically relate passenger acceptance to critical system-performance parameters such as the maximum acceptable sustained or transitional acceleration in a maglev system.

The motion parameters which are potentially critical are:

- Positive and negative g in the vertical direction.
- Roll rate.
- Longitudinal and lateral g.
- Rate of change of acceleration (jerk).
- Rate of change of roll rate.

2.4 VERTICAL g ASSOCIATED WITH CHANGES IN ELEVATION

In order to minimize construction costs associated with changes in elevation where the guideway crosses over obstacles, it will be necessary to determine the maximum positive and negative vertical g forces acceptable to the majority of potential passengers. These forces will dictate the minimum distance over which the elevation of the guideway may change and the speed at which the maglev vehicle may traverse the change in elevation.

2.5 VERTICAL g AND ROLL RATE ASSOCIATED WITH TRAVERSING CURVES

Entering, traversing, and exiting curved guideway segments at high speed will result in passengers experiencing increased vertical g forces and roll motions. Passenger acceptance of these forces dictates the minimum radius curves to be used and the maximum speeds through these curves. The maximum roll rate passengers will accept will dictate the minimum spiral lengths, and the maximum speeds that can be used to negotiate the curves and spirals. The length of the spiral is a very important consideration in fitting a guideway to an existing right of way.

The impact of the movements required to traverse an obstacle and the movements required to negotiate a properly super-elevated curve can be simulated in an aircraft flying an appropriately configured course.

The maglev vehicle will change speed for various reasons, e.g., to traverse obstacles, curves, and stops at intermediate stations. The trip time and the number of intermediate stops will be affected by the maximum longitudinal acceleration, maximum duration of acceleration, and the maximum rate of change of acceleration acceptable to the passengers. Maglev vehicles will be capable of far higher accelerations and rates of changes of acceleration than are rail vehicles. The maximum acceptable levels of such longitudinal accelerations and changes in acceleration might be simulated using a road vehicle on a fixed course.

The effects of traversing super-elevated curves at the appropriate design speed can be simulated in an aircraft flying a coordinated turn.

Studies of the impact of traversing super-elevated curves at speeds significantly above or below the design speed are problematic and could not be accomplished in this study. The effects of unbalanced lateral forces occurring when traversing a curve are not easily simulated. The simple effects of lateral acceleration might be studied in a land vehicle. The combined effects of traversing the curve and the unresolved g might possibly be observed in existing high speed rail systems.

The present study focused on sustained vertical accelerations, and roll maneuvers, which led to the use of a small passenger aircraft to provide the required motions and forces.

The focus of this study was ride comfort for seated passengers. No testing was done with standing passengers. Therefore, all conclusions are intended to apply to systems where passengers spend most of the time seated.

3.0 METHOD

3.1 EQUIPMENT

The ride motions were simulated in a Cessna Citation I jet aircraft. This executive-type jet aircraft was chosen because: its propulsion system provided less vibration than a propeller-driven aircraft; its straight-wing design provided more stability during maneuvers than a swept-wing design; and its small size and rental cost permitted the relatively large number of flights required to meet the statistical design requirements of the study.

The aircraft had four passenger seats facing forward as well as a rear-facing seat for the experimenter just behind the pilots. The seats were as comfortable but not quite as large as first-class seating in an airliner. Figures 1 and 2 illustrate the exterior and interior of the aircraft.

The original intent was to derive all physical measurements from the Wyle Laboratories Ride Quality Meter. However, early tests indicated it was not capable of measuring long duration (1 to 20 second) bank angles and roll rates.

The Wyle instrument uses three linear accelerometers oriented in the x, y and z directions with respect to the vehicle's axis, two angular accelerometers oriented for roll and pitch and a computer programmed to calculate the ride quality index developed by the University of Virginia and NASA, Langley (Pepler et al.) equations. The instrument provided calculated values of the ride quality index (RQI), the contribution of each of the types of motion to the RQI and direct-coupled, unfiltered outputs from each the accelerometers.

The outputs from each of the five accelerometers and the calculated values were captured by a laptop computer using Labtech Technology's Notebook data-acquisition software in conjunction with a suitable analog input card and the serial port. The data acquisition software was configured to calculate roll rate from roll acceleration by integration and display outputs graphically in real time as well as record them on disk, but there was considerable drift in the direct current (DC) outputs of the angular accelerometers. This drift had no effect on the RQI since appropriate filters are included to remove it. However, it rendered the accelerometers useless for the purpose of measuring roll rates with periods on the order of 10 seconds. Accordingly, a gyro-stabilized device was acquired to measure roll rates, as described below.

The Wyle instrument was used to determine the RQI value for the aircraft during an early test flight. Even in the most extreme maneuvers (45-degree banks), at the test altitude of 3048 to 4572 meters (10,000 to 15,000 feet) the RQI never rose above 0.4 (very comfortable) on a scale of 0 to 6. Most maneuvers measured below 0.2. These low values occur because there were no significant vibrations, roll or pitch motions above 1 Hz when the maneuvers were flown at the test altitude and because the acoustic noise level input was not connected. The acoustic input was not used because all subjects wore sound isolating headphones which reduced the perceived noise level below 65 dB (A-weighted), the minimum value considered by the RQI equations. Values as high as 2.5 were recorded during the descent as the aircraft encountered thermal

FIGURE 1. EXTERIOR VIEW OF THE CESSNA CITATION I AIRCRAFT

FIGURE 2. INTERIOR VIEW OF THE TEST AIRCRAFT

turbulence at 350 meters. Use of the Wyle Ride Quality Meter established that the aircraft ride motions at 1 Hz or above would not contribute significantly to passenger discomfort in smooth air.

For the remainder of the pre-test and data-collection flights, only two transducers were used: a linear accelerometer oriented to measure vertical g forces (Setra Systems model 141A), and a rate gyro (Collins model 345A-4B). The outputs of these devices were captured, displayed graphically, and recorded with the same computer, I/O card and software described above. Figure 3 shows the transducers and their associated power supplies, amplifiers and computer interface installed in the luggage compartment at the rear of the aircraft's cabin. In Figure 4, the data collector, Carol Preusser, is shown with data acquisition computer on her lap and the remaining equipment in the bag beside her seat.

Calibration of these transducers was verified as follows: For the linear accelerometer, a voltage corresponding to 1.00 g is expected when the device is at rest in its normal orientation. Turning it upside down should yield -1.00 g, while turning it on any side yields 0.00 g. The Setra device in combination with its associated amplifiers and offset compensation met these criteria to a tolerance of about +/- 0.02 g.

The Collins gyro was a standard aviation instrument. Due to time constraints on the study, only static testing using an improvised jig and integration of the transducer output to tilt angle were possible. This testing showed that the gyro could measure bank angles up to +/- 70 degrees with tolerance of about +/- 10 percent of the reading. However, it was determined subsequently that the output of the gyro was not linear for roll rates greater than about 7 degrees per second. Because early testing revealed that the effects of much higher roll rates would have to be evaluated, roll and bank data were derived from the linear transducer. This was possible because the turns in the aircraft are by nature "fully coordinated," that is, all forces are fully compensated or resolved.

In addition to the basic function of measuring and recording data regarding the physical motion of the aircraft, equipment was required to perform two other functions: provision of feedback to the pilot that the desired g forces were being attained, and cuing the pilot and subjects. The pilot feed back was supplied by attaching a remote meter to the vertical accelerometer's output.

To cue the pilot and subjects, a script for each maneuver was prepared such as that shown in Appendix A. Sequences of 36 maneuvers were combined as described in the "Procedures" section below into notebooks. Five different notebooks were used. From the notebook for each sequence and with the aid of a stop watch, a 2-channel audio tape was prepared with the cues for the pilot on one channel and those for the subjects on the other. A digital recorder was used because of the much more precise cuing controls and much more informative displays characteristic of this technology.

