NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

June 19, 2003

Human Performance

STUDY REPORT
VERTICAL MOTION SIMULATOR ACTIVITIES
PHASE II EXAMINATION

A. ACCIDENT

Operator: American Airlines (flight 587)
Location: Belle Harbor, New York
Date: November 12, 2001
Time: 0916 eastern standard time
Aircraft: Airbus A300-600, N14053
NTSB Number: DCA02MA001

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C. ACCIDENT SUMMARY

On November 12, 2001, about 0916 eastern standard time, American Airlines flight 587, an Airbus A300-600, was destroyed when it crashed into a residential area of Belle Harbor, New York, shortly after takeoff from the John F. Kennedy International Airport (JFK), Jamaica, New York. Two pilots, 7 flight attendants, 251 passengers, and 5 persons on the ground were fatally injured. Visual meteorological conditions prevailed and an instrument flight rules flight plan had been filed for the flight destined for Santo Domingo, Dominican Republic. The scheduled passenger flight was conducted under Title 14 Code of Federal Regulations (CFR) Part 121.

D. DETAILS OF THE INVESTIGATION

From August 12 to August 22, 2002 the Human Performance group convened at the National Aeronautics and Space Administration (NASA) Ames Research Center, Moffett Field, California to conduct observations and test activities using the NASA Vertical Motion Simulator (VMS). A description of the facility, and the observations and findings of the initial phase (Phase I) of these activities was presented previously.[1] This report addresses the second phase (Phase II) activities that involved an experimental exercise to examine human performance issues relevant to the investigation. The paper contains an overview of the exercise, its results, and a discussion of its limitations.[2]

E. PHASE II ACTIVITIES

E.1. PURPOSE

Because of the high-amplitude, high-frequency rudder inputs recorded on the FDR during the accident sequence, the Human Performance group conducted a structured examination of potential human performance issues that might contribute to an inadvertent rudder input by a pilot in simulated conditions approximating the accident sequence.

The examination focused on the issue of rudder system design. It addressed the “variable stop” rudder design employed by the A300-600 in which the forces and displacements needed to command maximum rudder travel decrease with airspeed. This is shown in Table 1, which plots the force and displacement characteristics of the A300-600 rudder pedal at three airspeeds as provided by

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[1] Human Performance Study Report, Vertical Motion Simulator Activities, Phase I: Backdrive of Accident Flight, October 3, 2002.

[2] Results have been drawn from two data analysis efforts: a statistical overview of findings by Safety Board staff described in this report and an independent analysis by a NASA specialist on human-control system interaction included as Attachment 1.

Airbus Industrie from static force-feel characteristics. [3] Table 1 also shows the corresponding values programmed into the VMS for the Phase II examination.[4] The examination evaluated whether this design increased the likelihood of unintended pilot inputs at higher airspeeds, for example whether a pilot at higher airspeeds would tend to enter all-or-none rudder and have difficulty making more precise inputs in a dynamic situation.[5] If such design effects were observed, the examination attempted to evaluate the magnitude of the effects to appreciate how they might affect practical applications. Secondary issues related to airplane motion, task demand, and pilot inputs on multiple controls were also examined to identify how these factors might interact with rudder design factors.

Table 1. Variable Stop Rudder Design – Force and Displacement

		165 kts		240 kts		310 kts	
	Breakout Force (lbs) [6]	Max Pedal Force (lbs)	Max Pedal Travel (in)	Max Pedal Force (lbs)	Max Pedal Travel (in)	Max Pedal Force (lbs)	Max Pedal Travel (in)
A300-600	22	66.1	4	35.3	1.44	28.6	0.66
VMS simulation	22	66.1	3.5	40.6	1.48	31.8	0.78

E.2. METHOD AND DATA COLLECTION

Seven subjects participated in the Phase II exercise. Two were members of the Human Performance Group and test pilots with type ratings in the A-300-600 (Jacob, Thompson). A third subject was a NASA test pilot not type rated in the airplane. The remaining four subjects were American Airlines A-300-600 line pilots current in the airplane, whose total flight time in the airplane ranged from 1,331 to 2,501 hours.[7]

The exercise employed a tracking task in which subjects were instructed to move the VMS airplane controls to correspond with commanded control positions shown on a visual display located on the front panel before the subject. Both

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[3] An alternative rudder design is that of the "variable ratio" in which the max pedal force and max pedal travel characteristics do not change with airspeed. Since the VMS did not respond to pilot inputs in Phase II, the rudder characteristics at V=165 kts might also be considered representative of those employed in a "variable ratio" design when compared to those at the other airspeeds tested.
[4] The VMS values were developed from earlier calculations of the force vs. displacement and vary by as much as 18% from the nominal A300-600 values provided by Airbus. In the case of the 240 and 310 knots airspeeds, the VMS programmed force and displacement values have a slightly more conservative reduction than the actual airplane.
[5] The "all-or-none" example is of special interest because of its relation to the accident pilot's performance during the accident sequence, although the study examined numerous measures to fully evaluate precision of response throughout the response range.
[6] This"breakout force" is comprised of both breakout and friction forces. See Attachment 1 for further details on the force and displacement characteristics of the VMS simulation.
[7] The accident first officer had a flight time in the A-300-600 of 1835 hours.

commanded and actual control positions were presented on this display continuously (Figure 1). For example, the commanded pedal position (“pedal target”) was shown as a solid triangle that moved left and right with varying frequencies and amplitudes while the actual pedal position (“pedal actual”) was shown as an empty triangle below it that moved left and right in response to the subject’s control inputs. The commanded wheel and column positions were shown in a solid diamond, and the actual wheel and column positions in an open circle.

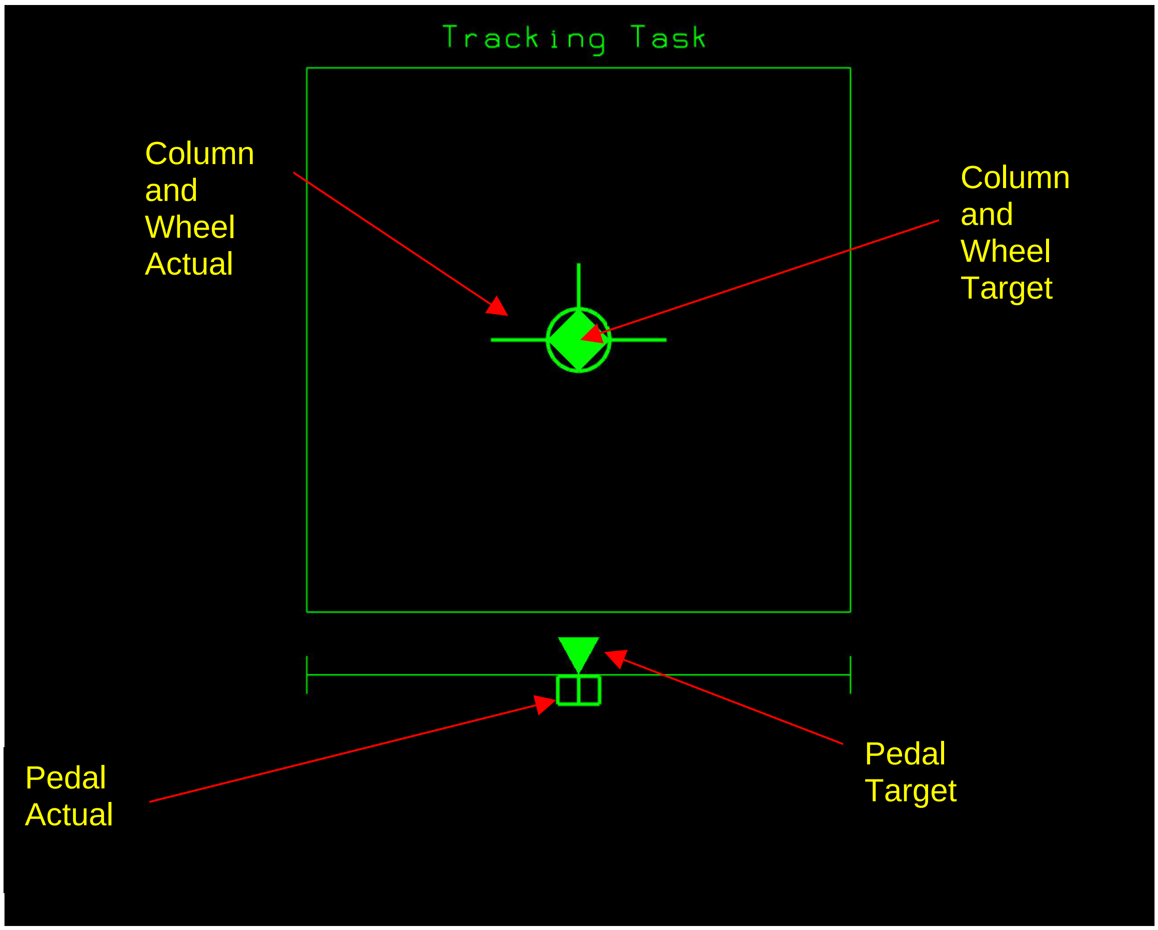

Figure 1: Tracking task visual display and symbology.

Each subject performed a total of 54 trials, which were preceded by a short training session to familiarize the subject with the controls, task display, and cab motion. Each trial was 60-seconds in duration. Four experimental conditions were presented in a crossed design so that each subject received every combination of experimental conditions once within the 54 trials. The conditions were as follows:

1) aircraft calibrated airspeed of 165, 240, or 310 knots[8]
2) flight control axes of pedal only, pedal and wheel, or pedal, wheel, and column
3) cab motion either on or off[9]
4) tracking task of A, B, or 587

Task A represented a smooth, slow moving target. The pedal and the wheel followed the same target path while the column followed a slightly different path. Task B represented a more rapidly moving target. Again, the pedal and wheel followed the same path and the column followed a slightly different path. The 587 task tracked the flight control inputs from the accident flight. Figures 2 to 4 display the commanded tasks for the pedal for Tasks A, B, and 587, respectively, along with actual sample data from one subject (chosen arbitrarily).[10]

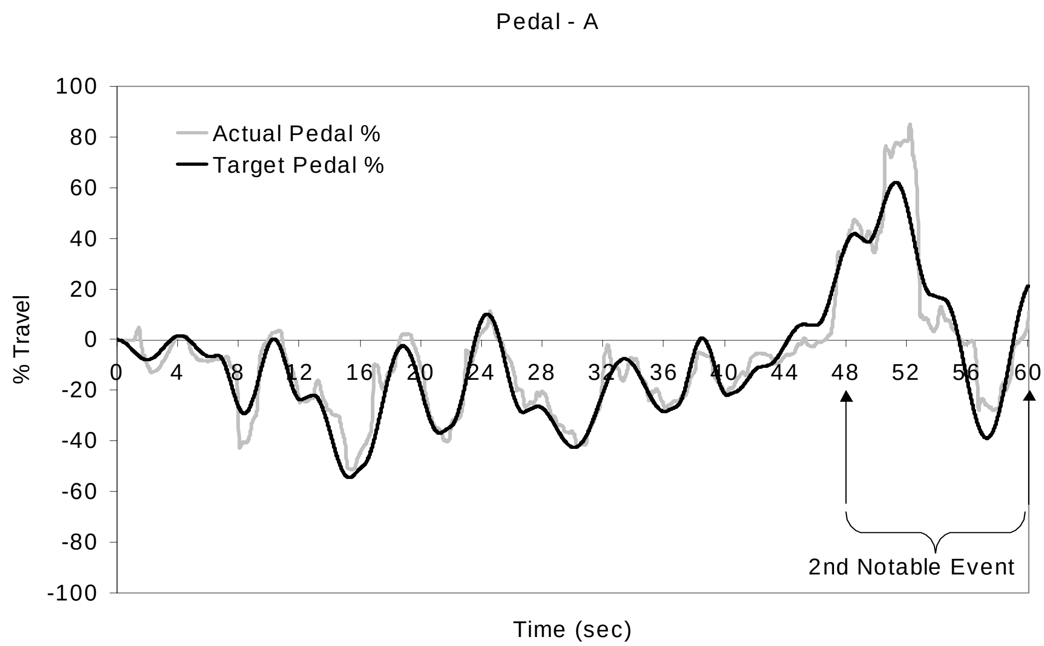

Figure 2: This chart displays tracking task A for the pedal. The target is shown in solid black as a percent of full available pedal travel. The actual pedal input by the subject is shown in gray. (310 knots)

[8] The airspeed affects both the pedal and column flight controls. For the column, the amount of force to displace the column a given distance increases as the airspeed increases and is proportional to actuator extension.
[9] When on, cab motion in all treatments was the VMS recreation of motions from the last 60 seconds of the 587 accident FDR.
[10] Figures 2-4 show the time period of the "2nd Notable Event", the primary accident period during which cab motion was relatively active in each condition whenever cab motion was on.

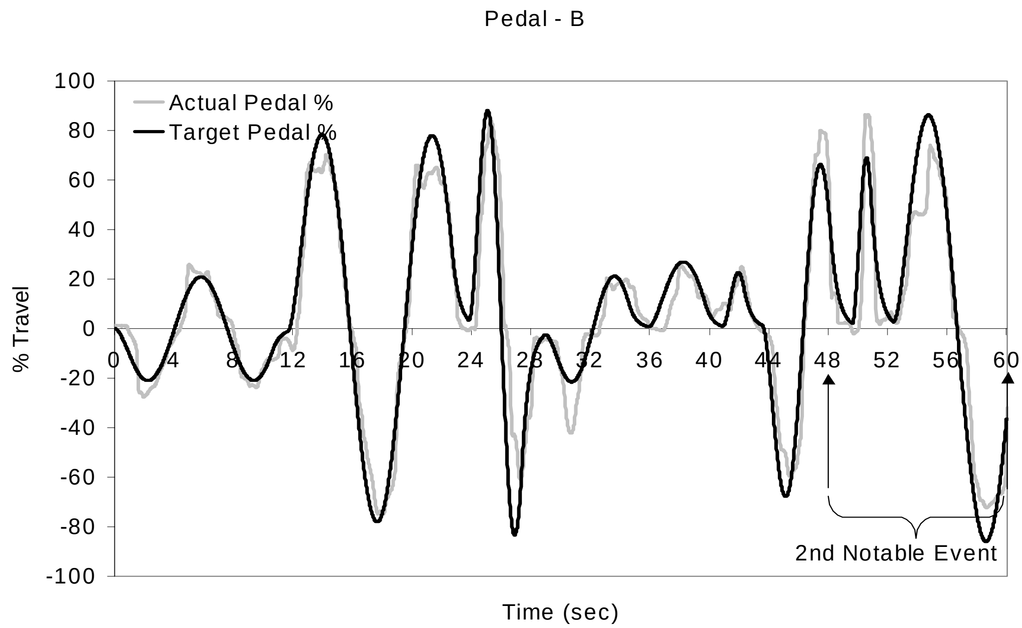

Figure 3: This chart displays tracking task B for the pedal. The target is shown in solid black as a percent of full available pedal travel. The actual pedal input by the subject is shown in gray. (310 knots)

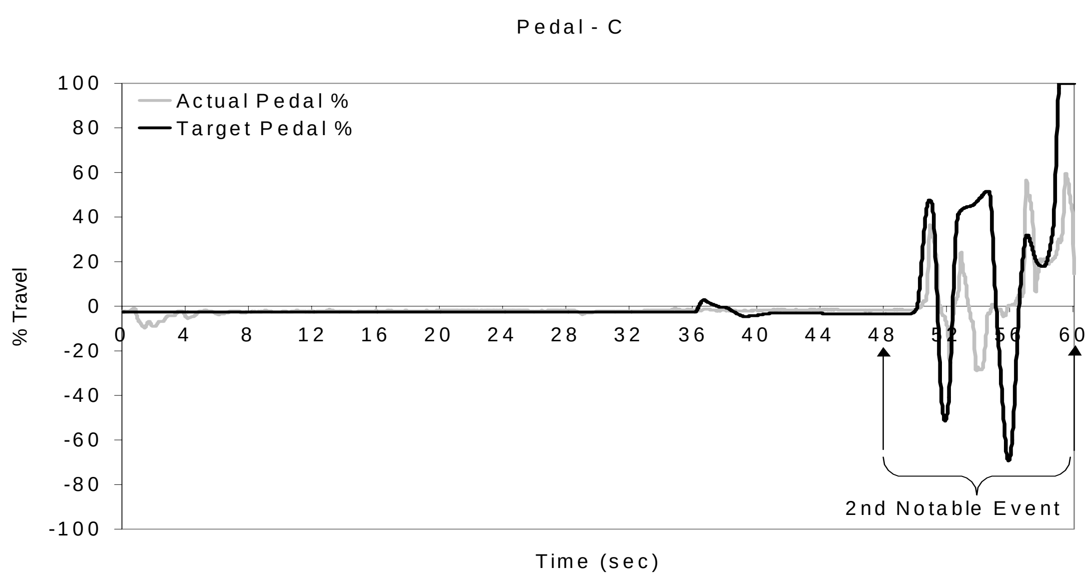

Figure 4: This chart displays tracking task 587 for the pedal. The target is shown in solid black as a percent of full available pedal travel. The actual pedal input by the subject is shown in gray. (310 knots)

The presentation of Airspeed and Motion were randomized. The flight control axes were sequential with all cases of pedal only occurring first, then pedal and wheel, then pedal, wheel, and column. Similarly, subjects saw the tasks in the order of A, B, and 587.

The subject's inputs on all flight control axes were sampled at 50 Hz. during the trial. For statistical analysis, however, the present examination was limited to pedal data (including pedal data when the subject was performing on multiple flight control axes) to focus on issues of pedal input precision.

Three dependent measures were derived:

Root mean square error (RMSE). A statistical summary measure of the mathematical deviation between the actual pedal inputs and the target pedal inputs, RMSE was computed on a point-by-point basis for all data in each trial (disregarding the direction of the deviation). A low score means that the actual and target patterns were very similar while a high score means that the two patterns were very different.

Number of maximum pedal displacements. A summary measure of extreme input, the number of maximum pedal displacements counted the number of times during the trial that the subject touched the upper stop of the available pedal travel.[11] On tasks A and B, the subject was never commanded by the target to touch the upper stop so this measure would indicate an overshoot. On the 587 task, the subject was commanded by the target to make rapid entries approaching the upper stop so this measure could indicate pedal inputs resembling those of the accident sequence.[12]

NASA Task Load Index (TLX) ratings. At the completion of each trial, every subject provided a number from 1-10 (lowest to highest ranking) in response to each of six sub-scales on the NASA TLX to subjectively rate their workload. The six sub-scales were Mental Demand, Physical Demand, Temporal Demand, Effort, Performance, and Frustration.

[11] To avoid confounding when a subject hovered around the upper stop for a fraction of a second, a subject was scored for only one maximum pedal displacement within any 15 successive data points (i.e. 1/3 of a second).
[12] As shown in Figure 4, the 587 command inputs programmed into the VMS did not reach the upper stop until the end of the trial. This is contrary to the more extreme pedal inputs made in the accident sequence.

E.3. FINDINGS

NTSB Analysis

To obtain an overview of the results, an analysis was conducted within the framework of a fully crossed analysis-of-variance design that examined aggregate data (RMSE, pedal displacements, TLX data) collected across the entire 60-second trial for the variables of aircraft airspeed, flight control axes, cab motion, and A and B tracking tasks. [13],[14]

According to all three dependent measures, the rudder pedal characteristics at the 165 knots airspeed provided the most accurate tracking, the rudder pedal characteristics at the 240 knots airspeed provided an intermediate tracking accuracy, and the rudder pedal characteristics at the 310 knot airspeed provided the least accurate tracking of the three aircraft airspeeds (where accuracy of tracking was indicated by low RMSE,[15] fewer maximum pedal displacements,[16] and lower subjective workload ratings[17]). All dependent measures indicated that the A task provided more accurate tracking than the B task.[18] With regard to flight control axes, there was evidence suggesting that controlling the pedal alone provided the most accurate tracking, and controlling the pedal, wheel, and column provided the least accurate tracking of the three conditions.[19] With regard to motion, there was evidence suggesting that the no motion condition

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[13] Due to a simulator problem, the first two subjects experienced a simulator motion similar but not identical to that of the remaining five subjects. Based on the judgment of an NTSB observer present during all trials and a comparison of the results of these two subjects with those of the remaining subjects, a decision was made to retain these subjects for the analysis.

[14] The 587 task was not included in the overview analysis because it varied significantly from tasks A and B. The first 48 seconds of the 587 task contain very little activity while the last 12 seconds contain substantial activity, effectively "washing out" the 60-second RMSE measure and making it incompatible with tasks A and B. The 587 task is also the only one that has the potential for a task-cab motion confound.