An audio interface module was custom built to route the pilot cues to the pilot's earbud and to one earphone in the experimenter's headset. The subject cues were fed to the other earphone of the experimenter's headset and to the standard aircraft intercom system (PS Engineering's

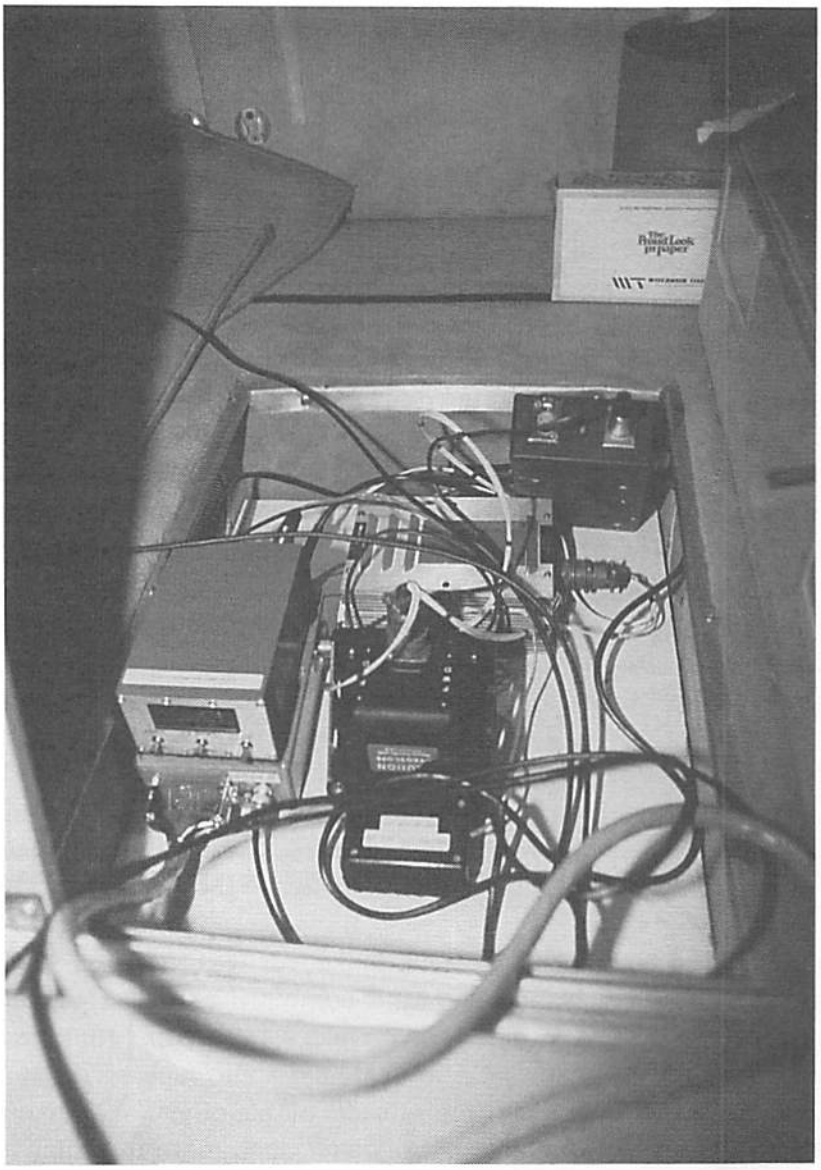


FIGURE 3. ACCELEROMETER, RATE GYRO AND ANCILLARY COMPONENTS INSTALLED IN THE LUGGAGE COMPARTMENT

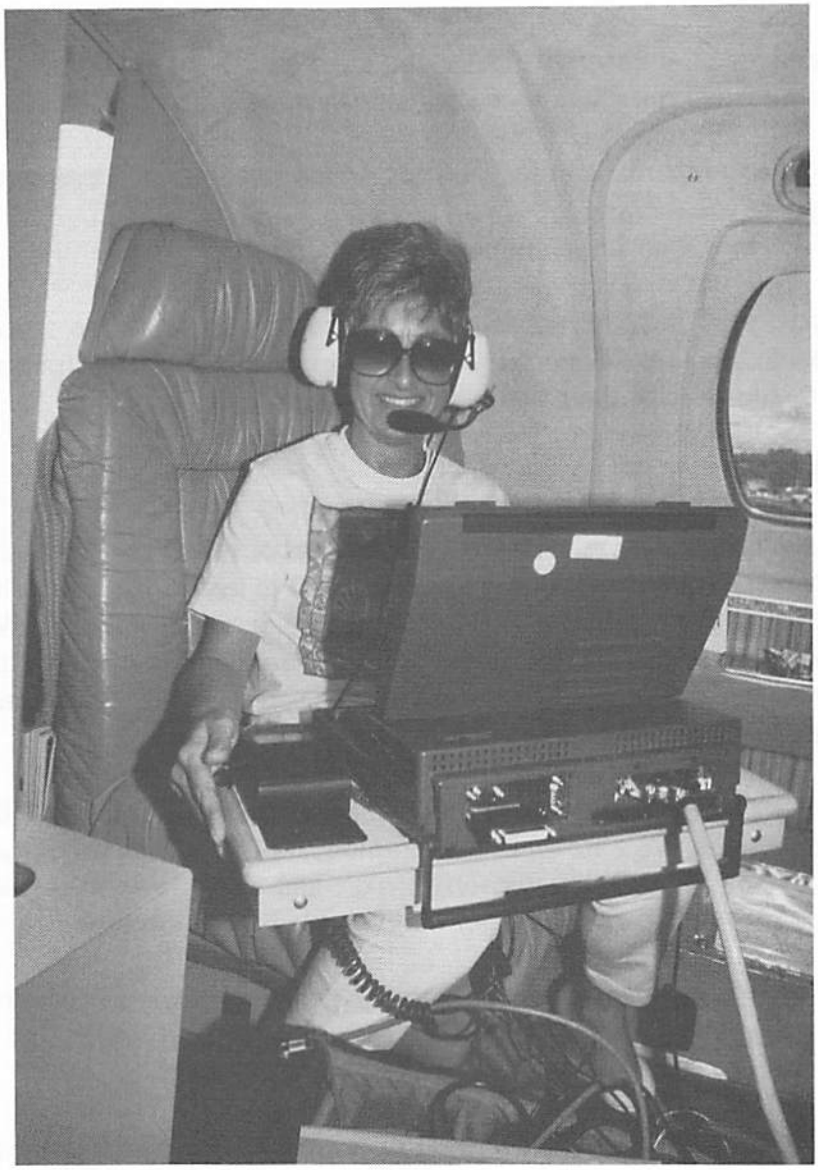


FIGURE 4. CAROL PREUSSER WITH DATA ACQUISITION COMPUTER AND DATA RECORDER

Aerocom II) by means of which the subjects were able to hear their cues and converse with one another and the experimenter. The subjects wore Peltor Type 7004 headsets which provided 26 dB noise attenuation as well as individual control of listening level.

3.2 SUBJECTS

Forty subjects were used in the study. The subject passengers were recruited by Preusser Research from residents of southern New Hampshire. The criteria used resulted in population with the following characteristics:

1. Roughly equal numbers of males and females.
2. Roughly equal distribution of ages among three groups: 18-30, 31-50, 51-65 years old.
3. All subjects had made at least 6 trips on aircraft, two of these occurring in the last year.
4. Two subjects with limited mobility.

These criteria were used in an effort to obtain a sample that would be representative of the population of people who would be likely to use a magnetic levitation transportation system. All subjects were paid $75 for their participation.

3.3 PROCEDURE

The purpose of the current study was to assess the effects of relatively long-duration maneuvers on comfort and passenger acceptability. It was important to assure that ride vibration and noise did not impact comfort and acceptance. Based on the outputs of the Wyle Ride Quality Meter, the levels of vibration that occurred during the flights were quite low and would be considered better than "very comfortable" based on the RQI. The level of acoustic noise in the aircraft was not a factor because all subjects wore sound-isolating headsets.

The forty subjects were tested in ten flights carrying four subjects each. The flights took place in July 1992. Four flights were flown in the morning, four in the afternoon, and two at night. All flights took off from the Manchester, NH airport and were flown in smooth air in a block of reserved air space about 160 km long by 64 km wide by 1.5 km high.