[15] Airspeed main effect: $F(2,12) = 11.6$, $p<.01$. This indicates, in standard statistical notation, that the main effect observed for Airspeed would be expected to appear by chance fewer than 1 time in 1000 observations.

[16] Airspeed main effect: $F(2,12) = 23.6$, $p<.001$.

[17] Airspeed main effect: Mental Demand, $F(2,12) = 5.8$, $p<.05$; Physical Demand, $F = 6.1$, $p<.05$; Temporal Demand, $F = 8.7$, $p<.01$; Effort, $F = 16.7$, $p<.005$); Performance, $F = 5.3$, $p<.05$; and Frustration, $F = 4.3$, $p<.05$.

[18] Task main effect: RMSE, $F(1, 6) = 273.0$, $p<.001$; Number of maximum pedal displacements, $F = 20.8$, $p<.005$; Mental Demand, $F = 32.9$, $p<.005$; Physical Demand, $F = 13.9$, $p<.05$; Temporal Demand, $F = 15.4$, $p<.005$; Effort, $F = 29.2$, $p<.005$; Performance, $F = 186.9$, $p<.001$; and Frustration, $F = 95.1$, $p<.001$.

[19] Flight control axes main effect: RMSE, $F(2, 12) = 64.8$, $p<.001$; Mental Demand, $F = 36.5$, $p<.005$; Physical Demand, $F = 34.9$, $p<.001$; Temporal Demand, $F = 10.5$, $p<.005$; Effort, $F = 37.6$, $p<.001$; Performance, $F = 9.7$, $p<.005$; and Frustration, $F = 7.2$, $p<.01$. Number of maximum pedal displacements showed the pedal condition as the most accurate with the pedal, wheel, and column condition the second most accurate, $F = 8.3$, $p<.01$.

provided more accurate tracking than the motion condition.[20] Finally, there was evidence of an interaction between Airspeed and Flight control axes that applied to both RMSE[21] and Number of maximum pedal displacement[22] measures, an interaction between Airspeed and Task that applied to Number of maximum pedal displacements,[23] and several small interactions that applied to TLX measures.[24]

To evaluate the magnitude of the differences related to rudder pedal characteristics, Figures 5-7 plot the Airspeed results for each dependent measure. Figure 5 plots the Airspeed effect on RMSE scores displaying the significant interaction between Airspeed and Flight control axes. As shown in Figure 5, Airspeed effects tended to be more or less pronounced in different Flight control axes conditions. In the simplest case, when the subject was responsible for controlling only the pedal, the RMSE score indicated that subjects were about 19% less precise in their tracking when they used the rudder design characteristics at the 310 knots airspeed, and about 4% less precise when using the rudder design characteristics at the 240 knots airspeed, than when they used the rudder design characteristics at the 165 knots airspeed. In the most severe case, when subjects were responsible for controlling pedal, wheel, and column at the same time, the RMSE score indicates that the respective losses of precision were about 30% and 20% for the 310 and 240 knot conditions, respectively, when compared to the 165 knot condition.

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[20] Motion main effect: RMSE, $F(1, 6) = 73.5$, $p<.05$; Mental Demand, $F = 11.2$, $p<.05$; Temporal Demand, $F = 15.0$, $p<.01$; and Effort, $F = 12.1$, $p<.05$. Physical Demand, Performance, and Frustration results were not significant at the $p<.05$ level, while Number of maximum pedal displacements showed a non-significant opposite trend.

[21] $F(4,24) = 3.6$, $p<.05$

[22] $F(4,24) = 2.9$, $p<.05$

[23] $F(2,12) = 15.2$, $p<.005$

[24] Interaction effects significant at the $p<.05$ level appeared for Physical demand on the Flight control Axes x Task interaction; and for Temporal demand on the Airspeed x Motion interaction.

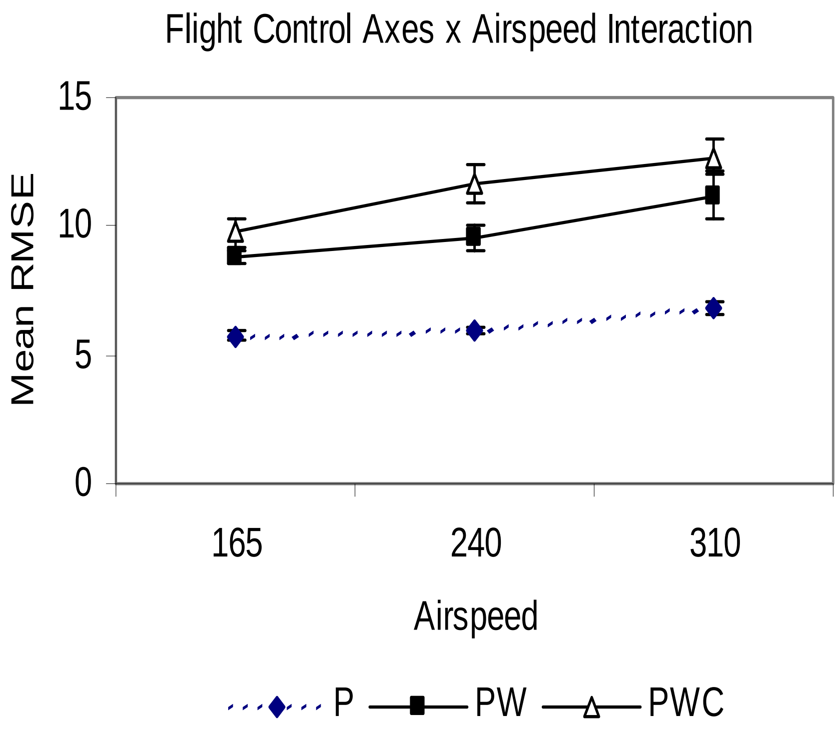

Figure 5: Flight control axes x Airspeed interaction (tasks A and B only).

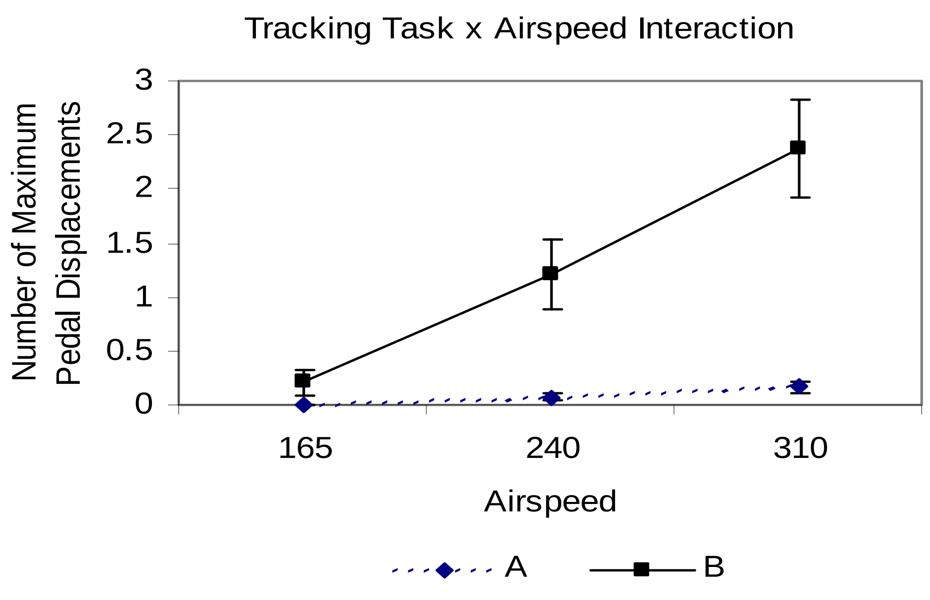

Figure 6: Task x Airspeed interaction (tasks A and B only).

Figure 6 plots the Airspeed effect on the Number of maximum pedal displacements displaying the significant interaction between Airspeed and Task.

Task A produced almost no cases of maximum pedal displacements, while Task B, which commanded subjects to make large pedal inputs more frequently, showed an increasing number of maximum pedal displacements as subjects used the rudder system design characteristics at the 240 and 310 knots airspeeds, respectively. Such displacements were still relatively rare, however, averaging only 2.4 maximum displacements over the course of the 60-second trial in the most severe case (contrary to what might be expected from an all-or-none pilot response model).

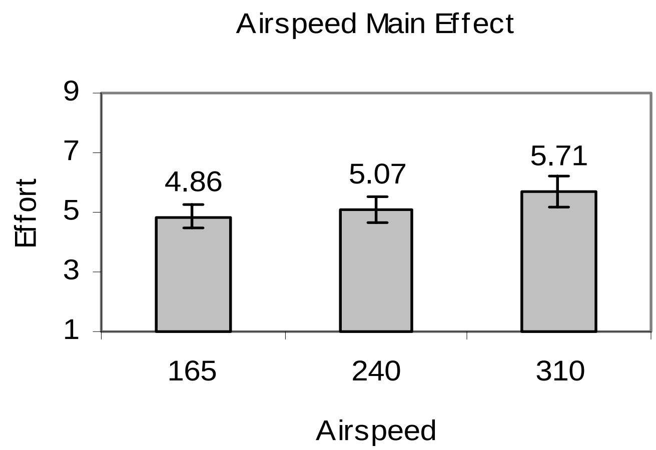

Figure 7: The effect of Airspeed on subjective workload assessment on the NASA TLX sub-scale of Effort.

Figure 7 plots the Airspeed effect on the TLX sub-scale of effort (the TLX scale that responded most significantly to Airspeed). Subjects rated the rudder system characteristics at the 310 knots airspeed as requiring 17% more effort, and the rudder system characteristics at the 240 knots airspeed as requiring 4% more effort, than the rudder system characteristics at the 165 knots airspeed. As shown in Figure 7, all average ratings were in the middle portion of the available rating scale. For the remaining TLX sub-scales, the percentage increase in subjective ratings between the 310 knots airspeed and the 165 knots airspeed was as follows: Mental demand, 16%; Physical demand, 16%; Temporal demand, 17%; Performance, 11%; and Frustration, 13%. All average scores were in the lower or middle portion of the available rating scale (3.5-5.4).

Finally, an analysis was made of pedal responses during a dynamic situation that consisted of the last 12 seconds of the 587 task (corresponding to the second notable event of the accident sequence), with cab motion on, and the subject responsible for pedal, wheel, and column inputs. It was found that RMSE scores increased with airspeed condition but that the differences did not reach statistical significance.[25] The number of maximum pedal displacements increased with airspeed condition.[26] However, it was observed during the tests

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[25] $F(2,12) = 2.6$, $p>.05$.
[26] $F(2,12) = 6.040$, $p<.05$.

and noted by subjects that target pedal was at times ignored when workload was high.

Outside expert analysis

Dr. Barbara Sweet, an aerospace engineer at the NASA-Ames Research Center with expertise in human-control system interaction[27] who also participated in the VMS Phase I exercise and observed the tasks for Phase II, prepared a report of the Phase II activity that examined selected areas of the data to further focus on control issues. Her report is included as Attachment 1.

E.3. LIMITATIONS

The Phase II exercise attempted to explore factors related to rudder input that might be relevant to the accident situation. In interpreting the results, it is important to recognize that the exercise:

- did not use a piloting task but rather a tracking task in which the pilot's inputs did not influence the motion of the cab;
- used a small sample of subjects who had some familiarity with the accident and the nature of the exercise;
- provided subjects with immediate, precise feedback by means of a visual display concerning the actual degree of pedal input being made, unlike an actual flying situation in which such precise feedback would not be available.

Submitted By:

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Malcolm Brenner, Ph.D.
National Resource Specialist--Human Performance

[27] e.g. "The Identification and Modeling of Visual Cue Usage in Manual Control Task Experiments." Ph.D. Dissertation, Stanford University, 1999.

Attachment 1
Report prepared by Dr. Barbara Sweet

Data Analysis Description
NTSB VMS Simulation Study - Tracking Task

Barbara T. Sweet
June 5, 2003

1.0 Background

On November 12th, 2001, American Airlines flight 587 crashed shortly after takeoff from JFK airport. It was determined that the vertical stabilizer and rudder separated from the airframe in flight, causing a loss in controllability of the aircraft. The flight data recorder indicates that several large rudder and pedal movements preceded the loss of control, and analysis indicates that the rudder movements and corresponding aircraft motion would have resulted in loads that would exceed the ultimate load limit of the vertical stabilizer.

In August 2002, the NTSB conducted a simulation study in the Vertical Motion Simulator (VMS) at NASA Ames Research Center. The purposes of this simulation were twofold: 1) to evaluate the accelerations experienced during the accident event, and 2) evaluate the effects of flight control characteristics and accelerations similar to those experienced during the accident event on subject perception and performance. The simulation was conducted in two phases. In Phase I, the backdrive phase, the simulation was programmed to replicate (to the greatest extent possible) the visual scenery, control positions, and accelerations associated with the flight up until the loss of control.

In Phase II, the tracking study, subjects performed a control-tracking task. The remainder of this report describes the analysis of a portion of the data obtained in this second phase of the simulation study.

2.0 Tracking Study Description

Seven pilots participated in the tracking study. Four subjects were current American Airlines A-300-600 line pilots with flight times in the airplane ranging from 1331 to 2501 hours. The remaining three subjects were test pilots, two of whom were type rated on the A-300-600. In the study, subjects were instructed to move the controls to correspond with commanded control positions. The commanded position and actual position were displayed on a CRT on the panel of the simulator (Figure 1), and the outside visual scene was turned off during the study.

There were three different one-minute tracking tasks, termed “A,” “B,” and “587.” The A and B tasks consisted of varying sinusoidal oscillations; the A task was characterized by relatively low frequency/low amplitude, the B task consisted of higher frequencies and amplitudes. The 587 task consisted of the control movements from the flight data recorder (the 60-second period preceding loss of aircraft control). Two movement conditions were used: 1) motion-off (no simulator movement); and motion-on, in which the motion system of the VMS was programmed to closely correspond to the accelerations experienced by the flight crew. Three control tasks were done, corresponding to the number of control axes being tracked: 1) pedal only; 2) pedal and wheel; and 3) pedal, wheel, and column.

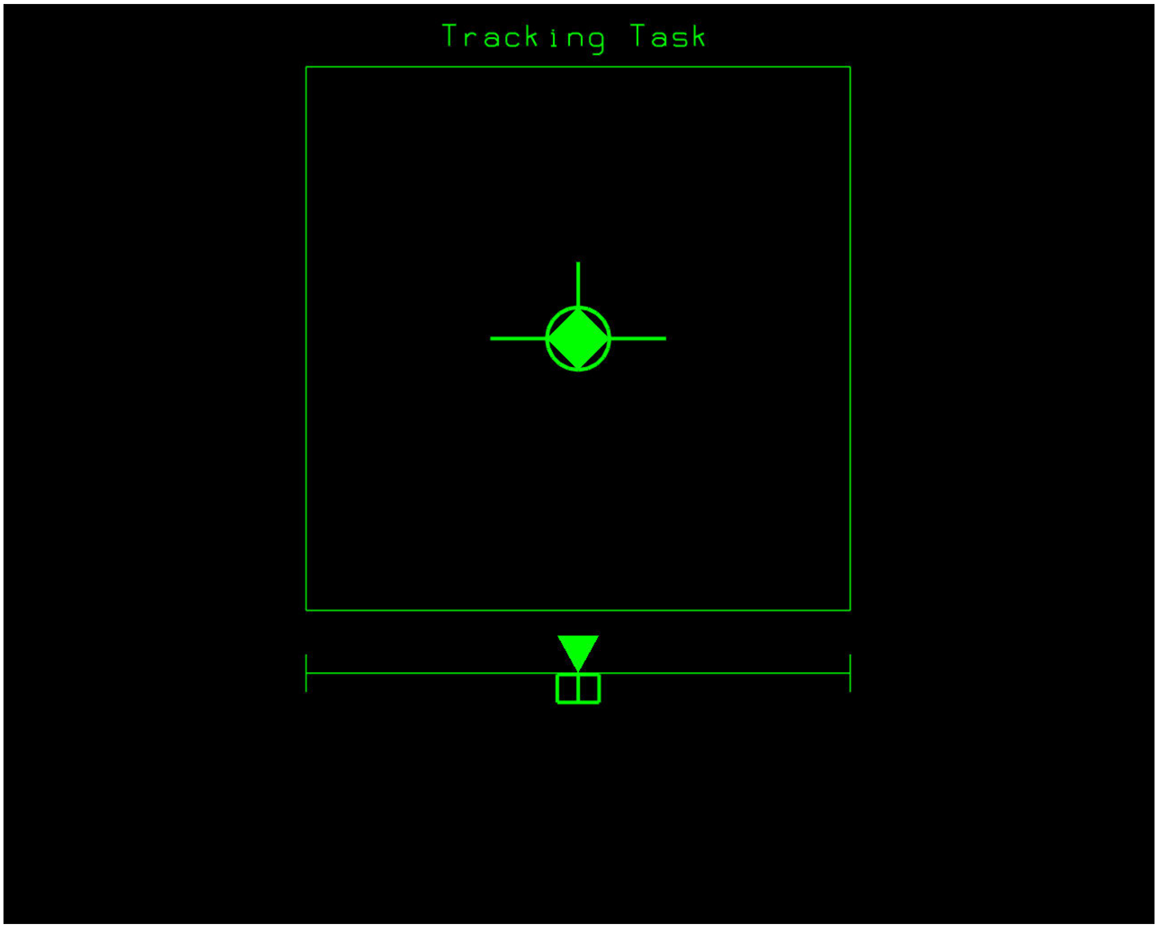

Figure 1 – Tracking task display. The diamond's lateral and vertical displacement indicates the commanded wheel and column position (e.g., up = pitch up column), respectively. The airplane symbol indicates the actual wheel and column position. The triangle indicates commanded pedal position, and the rectangular "bug" indicates actual pedal position.

The VMS force-feel control system was programmed to make the controls similar to the control system characteristics of the A300-600 aircraft. The VMS pedal was programmed to have a fixed stop location that varied as a function of airspeed condition. Breakout force, friction force, and force gradient (force per unit of displacement) were constant for all airspeed conditions. Table 1 contains a summary of the force/displacement characteristics programmed on the VMS. The force necessary to reach maximum displacement for a given airspeed condition can be calculated by summing the contribution of breakout force, friction force, and force gradient. For example, at the 165 knot condition, the force necessary to reach maximum displacement is:

F_{max} = 10 pounds + 12 pounds + (12.6 pounds/inch)*3.5 inches = 66.1 pounds

Airspeed condition (knots)	165	240	310
Breakout Force (pounds)	10	10	10
Friction Force (pounds)	12	12	12
Force Gradient (pounds/inch)	12.6	12.6	12.6
Max Displacement (inches)	3.5	1.48	.78
Force at Max Disp. (pounds)	66.1	40.6	31.8

Table 1 – Programmed characteristics of the pedal force-feel system on the VMS

It should be noted that the tracking task performed in the simulator differs from the task of flying an aircraft in several important respects. In the flying task, the pilot moves the control effectors to achieve the desired aircraft state. There is no visual display of desired or actual control positions and, particularly with the pedal, the pilot does not have accurate visual feedback of control position. Instead, the pilot senses the aircraft state through visual information (both out-the-window and displayed) and non-visual information (proprioceptive, somatosensory, and vestibular). In the tracking task, the subject viewed a panel display showing both commanded and actual control positions; the subject's task was to move the control effectors to match the commands. As in the flying task, the subject had additional sources of non-visual information of limb positions and forces exerted on the controls (proprioception, somatosensory perception). The simulator cab, in some conditions, underwent large motions that produced perceptable accelerative forces on the subject; however, the motion of the cab was not a result of the actions of the subject.

3.0 Analyses

Three analysis methods were investigated; two of the methods and their results will be described in detail; a third method, which yielded little information, will be only briefly discussed. These analysis methods were 1) ANalysis Of VAriance (ANOVA), 2) Multiple Regression, and 3) Time History Analysis.

3.1 ANOVA

Upon initial examination of the tracking data, it became apparent that in some cases subjects had difficulty matching the amplitudes of the commands. The purpose of this analysis was to do a factorial analysis to determine which of several factors were contributing to inaccurate responses, and to quantify the levels of inaccuracy that were observed.