During each flight, 36 maneuvers were executed: 12 vertical maneuvers, 22 roll/bank maneuvers, and 2 dummy maneuvers (throttle reduction, but no vertical or rotational force generated).

Subjects remained seated throughout each flight since there was no room in the aircraft for them to move about or even stand erect.

The following 7-point scale was used by the subjects to rate the comfort of each maneuver:

1. Very comfortable
2. Comfortable

3. Somewhat comfortable
4. Neutral
5. Somewhat uncomfortable
6. Uncomfortable
7. Very uncomfortable

This scale has been used extensively in NASA, DOT, and university studies of ride quality, and was used in developing the RQI equations. Further data taken with this scale has been used in estimating ride acceptability.

Subsequent to recruitment, subjects were briefed on the purposes of the study, the nature of the maneuvers, and the use of the reporting scale. After each maneuver, each passenger recorded his or her comfort level in a test booklet.

Each maneuver (simulation case) was specified by a vertical acceleration profile or a bank/roll profile. These profiles were varied systematically to parametrically simulate the ride motions. Each profile was chosen to represent a potential alternate specification limit for maneuvers for the maglev vehicle.

Simulation cases were developed to expose subjects to positive and negative accelerations ranging from -.25 to +.25 g relative to the normal 1 g (that is vertical accelerations ranged form 0.75 g to 1.25 g). There were six different vertical maneuvers in each flight. The target values of the g forces for these maneuvers are shown in Table 1.

TABLE 1. TARGET VALUES OF g FORCES FOR VERTICAL MANEUVERS

-.25	-.20	-.15	+.15	+.20	+.25

Simulation cases were also developed to expose subjects to bank angles ranging from 25 to 40 degrees and these bank angles were achieved at roll rates ranging from 3 degrees per second to 15 degrees per second. The duration in each case was determined by the constraint that the total heading change for the entire maneuver be 45 degrees. The values (bank angle/roll rate) found in Table 2 were used in the study, but the full set of target values was not used in every flight. Instead, some subset consisting of 11 of these was used with each of the 11 occurring twice in the course of the flight. The earlier flights used the less severe maneuvers (such as 25/3), while in later flights these were replaced by more severe maneuvers (e.g., 40/15). This was done because the preliminary results indicated that almost all passengers rated the very mild maneuvers as very comfortable.

TABLE 2. BANK ANGLE, EQUIVALENT VERTICAL ACCELERATIONS, AND ROLL RATES

Bank Angle in Degrees	Equivalent Acceleration in g	Roll Rate in Degrees per Second				
		3	5	7	11	15
25	.10	X	X	X	X	
30	.15	X	X	X	X	
35	.22	X	X	X	X	X
40	.31		X	X	X	X

Not all combinations of bank angle and roll rate were possible. It was impractical to test the highest bank angles at the lowest roll rates because of the period of time required to attain and recover from the bank (and still end up with a heading change of 45 degrees). Moreover, these cases did not appear to be practical for a maglev system. The pilots could not execute accurately the two smallest bank angles (25 degrees and 30 degrees) at the highest roll rate (15 degrees per second) and the largest bank angle 40 degrees would have required an extreme change in the heading of the aircraft at the lowest roll rate (3 degrees per second).

The pilots of the aircraft attempted to follow each profile as closely as possible. The vertical accelerations, whether caused by coordinated turns or by climbing or descending, were measured accurately by the vertical accelerometer. Thus, this aspect of the maneuver was known without requiring that the pilot execute the maneuver with complete accuracy. However, in the case of roll rates, deficiencies in the roll gyro rendered the data collected invalid for rates higher than 7 degrees per second. Hence, these roll rates had to be derived from the vertical acceleration data.

The sequences of maneuvers were constructed to:

1. Avoid presenting a group of very similar maneuvers in succession.
2. Ensure that severe maneuvers did not consistently follow or precede very mild maneuvers.
3. Ensure that each maneuver used in the flight occurred in both the first half and the second half of the flight.

Reverse sequences were used to help achieve counterbalancing. That is, every sequence used in the study was used in reverse order as well as the original order.

4.0 ANALYSIS AND RESULTS

In the physical data, each maneuver was represented by 450 readings from the vertical accelerometer (45 seconds times 10 Hz sampling rate). To reduce these for analyses, the data corresponding to a maneuver were first smoothed using a 4-second moving average. Then the maximum absolute value of the positive and the negative smoothed vertical g's were recorded for each maneuver. These maxima were then used to assign the maneuver to one of the vertical group ranges shown in Table 3.

TABLE 3. RANGES FOR VERTICAL g CATEGORIES

Range	
From	To
lowest	-.25
-.24	-.20
-.19	-.15
-.14	0
0	.14
.15	.19
.20	.24
.25	highest

4.1 VERTICAL MANEUVERS

Figure 5 shows the mean rating given to the vertical maneuvers in each of the eight vertical g ranges. The number of responses contributing to each mean is also shown in the figure. As expected, in all cases the greater magnitude g ranges are associated with less comfortable (higher) mean ratings. Also, in all cases the negative g conditions receive less comfortable ratings than positive g conditions of the same magnitude.

Another method of understanding the data is to consider the number of responses which were equal to or greater than a given threshold. Figure 6 shows the percent of responses worse than "somewhat comfortable" (i.e., above rating 3) for each of the eight vertical g ranges. The qualitative shape of this graph is similar to that of Figure 5. Again there is a monotonic relationship between the magnitude of the g's (i.e., the vertical g group) and the height of the bars. Also, the negative g conditions are always rated worse than the positive g conditions of the same magnitudes.