3.1.1 Methodology

After some initial investigation, the response of the subjects to particular well-defined pedal inputs was chosen for analysis. For each task, a time window was chosen in which a large-amplitude, well-defined pedal input was commanded. In order to study the effect of platform motion (on or off) as a factor, all of the time windows were chosen to be in the time period with large amplitude motions (50 seconds and later). Figures 2-4 show the analysis windows for each pedal-tracking task (A, B, and 587, respectively). Subjects generally exhibited good tracking behavior in the one-axis tracking task, while in the two- and three-axis tasks, tracking of pedal was much more erratic as attention was divided among the different tasks. Since the main focus of the investigation is on the subject's pedal inputs and the subject's ability to make accurate inputs with variable pedal loading characteristics and high amplitude motion, the analysis was limited to the one-axis (pedal-only) pedal-tracking task.

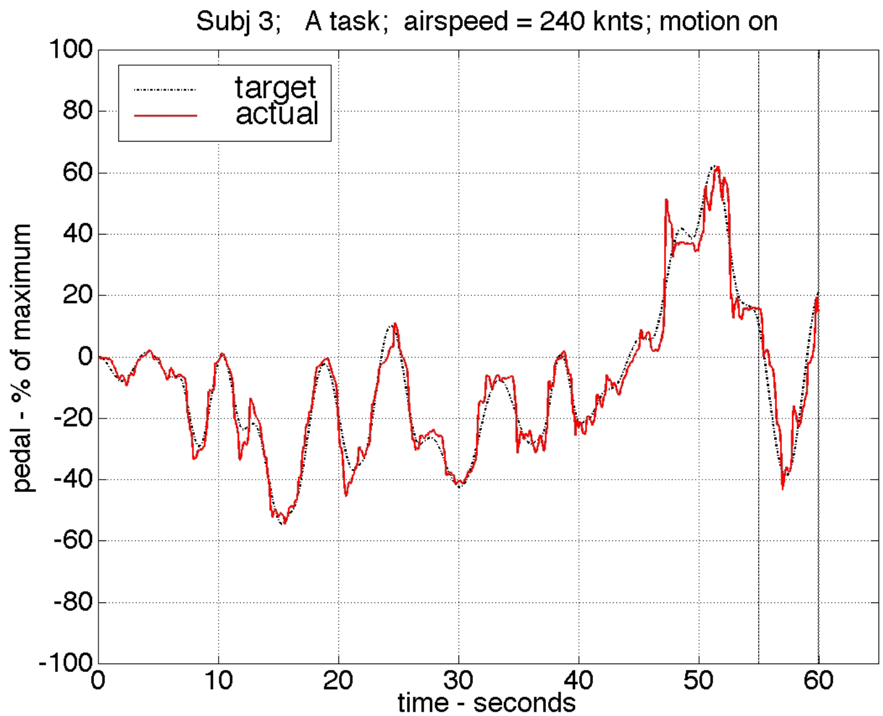

Figure 2 - Representative time history for the A task (analysis window bracketed with vertical black lines).

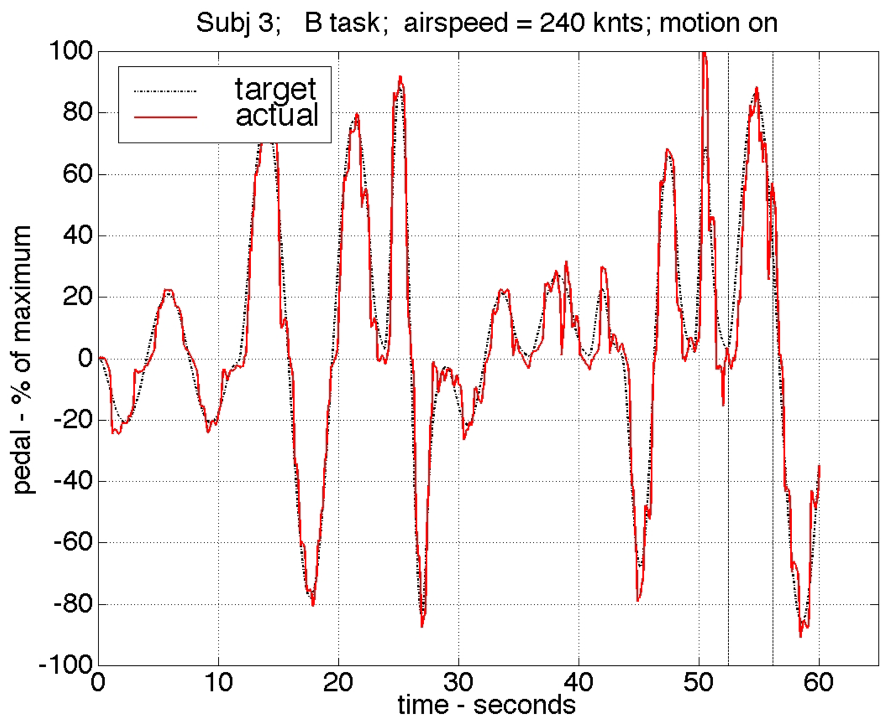

Figure 3 - Representative time history for the B task (analysis window bracketed with vertical black lines).

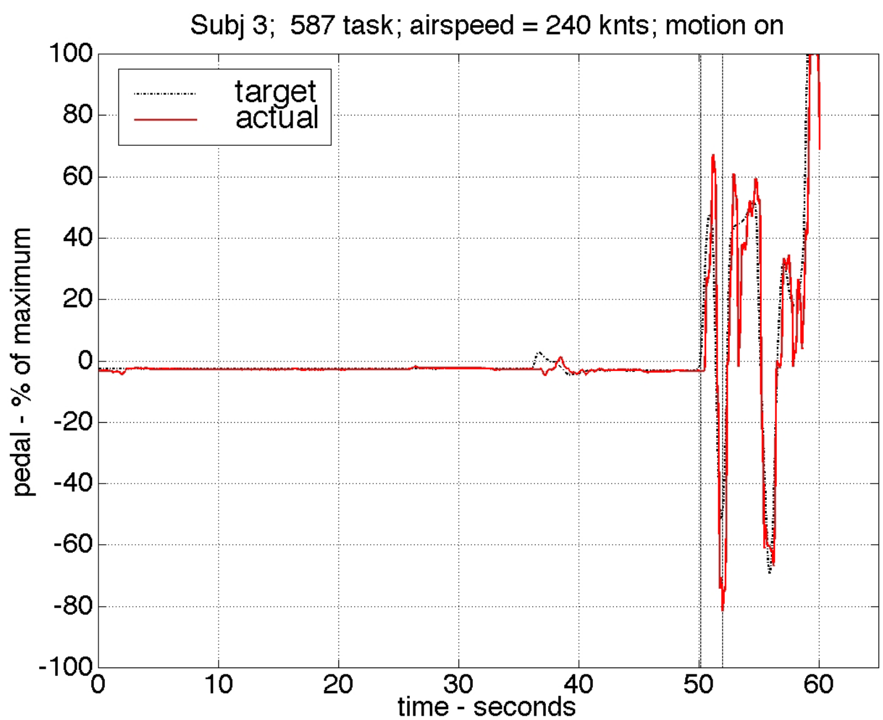

Figure 4 - Representative time history for 587 task (analysis window bracketed with vertical black lines).

Two dependent measures were developed. The first, an overshoot ratio, was obtained by determining the maximum control deflection of the subject within the analysis window. This deflection was then divided by the maximum commanded deflection within the window to obtain the overshoot ratio:

overshoot ratio = (actual maximum pedal input)/(maximum commanded pedal input)

The second dependent measure was the time delay between commanded peak deflection and actual peak deflection. The time of the actual peak minus the time of the commanded peak is the delta peak time:

delta peak time = actual peak time - commanded peak time

Note that a positive delta peak time implies that the subject achieved the peak value after the commanded input; a negative peak time implies that the subject achieved the peak value before the commanded input.

A sample measurement window is shown in Figure 5; in this condition, the commanded pedal input peaked at a value of 47.82 at 50.92 seconds. The actual pedal input peaked at a value of 67.39 at 51.20 seconds. For this condition, the dependent measures are:

overshoot ratio = 67.39/47.82 = 1.41

delta peak time = 51.20 – 50.92 = 0.28 sec

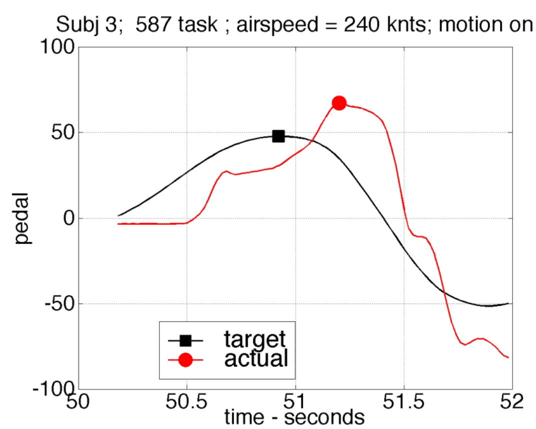

Figure 5 - Example plot showing dependent measure analysis.

3.1.2 Results

Within-subjects ANOVAs were performed on these dependent measures with the following factors: 1) task (A, B, 587), 2) airspeed (165, 240, 310), and motion (on or off).

3.1.2.1 Overshoot Ratio

There was a significant effect of airspeed (F = 9.136, p = .011), with overshoot ratio greater at the higher airspeeds (see Figure 6).

There was a significant effect of task (F = 85.016, p < .0005). The 587 task had a much higher overshoot ratio that either the A or B tasks; the lowest overshoot ratios were associated with the B task (see Figure 7).

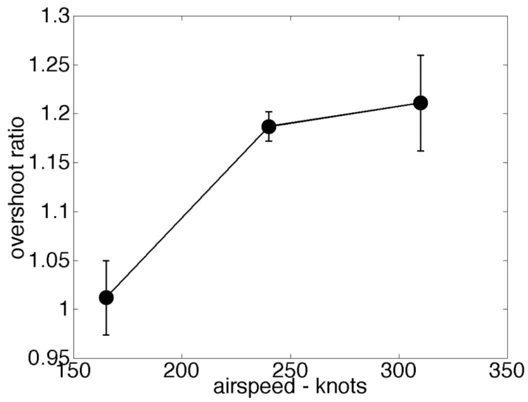

Figure 6 - Mean overshoot ratio as a function of airspeed.