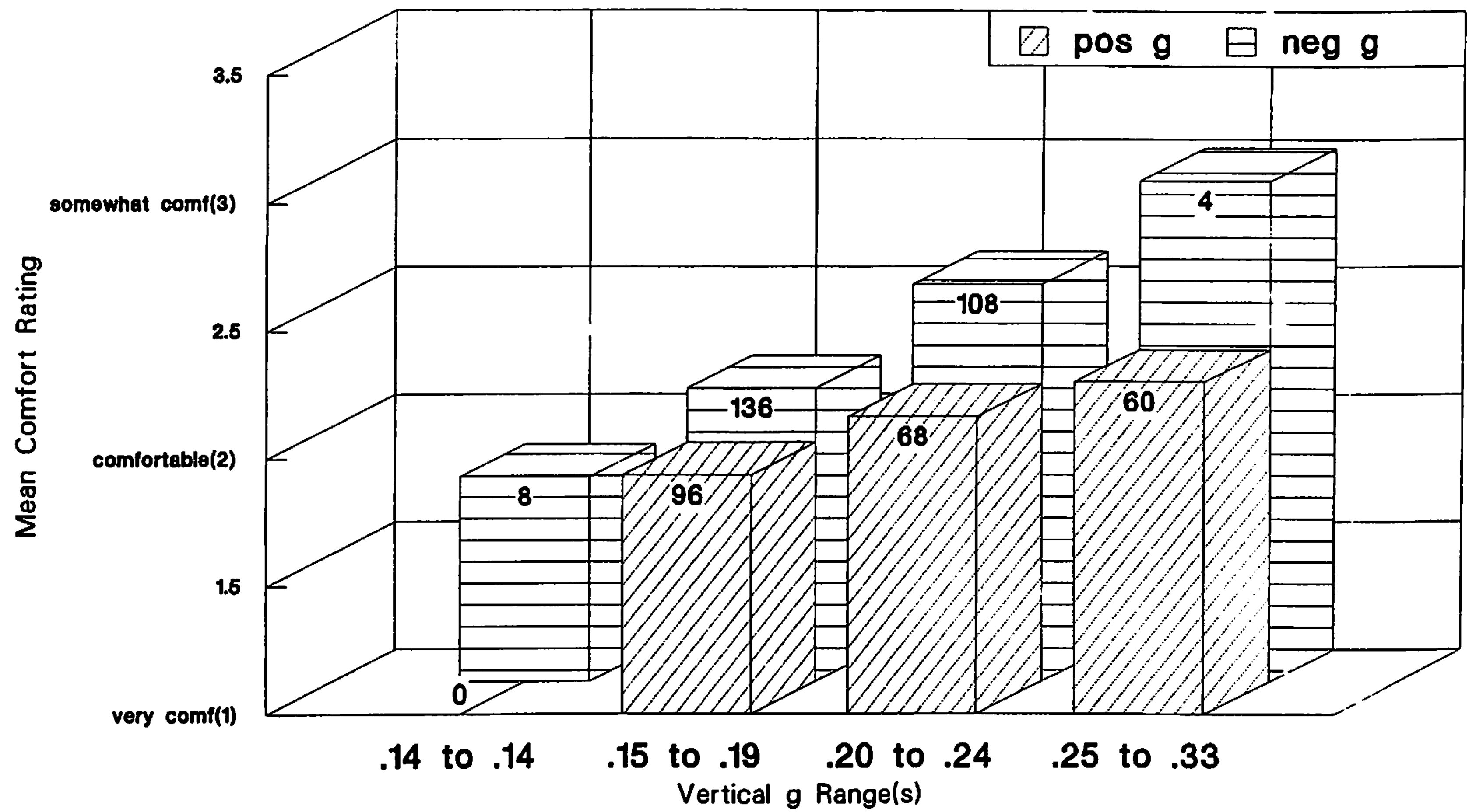


FIGURE 5. VERTICAL MANEUVERS MEAN COMFORT RATING BY POSITIVE AND NEGATIVE VERTICAL g

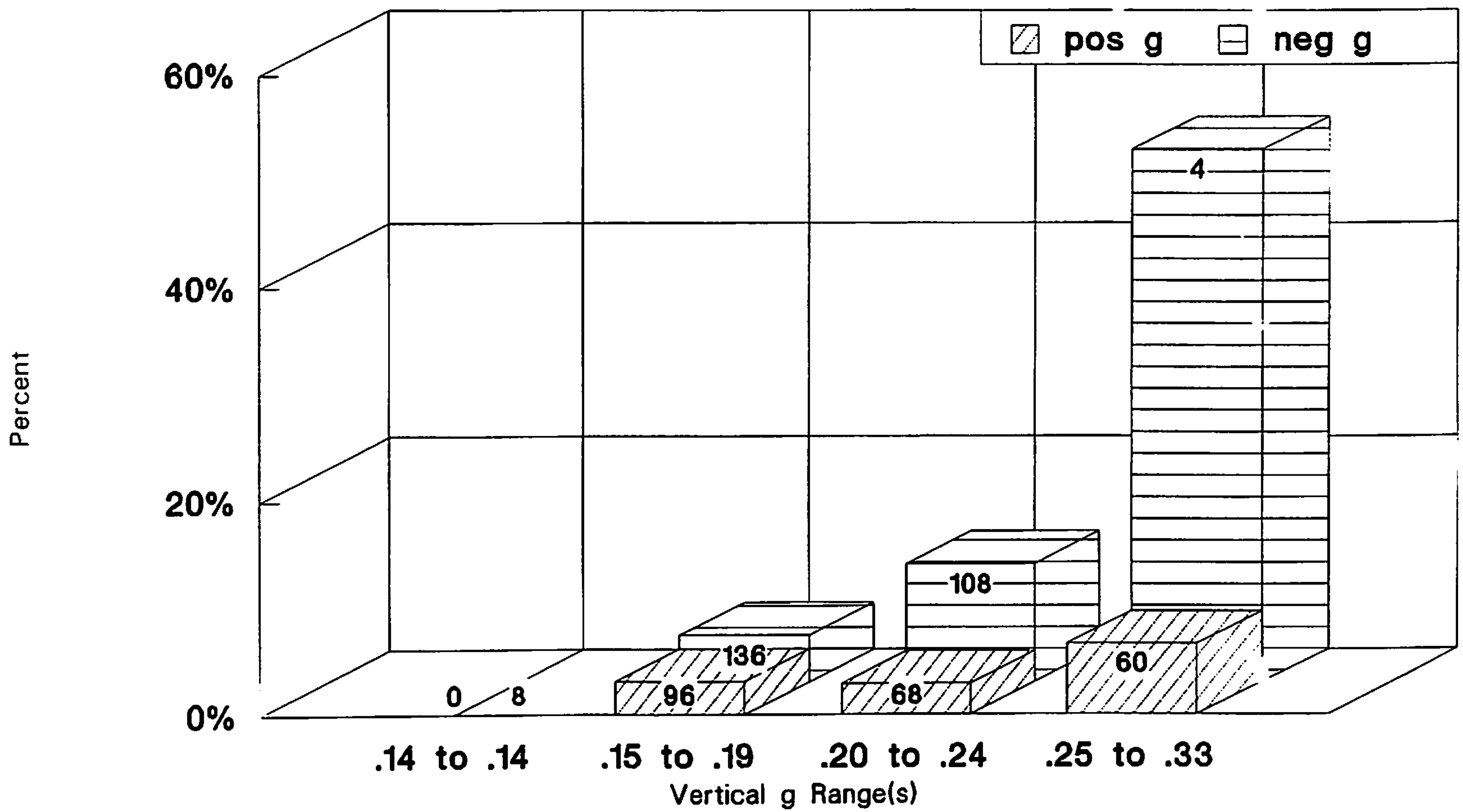


FIGURE 6. VERTICAL MANEUVERS PERCENT WORSE THAN "SOMEWHAT COMFORTABLE" (3) BY POSITIVE AND NEGATIVE VERTICAL g

4.2 ROLL MANEUVERS

The roll maneuvers were analyzed in a similar fashion. Figure 7 shows the mean rating given to each combination of roll rate and bank angle which was used in the study. There were 5 roll rates and 4 bank angle groups, but data were not collected for all 20 combinations of roll rates and bank angles appearing in the figure. Mean ratings increased (or comfort decreased) with increased roll rate and with increased bank angle. The same pattern is seen in Figure 8 where the "percent worse than 'somewhat comfortable'" is graphed instead of the mean rating.

4.3 ESTIMATION OF THE EFFECT OF VERTICAL g's AND ROLL RATES ON ACCEPTABILITY (WILLINGNESS TO RIDE)

The work of Richards and Jacobson (1977) provide a method for estimating ride acceptability. These authors related passenger comfort ratings for scheduled airline flights to the percent of passengers satisfied with the flight. The comfort rating was assessed just prior to landing with the following questionnaire item:

Please indicate your overall reaction to this flight:

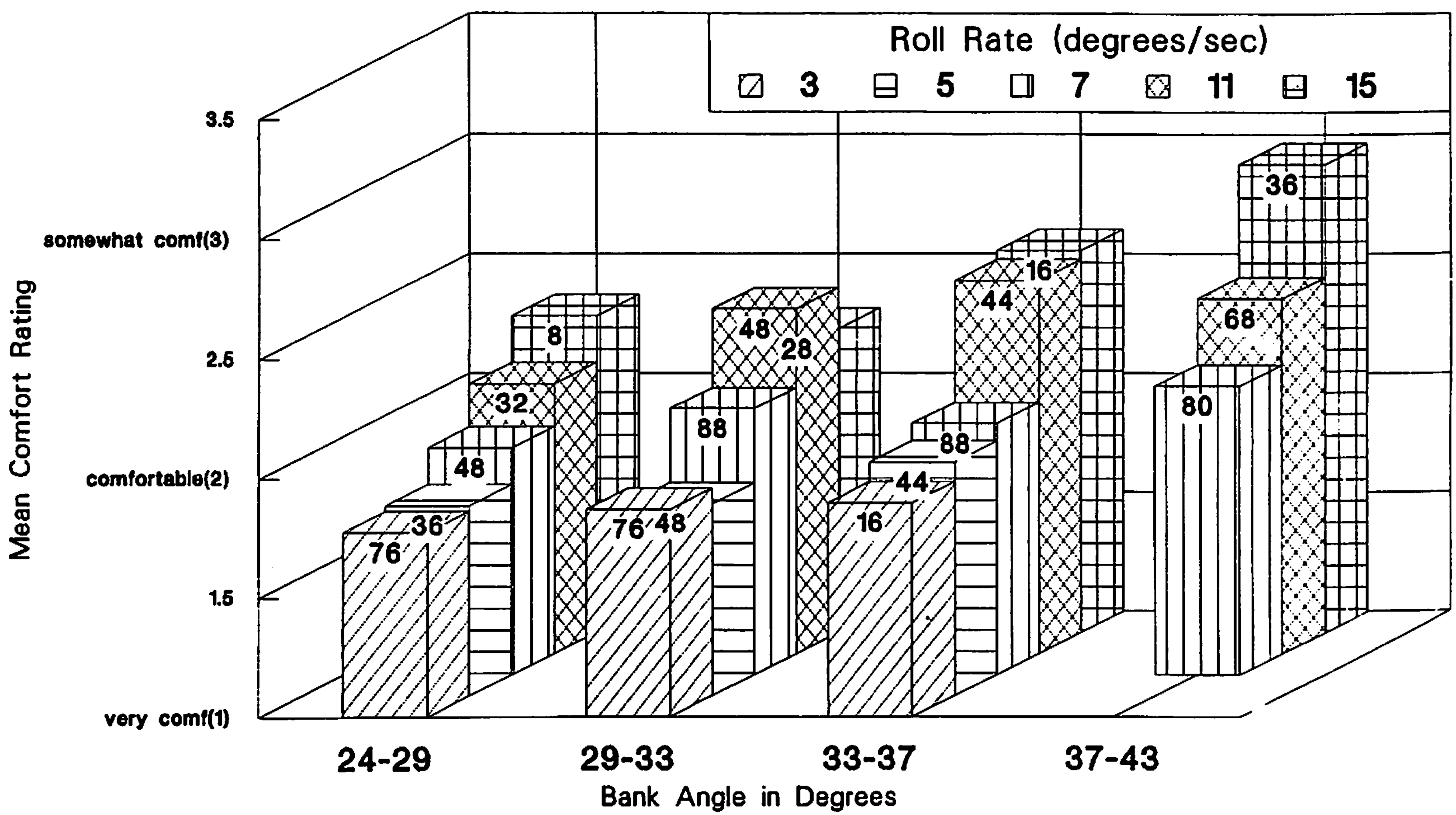
1. Very comfortable
2. Comfortable
3. Somewhat comfortable
4. Neutral
5. Somewhat uncomfortable
6. Uncomfortable
7. Very uncomfortable

This item provides the same 7-point scale used in the current study to rate <u>each maneuver</u>. Also, Richards and Jacobson assessed the passengers' satisfaction with the following item:

After experiencing this flight, I would:

- Be eager to take another flight.
- Take another flight without any hesitation.
- Take another flight, but with some hesitation.
- Prefer not to take another flight.
- Not take another flight.

For the purpose of estimating the relationship between comfort rating and satisfaction, a passenger was considered satisfied if his or her response to the above item was either the first or second response level. Thus, a passenger is considered ***dissatisfied*** if his or her response indicates hesitancy to take another flight (or worse). For each of the seven comfort levels, the percentage of respondents who were satisfied with the flight was computed and the data were plotted. Examination of the Richards and Jacobson plot results in the transformation shown in Table 4.



Bank angle inferred from vertical g forces

FIGURE 7. BANK/ROLL MANEUVERS MEAN COMFORT RATING BY ROLL RATE AND BANK ANGLE

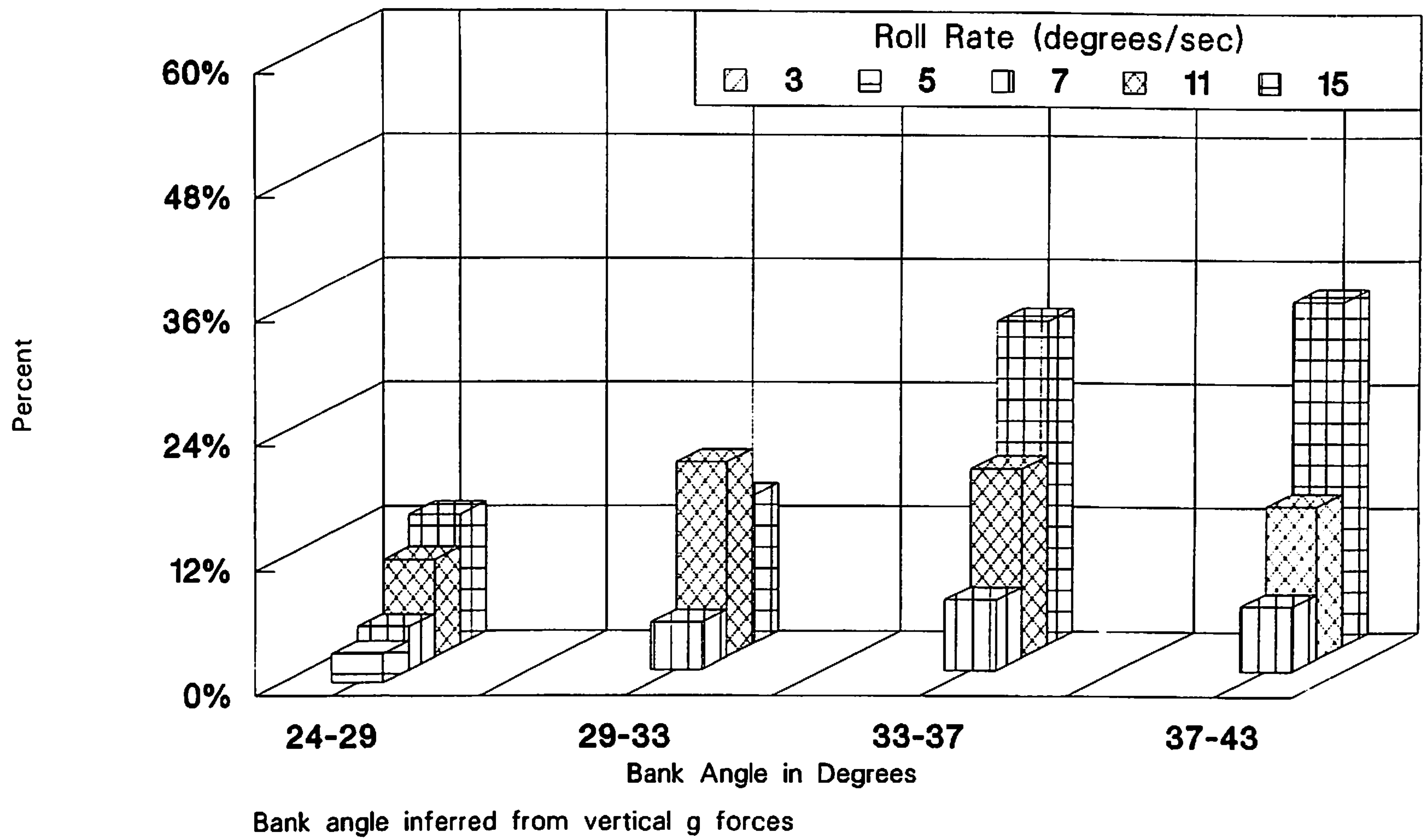


FIGURE 8. BANK/ROLL MANEUVERS PERCENT WORSE THAN "SOMEWHAT COMFORTABLE" (3) BY ROLL RATE AND BANK ANGLE

TABLE 4. RELATIONSHIP BETWEEN PASSENGER RATING AND PROBABILITY OF SATISFACTION

Rating	1	2	3	4	5	6	7
Transformed Value	1.0	.98	.92	.81	.66	.47	.23

Each rating by each subject was thus transformed into an inferred probability of satisfaction according to the Richards and Jacobson transformation. The mean value of this transformed rating or "percent satisfied" index was then calculated over groups of subjects evaluating similar maneuvers. The results are shown in Figure 9 which is similar to Figure 5 except that instead of mean ratings the plot shows the estimated percent dissatisfied. Figure 9 shows the estimated percent dissatisfied as a function of vertical g condition for the vertical maneuvers. Again, the negative g conditions appear to be worse than the positive g conditions. Also, the larger g's (in magnitude) received worse scores than the smaller g's. It appears that negative vertical g's with magnitudes below .25 would not be unsatisfactory to more than a small percentage of potential passengers. Based on the scaling of the Richards Jacobson curves, at least 90 percent of the public would accept the ride motions. For positive vertical g the acceptance appears to be considerably higher. Even values in the range .25 to .33 g appear to be acceptable to the great majority of passengers. Based on the scaling of the Richards Jacobson curves, at least 95 percent of the public would accept these ride motions.