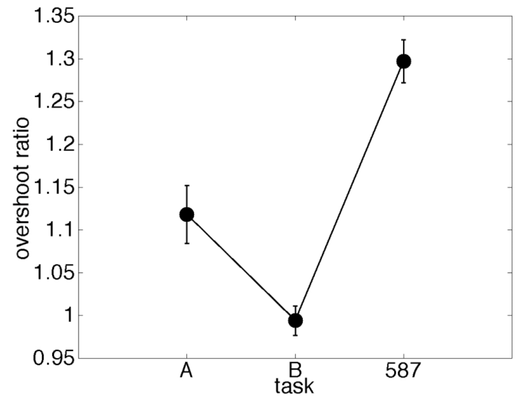

Figure 7 - Mean overshoot ratio as a function of task.

There was a trend towards an interaction between airspeed and task (F = 4.067, p = .054); see Figure 8. An additional analysis was performed to examine the effect of airspeed for each task separately. The effect of airspeed was significant for the A and the 587 tasks; it was not significant for the B task. For the A task, F = 4.854, p = .029; for the 587 task, F = 7.655, p = .007.

The effect of motion was significant (F = 8.08, p = .036); the motion-on condition was associated with higher overshoot ratios than the motion-off condition. There was a significant interaction between motion and task (F = 8.508, p = .021; see Figure 9). Separate tests for the effect of motion were done for each task; only for the 587 task did motion have a significant effect, with higher overshoot ratios in the motion-on condition (F = 23.68, p = .003). It should be mentioned that subjects 1 and 2 experienced different motion than subjects 3 through 7. This motion difference did not impact the effect of motion (on-off) in the 587 task.

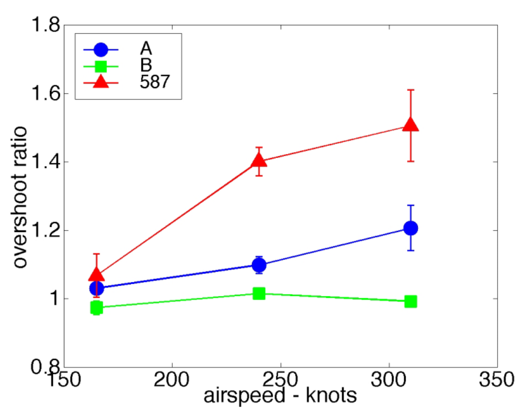

Figure 8 - Mean overshoot ratio as a function of airspeed for the three tasks.

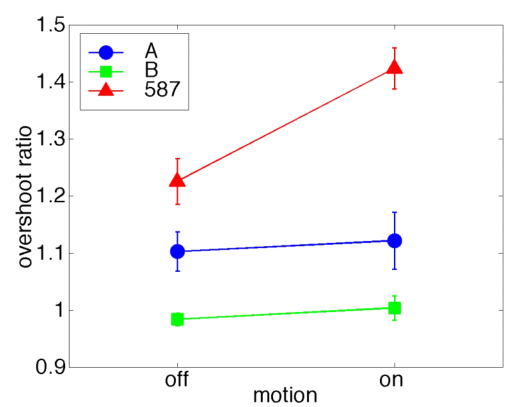

Figure 9 - Mean overshoot ratio as a function of motion for the three tasks.

3.1.2.2 Delta Peak Time

There was a significant effect of airspeed on delta peak time ($F = 9.78$, $p = .019$). As airspeed increased, delta peak time decreased, going from a mean positive value at low airspeed (165 knots) to a mean negative value at high airspeed (310 knots); see Figure 10.

There were no other significant effects or interactions for delta peak time.

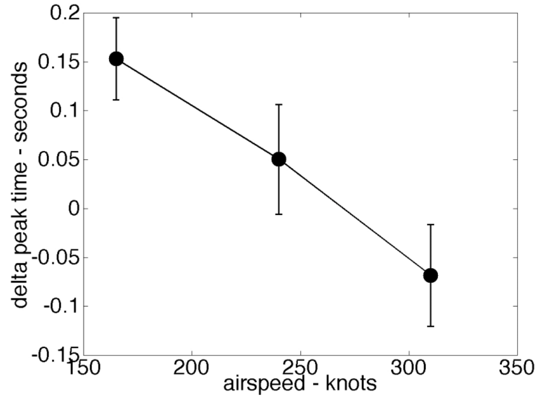

Figure 10 - Mean delta peak time as a function of airspeed.

3.1.3 Discussion

The task performed by the subjects in this experiment is known in manual control as a pursuit tracking task[28]. In pursuit tracking, the subject is given an indication of both the commanded position and the actual position. In these types of tracking tasks, the subject's response can be fairly effectively described by a simple model, shown in Figure 11.

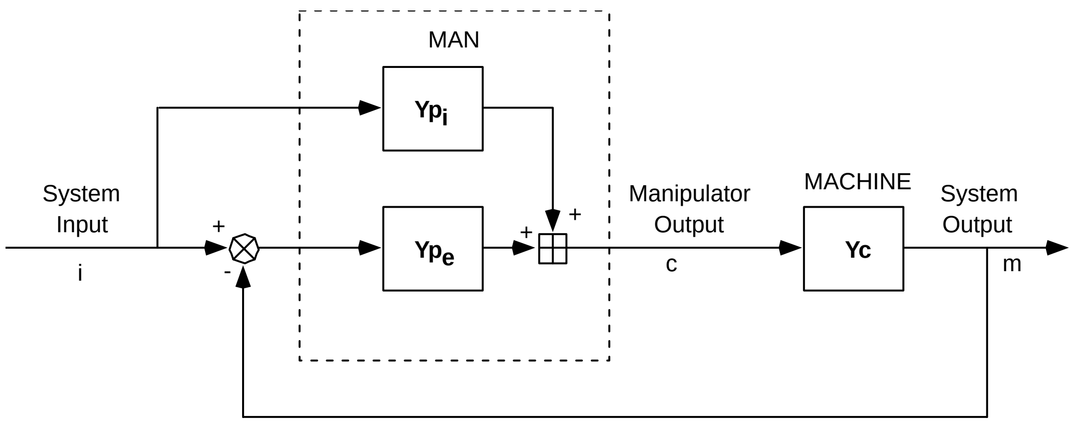

Figure 11 - Control structure for human manual control pursuit behavior (from Allen and McRuer, 1979)

[28] The two other most common modeling paradigms in manual control are: 1) compensatory tracking, in which the subject is presented with only the error between commanded and actual position; and 2) preview control, in which the subject is presented with not only current command but also future command.

In the diagram, Yp_e represents the compensatory action that the subject takes to minimize error, and represents a closed-loop control element (note that the system output, m, is used to create the input to that block). The element Yp_i is part of a feedforward pathway – the subject acts on the system input and makes a control movement based only upon the input, not the current system state or error. Yc represents the controlled element. A well-trained subject will learn to control his or her actions in such a way that $Yp_i*Yc \approx 1.0$; when the subject is doing this effectively, the requirement for closed-loop error control through the element Yp_e is greatly diminished.

This model will be used to discuss some of the observed effects of the tracking experiment.

3.1.3.1 Overshoot Ratio Effects

The largest effects observed in the tracking data occur in the 587 task. There is a strong effect for airspeed and motion on this task. The A task showed only a modest effect for airspeed, increasing from a mean low of 1.03 to a mean high of 1.21. The B task showed no significant effect of airspeed. The 587 task was greatly affected by airspeed; mean overshoot ratio went from 1.07 at 165 knots to 1.40 and 1.51 at 240 and 310 knots, respectively. The reason for the differences among the tasks for these measures is likely related to the speed of the command onset. Figure 12 shows the magnitudes of commanded pedal in the three task analysis windows. In the A and B tasks, the command ramps up over a longer time period than with the 587 task – the commands in the A and B tasks peak at 2.30 and 2.26 seconds after onset of command, respectively. The 587 command reaches a peak at .76 seconds after onset. These two types of commands will likely produce different responses. The sudden command onset will lead to a sudden, large, feedforward input from the subject. This feedforward input, as stated before, is based upon the subject's training and experience. If the characteristics of the system represented by Yc are different than those the subject anticipates, the feedforward control input could be inappropriate. When the commanded pedal input builds up more slowly, errors of inaccurate feedforward responses are likely to be smaller and more easily corrected by feedback command. It is unclear why the A and B task responses differed from each other; the fact that these commands are similar to each other except for amplitude implies that command amplitude could have an effect on tracking accuracy.

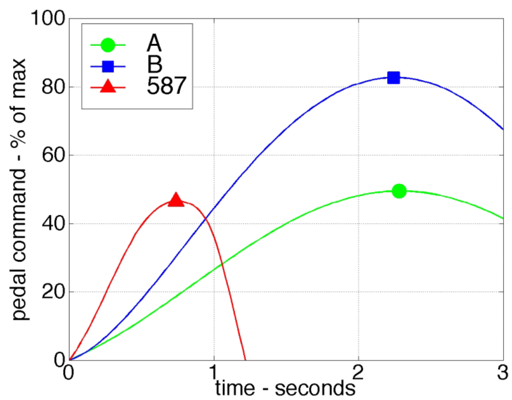

Figure 12 - commanded pedal inputs in analysis windows for the different tasks

The other major effect on the overshoot ratio was from motion – although the overshoots on the A and B tasks were not affected by motion, the 587 task was affected by motion. The motion-off condition had a mean overshoot ratio of 1.23, the motion-on condition had a mean overshoot ratio of 1.42. One possibility is that the subject's proprioceptive feedback (specifically, a sense of how far he had depressed the pedal from perception of his limb position) is compromised in a rapidly changing accelerating environment. It is also possible that the accelerations actually caused involuntary motions of the subject's limbs.

<u>3.1.3.2 Delta Peak Time Effects</u>

The effect of airspeed shows that the peak actual input occurs faster at higher airspeeds – at the highest airspeed, a negative delta peak time is observed. While this effect is statistically significant, it is probably not particularly meaningful for understanding the potential interaction between the subject/control system/aircraft due to changes in phase delay. With time delays of the human in manual control tasks generally varying in the range of 0.2 to 0.5 seconds, this small amount of variation is probably not particularly meaningful. However, it does mean that subjects were reaching the peak of their response more rapidly at higher airspeeds, implying that their responses were becoming more of a step-response at the higher airspeeds.

3.2 Multiple Regression Analysis

The ANOVA results indicated that motion, task, and airspeed all had varying effects on the amount of overshoot achieved. The effect of task in the previous analysis is not easily studied or understood, because there are multi-dimensional variations represented in the task (i.e., the three commands). The time required to complete the command, and the amplitude of the command, are different in the three tasks (see Figure 12).