Figure 10 shows the estimated percentage dissatisfied as a function of the roll rate and bank angle group (vertical g was used to estimate bank). The pattern of results is similar to the pattern found for "mean comfort rating" and for "percent above three." In particular, the roll rates and the bank angle both appear to be influential. In conditions involving 15 degree per second roll rates and the highest two bank angle categories, the estimated percentage dissatisfied exceeded 8 percent.

Examination of these graphs reveals that passengers experience a substantially higher level of dissatisfaction for a given level of vertical g force, produced by a banking manuver, when it is accompanied by a relatively high roll rate. Indeed, high roll rates were associated with the least comfortable ratings of all of the maneuvers used in this experiment.

It appears that no bank angles up to the maximum tested (43 degrees) in combination with roll rates less than or equal to 7 degrees per second would be unsatisfactory to the majority of potential passengers. Based on the scaling of the Richards-Jacobson curves, at least 95 percent of the public would accept the ride motions. (For comparison, the standard roll rate for airliners on autopilot is 5 degrees per second.) However, for roll rates greater than 7 degrees per second, the level of passenger acceptance appears to fall off, particularly at high bank angles. With roll rates of 15 degrees per second at the higher bank angles, dissatisfaction may exceed 10 percent.

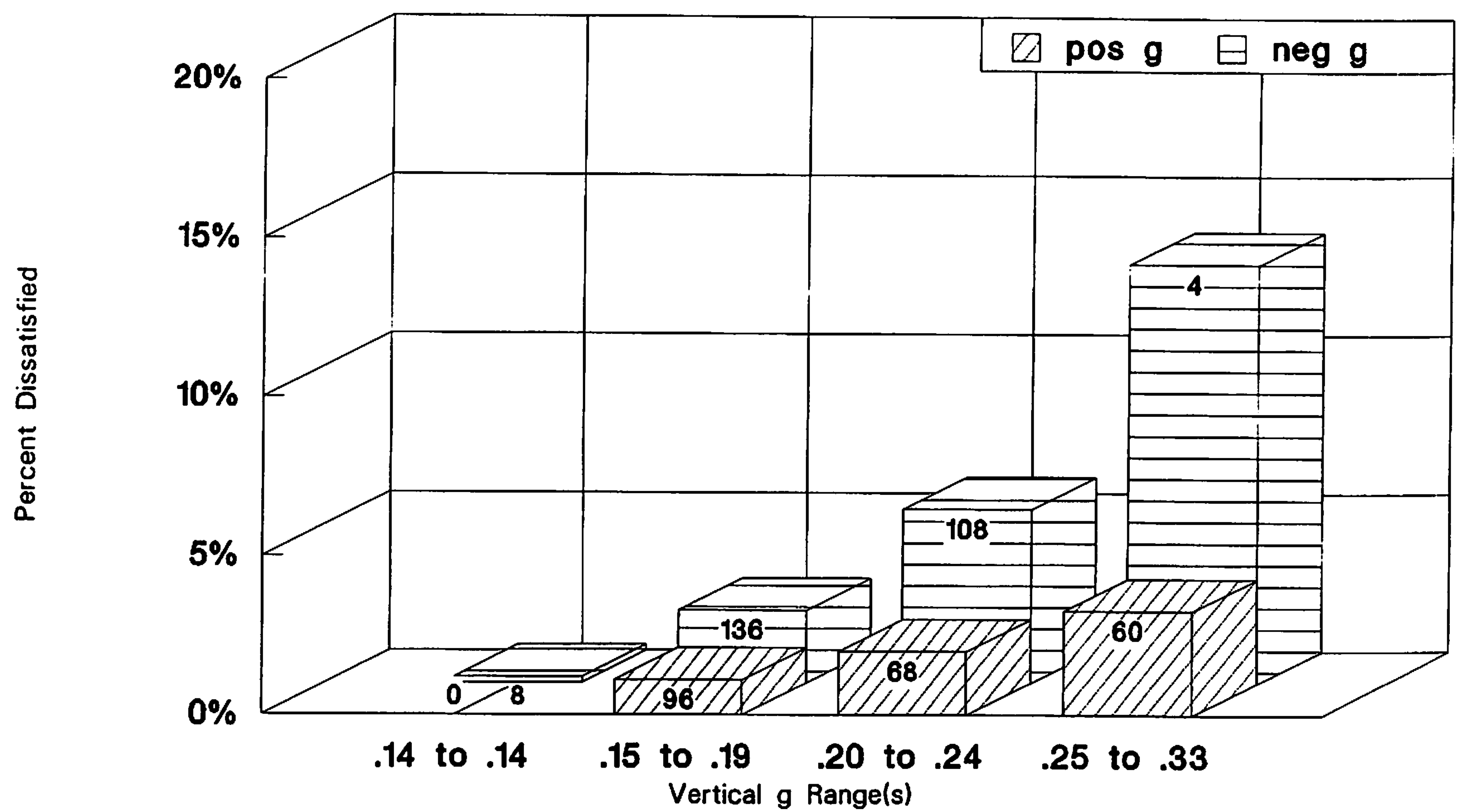


FIGURE 9. VERTICAL MANEUVERS ESTIMATED PERCENT DISSATISFIED BY POSITIVE AND NEGATIVE VERTICAL g

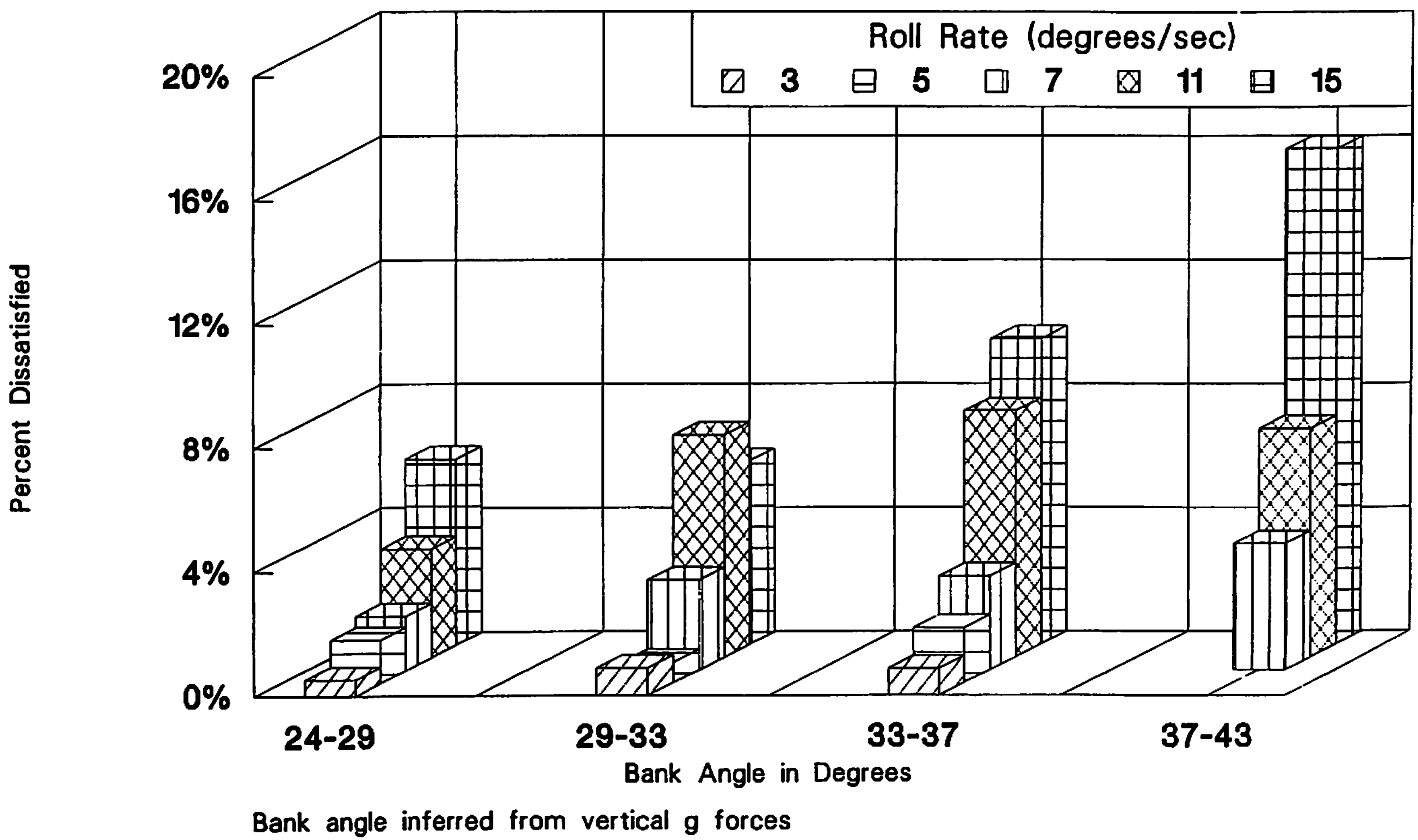


FIGURE 10. BANK/ROLL MANEUVERS ESTIMATED PERCENT DISSATISFIED BY ROLL RATE AND BANK ANGLE

Figure 11 depicts the effect of roll rate collapsed across all bank angles studied. If a conservative roll rate restriction is required (not more than 5 percent of passengers dissatisfied) interpolation suggests a ceiling of 9 degrees per second. Using this limit with bank angles greater than 33 degrees would presumably result in an increase in the proportion of passengers dissatisfied.

Further evidence suggesting a roll rate limit of 9 degrees per second appears in Figure 12. This plot shows roll rate and bank angle combinations that are predicted to lead to 2, 3, 5, and 10 percent dissatisfaction levels. The curves were created by fitting a regression using bank angle, roll rate and the interaction between bank angle and roll rate to predict the probability of dissatisfaction as measured by the Richards and Jacobson transformed scores. The resulting regression equation was then used with the four fixed dissatisfaction levels to form four functions relating roll rate to bank angle. The four functions are plotted in Figure 12. This plot suggests that to limit the ride dissatisfaction to the 5 percent level, a roll rate of 9 degrees per second should not be exceeded for 35-degree turns. Other authors have worked with a hypothetical limit for dissatisfied passengers as high as 10 percent (Pepler, Vallerie, Jacobson, Barber, and Richards, 1978).