An expanded analysis was undertaken to better understand the factors specific to the task that contribute to overshoot. For each of the tasks (A, B, 587), time windows were constructed to correspond to each specific commanded peak. The windows were chosen to correspond to times when the tracking command was at a minimum, or when the command passed through zero. This yielded a total of 9 peaks in the A task, 17 peaks in the B task, and 4 peaks in the 587 task. All of the time windows were analyzed to determine the overshoot ratio. Initially, the overshoot ratios were compared with several task variables to determine what trends, if any, could be observed. Two trends became somewhat apparent. First, it appeared that lower amplitude commands were associated with a tendency to overshoot; Figure 13 shows means and standard errors of overshoot (averaged across the 7 subjects) versus the amplitude of the command. The plot suggests an inverse relationship between overshoot and command amplitude: low amplitude commands tended to produce greater overshoots.

Another task factor that appeared to produce overshoots was the "aggressiveness" of the command (i.e., how quickly the command ramped up to maximum amplitude). One potential measure of the aggressiveness is the maximum velocity of the command divided by the amplitude of the command. Figure 14 shows the relationship between overshoot ratio and this aggressiveness measure – some direct correlation between command aggressiveness appears to exist. More aggressive commands (higher maximum velocity/amplitude) are associated with greater overshoot.

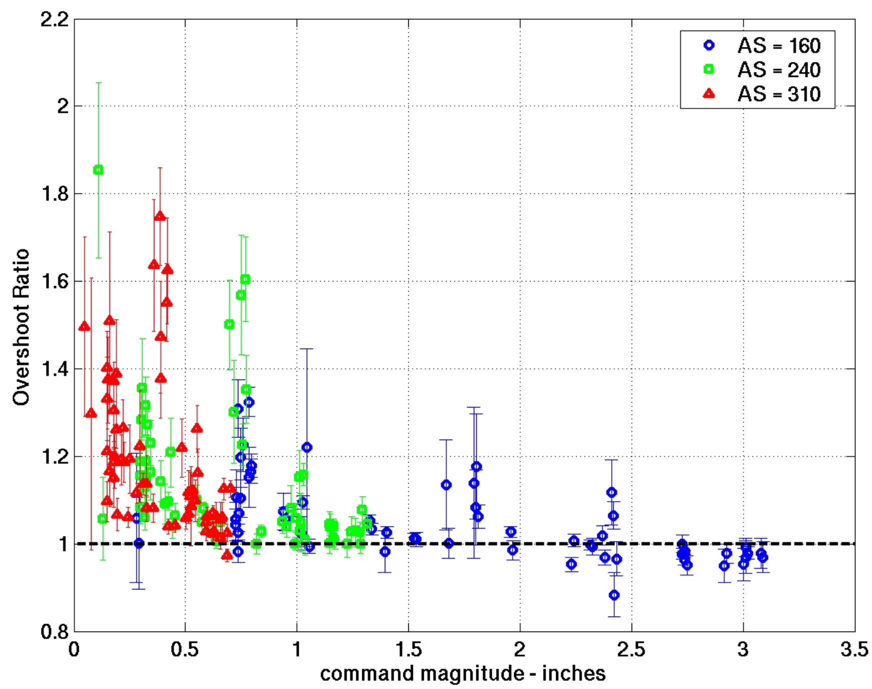

Figure 13 – Mean overshoot ratio as a function of magnitude of the command (standard error bars are shown).

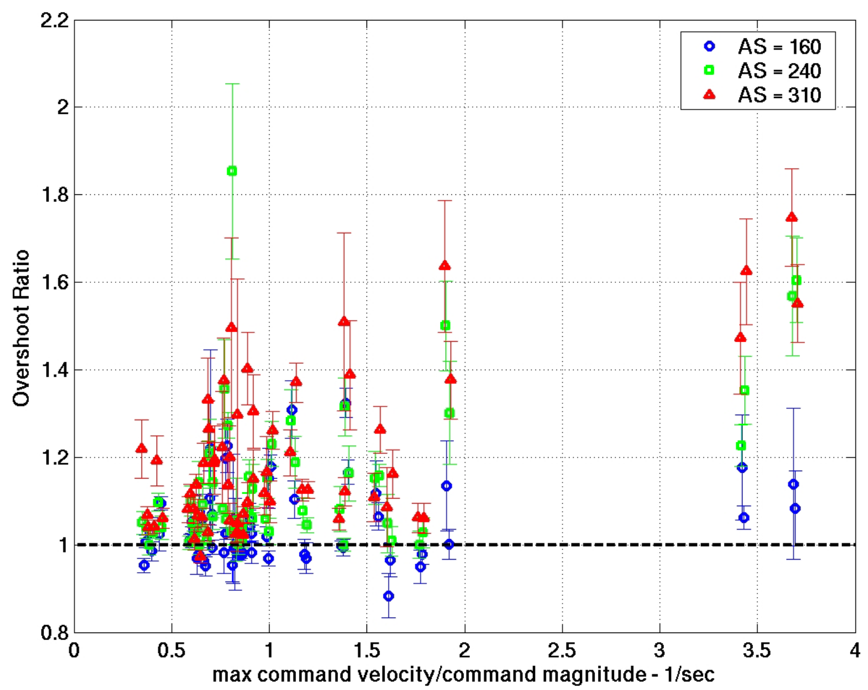

Figure 14 – Mean overshoot ratio as a function of magnitude of command velocity divided by command magnitude (standard error bars are shown).

Although trends can be observed in the data, what is desired is to develop an expression that shows the relationship between the potential causal factors and the dependent measure (in this case, overshoot ratio). Multiple regression analysis is a method well suited to this problem. Multiple regression analysis does not establish causality, but rather documents the predictive value of independent variables. Given a dependent measure, a relationship is postulated between the dependent measure and potentially n predictor variables. If we specify y as the dependent measure, x_i as the ith predictor variable (out of n possible), and c_0 through c_n as constants, the equation specifying the relationship between the dependent measures and predictor variables is:

$$y = c_0 + c_1 x_1 + c_2 x_2 + \ldots + c_n x_n + \varepsilon$$

In multiple regression analysis, a least-squares fit is done to determine the parameters (c_0 through c_n) that best fit the relationship between the dependent measures and the predictor variables. The term ε represents the variance not accounted for by the predictor variables.

3.2.1 Methodology

Several different types of predictor variables were considered in preliminary analyses. Some particular predictor variables showed good correspondence with the dependent measure, and were included in the multiple regression analysis. The predictor variables that were chosen to use in the analysis are:

T_{max}^{-1} = Normalized Inverse Command =
1/(proportion of maximum pedal deflection)

dT_{max} = Normalized Maximum Command Velocity =
(maximum velocity of command)/(maximum amplitude of command)

dT_0 = Normalized Initial Command Velocity =
(initial velocity of command)/(maximum amplitude of command)

The dependent measure chosen was the overshoot ratio, as defined previously:

OSR = Overshoot Ratio =
(maximum amplitude of response)/(maximum amplitude of command)

3.2.2 Results

Multiple regression analyses were done for each airspeed condition separately (to permit subsequent comparisons of the regression coefficients). The relationship used for the multiple regression was:

$$OSR = c_0 + c_1 T_{max}^{-1} + c_2 dT_{max} + c_3 dT_0 + \varepsilon$$

Table 2 shows the results of the multiple regression analysis for each airspeed condition. The number R^2 corresponds to the percent of the variance in the dependent measure that is accounted for by the predictor variables. The coefficients in the multiple regression equation above are shown next (c_0 through c_3). Standardized coefficients are also shown.

	Airspeed condition (knots)	165	240	310
	R^2	.268	.614	.709
Unstandardized Coefficients	c_0 (constant)	.943 ± .026	.839 ± .035	.867 ± .032
	c_1 (multiplies T_{max}^{-1})	.015 ± .005	.039 ± .006	.037 ± .006
	c_2 (multiplies dT_{max})	.081 ± .026	.209 ± .034	.245 ± .032
	c_3 (multiplies dT_0)	-.048 ± .021	-.073 ± .028	-.073 ± .026
Standardized Coefficients	β_1 (corresponds to T_{max}^{-1})	.365	.518	.462
	β_2 (corresponds to dT_{max})	.690	.962	1.065
	β_3 (corresponds to dT_0)	-.494	-.414	-.388

Table 2 – Results of the Multiple Regression Analysis for all conditions

To aid in visualization, the regression coefficients (as a function of airspeed) are also shown in Figures 15 through 18; confidence intervals have been calculated from the standard errors and are shown graphically. The coefficients c_0 and c_3 vary little with airspeed; the confidence intervals on the coefficients overlap considerably. The coefficients c_1 and c_2, multiplying the factors T_{max}^{-1} and dT_{max}, respectively, do show variation with airspeed. Specifically, the coefficients at the higher airspeeds differ significantly from the low airspeed condition (since the confidence intervals at the higher airspeeds do not overlap those at the lower airspeeds).

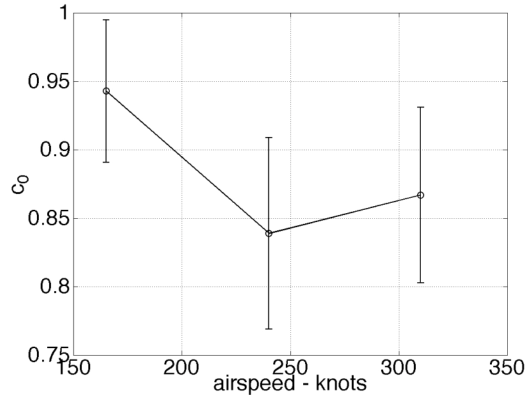

Figure 15 – constant coefficient (c_0) in regression equation as a function of airspeed

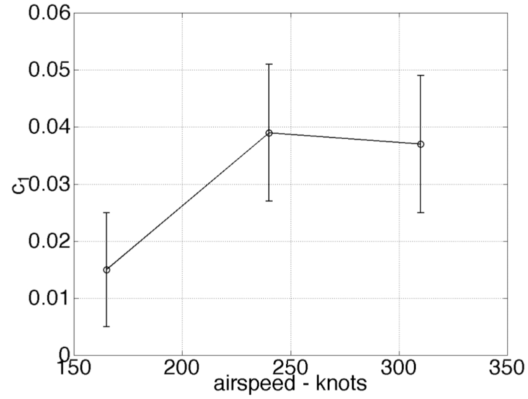

Figure 16 - multiplier coefficient (c_1) of normalized inverse command (T_{max}^{-1}) in regression equation as a function of airspeed

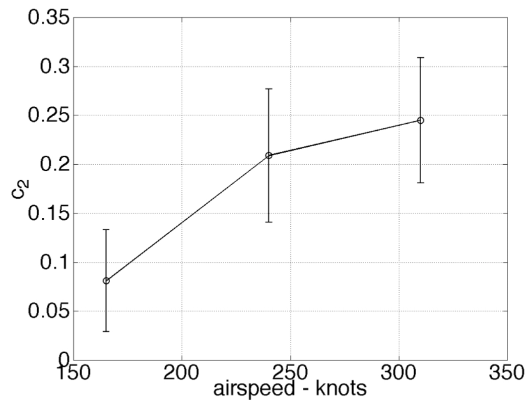

Figure 17 - multiplier coefficient (c_2) of normalized maximum command velocity (dT_{max}) in regression equation as a function of airspeed

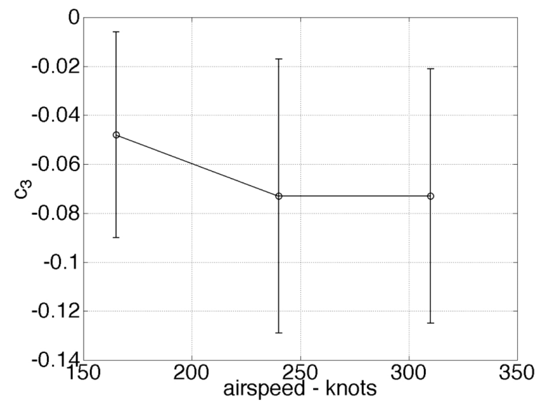

Figure 18 - multiplier coefficient (c_3) of normalized initial command velocity (dT_0) in regression equation as a function of airspeed

Because the predictor variables are often expressed in different units, and can have differing magnitudes, it can be difficult to determine which predictor variables are having the greatest predictive value – the equivalent of comparing apples and oranges. The standardized coefficients are normalized in such a way that we can assess the relative contribution of the predictor variables in predicting the dependent measure. Figure 19 shows these standardized coefficients as a function of airspeed.

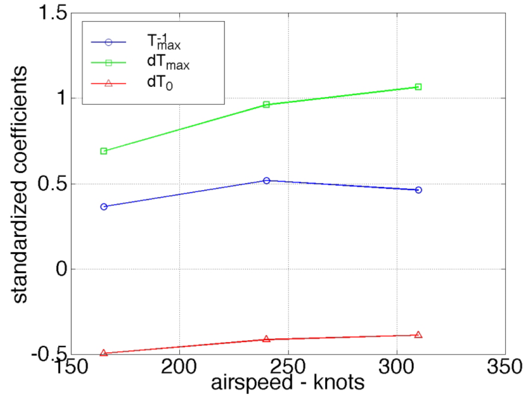

Figure 19 - Standardized coefficients as a function of airspeed

3.2.3 Discussion

In a perfect world, we would expect the response of the subject to match the commanded response – this would result in an overshoot ratio of unity in all conditions. The multiple regression technique helps to identify those variables that can help to predict when the overshoot ratio will vary from unity. As can be seen, the R^2 values indicate a relatively good predictive ability of the multiple regression equations, and the predictive value increases at the higher airspeeds. Figure 20 shows the predicted versus actual values of overshoot ratio; as can be seen, the regression equation does a good job of matching the overall changes in overshoot ratio.

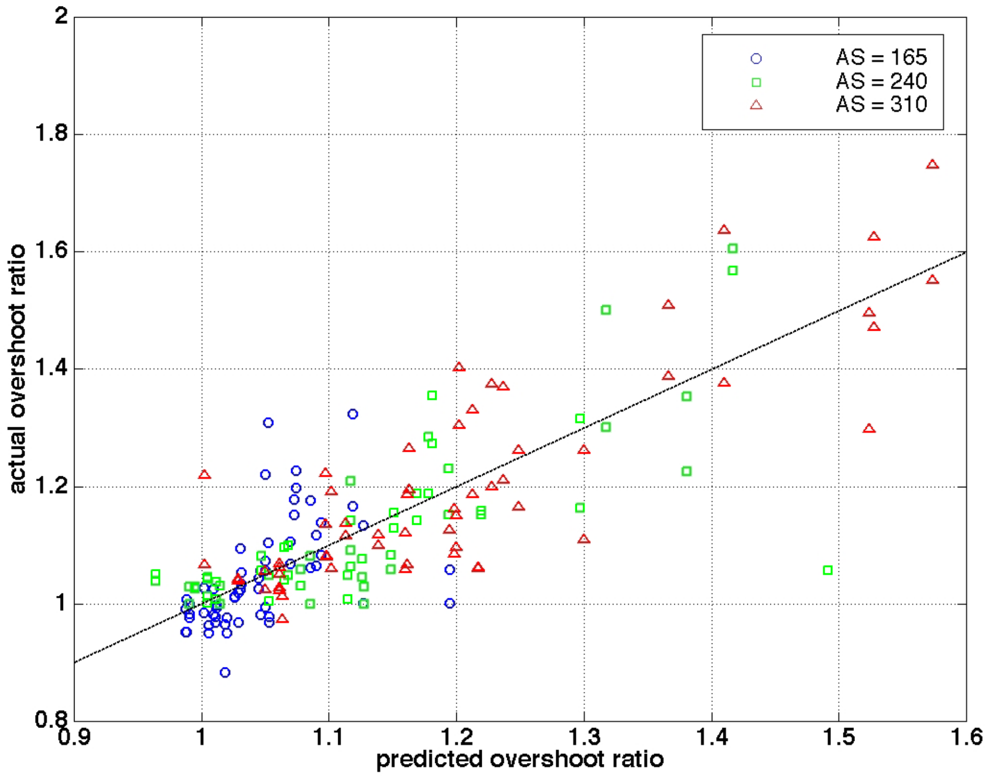

Figure 20 – Actual versus predicted overshoot using multiple regression equation.

Of the three predictor variables, the predictor variable intended to measure the "aggressiveness" of the command, dT_{max}, had the greatest effect in predicting the amount of overshoot. Additionally, this effect is increased at the higher airspeeds. Another predictor variable, dT_0, can moderate the effect of the aggressiveness. The coefficient on dT_0 is always negative; this implies that when the initial velocity is similar to the commanded velocity (i.e., the pedal is already in motion), the effect of the aggressiveness of the command is reduced. Conversely, when a command is initiated from zero velocity, the effect of command aggressiveness will be the greatest. This is consistent with the pedal mechanism – there is a constant friction force that opposes the direction of motion. If the pedal is already in motion, the subject is already generating this magnitude of force – the additional or "delta" force necessary for the subject to generate to achieve the breakout force is less than if the pedal were initially at rest. Specifically, this relationship implies that commands initiated from rest will have greater overshoots than commands that cycle from positive to negative displacement (or vice versa). Also, because the effect of dT_{max} increases with airspeed, and the moderating effect of dT_0 does not appear to change with airspeed, the results imply that aggressive commands will be associated with increases in overshoot, whether the command was initiated from rest or was a continuation from a previous input.

The amplitude of the command had an inverse effect on overshoot – low amplitude commands had higher overshoot than high amplitude. This effect is greater at higher airspeeds.

To better visualize these effects, Figure 21 shows the predicted effect of two of the three predictor variables (T_{max} and dT_{max}) at the three airspeed conditions. The effect of these predictor variables on predicted overshoot increases with airspeed.

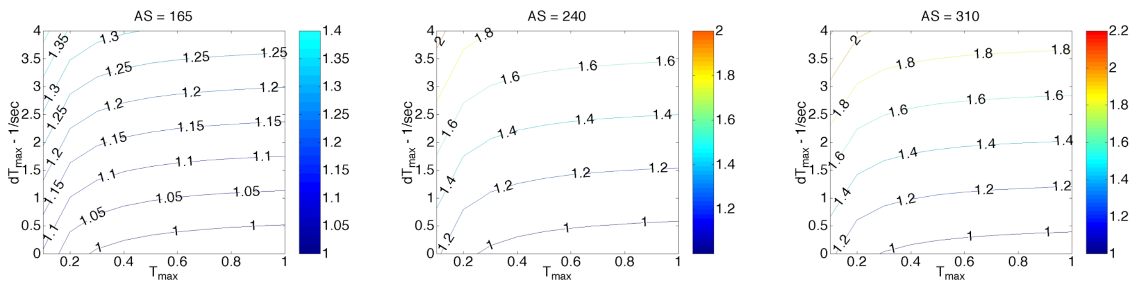

Figure 21 – Predicted effect of T_{max} and dT_{max} on overshoot ratio as a function of airspeed. Contour plots show level of overshoot predicted.

3.3 Time History Analysis

The third analysis method consisted of time-history modeling of the subject as a control element. This was done to examine whether the subject's control movements were possibly exaggerated by the motion of the aircraft. In general, it did not appear that the control motions were directly correlated with the motion of the aircraft. That is *not* to say that the motion did not affect the subject's ability to control the aircraft; rather, it suggests that the motion (specifically, the accelerative forces from the motion) did not appear to directly create control inputs.

4.0 Summary

The most relevant results of this study are that:

1) The change in the characteristics of the pedal control-effectors with airspeed contributed to greater overshoot at greater airspeeds; specifically:
   a) Aggressive commands were associated with more overshoot than non-aggressive commands, and the amount of overshoot increased with increasing airspeed.
   b) Low-amplitude commands were associated with more overshoot than higher amplitude commands, and the amount of overshoot increased with increasing airspeed.
2) Commands initiated from zero velocity were associated with more overshoot than commands that were a continuation of motion.
3) In an aggressive command, initiated from rest, accelerative forces similar to those experienced in the 587 flight were associated with greater overshoots.

The study showed that the changes in control-effector characteristics (which are functions of increasing airspeed in the aircraft) decrease the subject's ability to make accurate control inputs. These effects are most pronounced when the command amplitude is small, and when the command input is aggressive. They also show that motion of the platform decreases the ability of the subject to make accurate, sudden control inputs. The subject model referred to in the discussion section is highly simplistic, and is used only to help explain how apparently different control strategies can manifest themselves.

The differences between the tracking task and the flying task were discussed previously. The tracking task was specifically designed to examine the interaction between the subject and the control effectors. Whereas this study reveals that the accuracy with which the subject can produce control movements is affected by airspeed-related changes in the control effectors, the operational impact remains to be determined.