Schoonover (1976) conducted a similar study using the same 7-point comfort rating scale and the same transformation to the percent satisfaction scale. In that study, the author concluded, "A goal of 95 percent passenger satisfaction implies a maximum roll angle of 20 degrees and a maximum roll rate of 10 degrees per second." While the conclusions are similar to those of the present study with regards to roll rate, they differ with the conclusions concerning bank angle. It should be noted that the ratings were generally higher (less comfortable) in the Schoonover study than in the current study. One possible explanation for the discrepancy concerning acceptable bank angles is that while Schoonover held fixed the duration of the maneuvers (approximately 20 seconds at full bank angle), in the present study the heading change was held fixed so that a 40-degree maneuver was executed in less time than a 25-degree maneuver. Since this is a difference in duration of banking but not a difference in rolling into the final bank angle, it could account for the discrepancy described above. However, it is important to note that many other facets of the experiments were different; for example, the current study was performed in a jet aircraft while the Schoonover study was performed in a propeller aircraft with attendant higher levels of noise and vibration.

As part of the study, we investigated the hypothesis that ride comfort ratings for comparable maneuvers would get worse later in the flight compared to earlier. This hypothesis was motivated by the notion that the cumulative effects of the maneuvers would lead to a reduced tolerance for ride motions. This hypothesis was not substantiated by the data as evidenced by two separate analyses. First, because each maneuver occurred twice in each flight (once in the first half and once in the second half), it was possible to test the hypothesis by comparing the ratings for the first exposure and second exposure to each maneuver. The results showed that the mean ratings were an average of .09 rating points lower for the second maneuver -- that is, the second time a maneuver occurred it was rated as more comfortable. The other result that contradicted the hypothesis involved the ratings to two "dummy maneuvers" (throttle reduction, but no vertical or rotational forces). The first and last maneuver of each flight were dummy maneuvers. The mean rating for the first and last maneuvers were 1.4 and 1.25, respectively. On average, the dummy maneuvers were rated .15 rating points lower (greater comfort) the second time compared to the first.

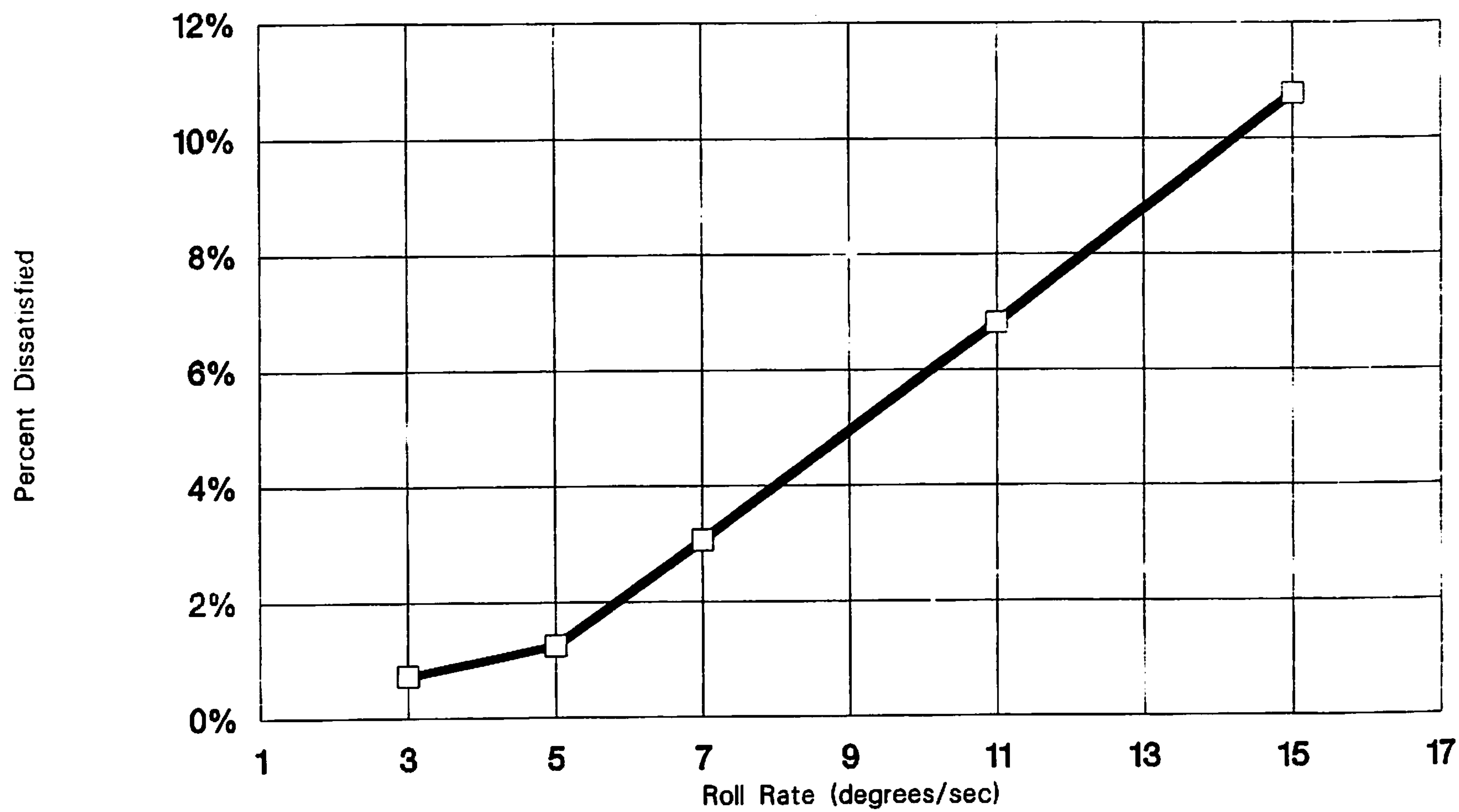
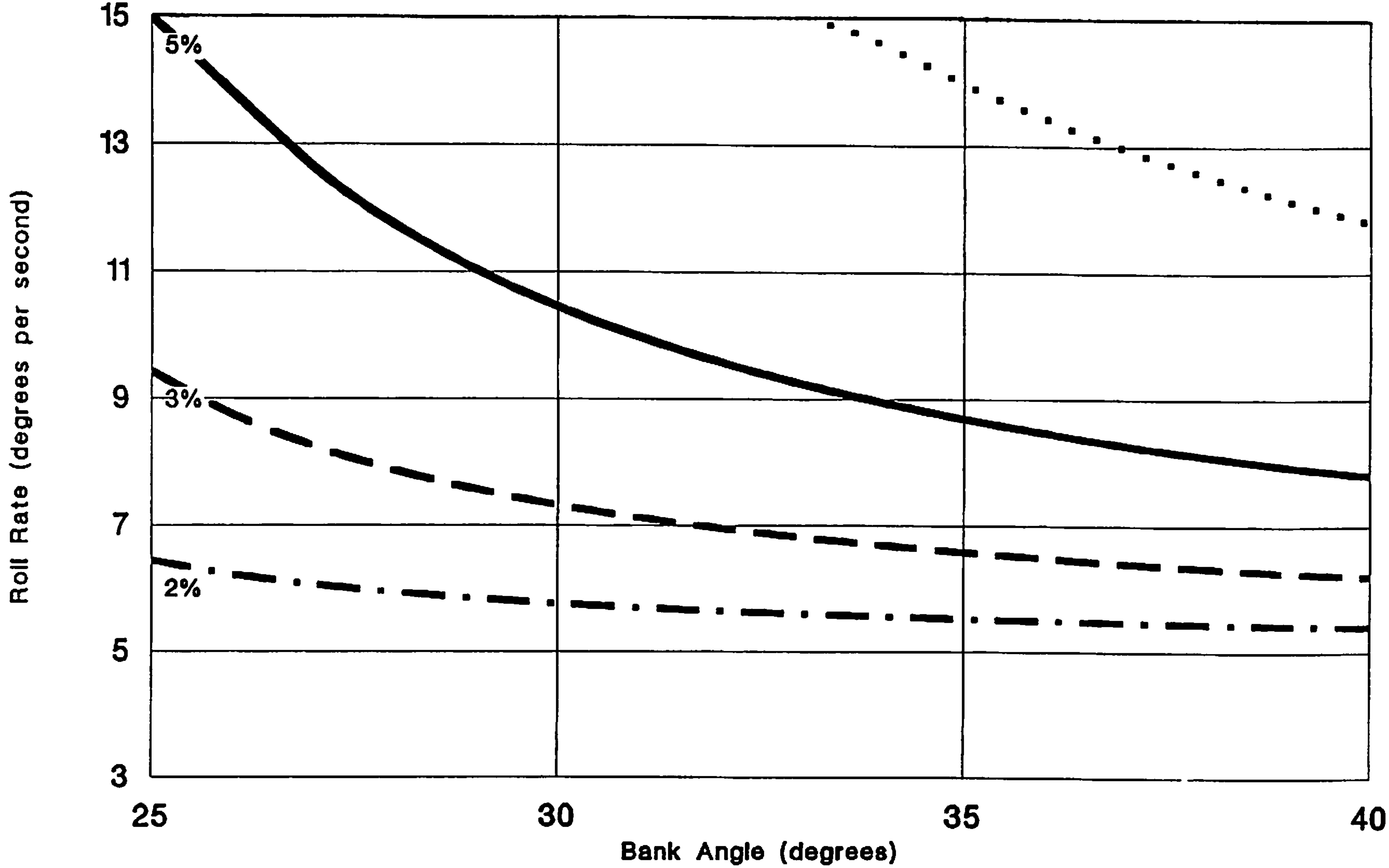


FIGURE 11. BANK/ROLL MANEUVERS ESTIMATED PERCENT DISSATISFIED BY ROLL RATE OVER ALL BANK ANGLES



Note: Curves are shown for 2% 3% 5% and 10% Dissatisfaction levels

FIGURE 12. CONSTANT ACCEPTABILITY CURVES

5.0 CONCLUSIONS

As expected, passenger discomfort increased with bank angle and roll rate in the case of roll maneuvers and it increased with the magnitude of the vertical g force in the case of the positive and negative vertical maneuvers. In transforming these comfort ratings to estimates of the percent of passengers dissatisfied, some conclusions can be drawn.

For roll maneuvers comparable to those used in this study, we estimate that fewer than 5 percent of the passengers would "hesitate to ride again" if the bank angle were less than 37 degrees and the roll rate were less than or equal to 7 degrees per second. While roll rates between 7 and 11 degrees per second were not tested in this study, interpolation suggests that at roll rates of 9 degrees per second approximately 5 percent of the passengers would be dissatisfied with the ride comfort. Furthermore, roll rates of 11 degrees per second or greater, when combined with bank angles of 30 degrees or more, would likely result in unsatisfactory ride comfort for more than 5 percent of the potential passengers.

For vertical maneuvers comparable to those used in this study (i.e., magnitudes less than .30 g), we estimate that fewer than 5 percent of the passengers would "hesitate to ride again" due to positive vertical g forces. However, for negative g forces the situation is different. The negative g forces were reported to be less comfortable than positive g forces of the same magnitude. This occurred in all of the g force ranges studied. Again, using the criterion that fewer than 5 percent of the passengers would be dissatisfied, negative vertical g forces should not have magnitudes in excess of 0.2 g.

Finally, we tested the hypothesis that the comfort ratings would get worse as a function of the length of time that an individual is exposed to ride motions. This hypothesis was not supported; in fact, there was a small but significant effect in the opposite direction. On average similar maneuvers were judged more comfortable during the second half of the flight than the first half.

While the present study investigated the effect of individual maneuvers on ride comfort, another concern is the manner in which a sequence of maneuvers such as would be encountered in a complete trip affects the comfort of the passengers. A study of this issue is planned for the Fall of 1993. The plans call for a complete trip on a high speed magnetically levitated transportation system to be simulated using a methodology similar to the present study. At various points throughout the trip the passengers will be asked to provide ratings of comfort. In addition to providing useful data for establishing the passenger satisfaction for magnetic levitation systems, the study would contribute to understanding the relationship between comfort ratings for single maneuvers and comfort ratings for sequences of maneuvers occurring in a complete trip.

APPENDIX: EXAMPLE SCRIPT FOR ONE MANEUVER

Maneuver: V+.25G

Description: The purpose of this maneuver is to generate a +.25g acceleration lasting five seconds, such as might be encountered by a Maglev descending into a valley and climbing out on the other side.

Pilot's Cue: For maneuver #__, prepare for slow transition to -1200 ft/min, 5-second transition to +1200 ft/min, & slow transition to level flight. Accelerometer should read +25 centi-g for 5 seconds.

Subjects' Cue: Maneuver #__ will start in a few seconds. It is intended to simulate descending into a valley and climbing out on the other side.

Pilot's Cue: 5,4,3,2,1, PITCH OVER

5 (-400 FT/MIN)

10 (-800 FT/MIN)

15 (-1200 FT/MIN)

16,17,18,19, YOKE BACK

21 (-720 FT/MIN)
22 (-240 ")
23 (+240 ")
24 (+720 ")
25 (+1200 "),26,27,28,29

30 (+1200 ")

35 (+800 ")

40 (+400 ")

45 LEVEL FLIGHT

Subjects' Cue: Please mark your rating for maneuver #__ now.

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