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Evaluation of Flight Crew Response to Wake Vortex Encounters During Takeoff

July 2019

Technical Report

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12. Abstract

This report presents the results of an ongoing known Wake Vortex Encounter (WVE) classification experiment. The research described in this report focuses on WVE during the takeoff phase of flight, specifically the first and second segment climb. The experiment was conducted in the FAA Boeing 737-800 full motion flight simulator. The purpose of this effort is to correlate aircrew subjective severity ratings of simulated WVE with the corresponding aircraft aerodynamic behavior during the takeoff phase of flight up to 1500 ft above ground level (AGL). This correlation would aid in the determination of a level of severity for the WVE, consistent with the Safety Management System (SMS) process. The results of the study indicate the crewmembers' severity level ratings were consistent with the magnitude of upset and were common to both crewmembers; however, altitude did not have a significant effect on subject pilot severity ratings. The magnitude of the aircraft upset was consistent with the strength of the vortex encounter.

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Executive Summary

This technical report presents the results of the Wake Vortex Encounter (WVE) classification experiment during the takeoff phase of flight, conducted in the Boeing 737-800 full motion flight simulator. The purpose of the experiment is to help establish criteria for the definition of a WVE severity consistent with the current Federal Aviation Administration (FAA) Safety Management System (SMS) process.

There are five levels of severity contained in the FAA SMS. FAA Order 8040.4, *Safety Risk Management Policy*[1], defines the levels as minimal (no safety effect), minor, major, hazardous, and catastrophic. Using existing data for the likelihood of a WVE encounter combined with the levels of severity derived by correlating crewmembers' subjective ratings of the simulated WVE with the resultant aircraft aerodynamic responses in this study, objective criteria for assessing total risk can be established. This will aid the FAA in determining the level of risk associated with a wake turbulence encounter for any new or modified flight procedure or operation.

The experiment consisted of 12 one-day simulator sessions using various WVE scenarios conducted from October 2018 to December 2018. Each session consisted of 75 predetermined scenarios where the flight crews experienced simulated WVEs. The focus of the experiment was WVE during takeoff; however, 18 of the 75 scenarios were WVE on arrival. For each encounter, the flight simulator objective data was recorded and each crewmember completed a subjective questionnaire. A total of 900 scenarios were completed over the course of the study.

The study was focused on investigating potential correlation(s) between the subjective and objective data. The strongest correlation existed between pilot severity ratings and the aircraft's maximum roll acceleration, maximum roll rate and maximum roll angle.

The results of the study indicate:

- Aircrew subjective responses indicated maximum roll rate and maximum roll angle were more impactful to the severity of the WVE classification than the other aircraft parameters with P-Values < 0.01;
- There was significant correlation between the pilot flying severity ratings and the magnitude of upset. The P-Values for the correlation were all < 0.01, except for maximum pitch angle. The magnitude of the aircraft upset was shown to correlate with the strength of the vortex encounter. This means as the gamma level (strength) of the wake vortex increased the greater the aircraft upset and the higher the severity level rating by the subject pilot;
- The gamma level (strength) value had a significant impact on the subjective severity rating with P-Value < 0.01, meaning the subject pilot severity ratings tended to be higher when the wake vortex gamma level was higher; and

[1]Federal Aviation Administration. 2017. *Safety Risk Management Policy, FAA Order 8040.4.*

- The altitude of the WVE during takeoff had a negligible impact on the crew's severity rating with a P-value < 0.01. However, in the small subset of approach scenarios altitude appeared to impact the crew's severity ratings, which is consistent with results from the 2014 experiment results[2].

[2] Doug Rodzon, Richard Greenhaw, Jeffrey Fierro, Paul Nelson, Larry Newman. 2014. *Evaluation and Scaling of Wake Vortex Encounters and Responses During the Approach Phase Flight Segment in the 737-800.* Oklahoma City, OK: Federal Aviation Administration.

1 Introduction

Currently, no internationally accepted criteria exists to evaluate and classify WVE severity; the FAA and NASA are collaborating to develop this criteria[3]. This report is intended to support the development of WVE severity level classification criteria and standards, and may be used in the future to evaluate the WVE level of risk associated with any new or modified flight procedure or operation.

The primary focus of this experiment was the terminal area phase of flight, specifically, the takeoff segment (up to 1500 ft AGL). A wake vortex encounter could be considered more hazardous during this phase of flight due to the close proximity to terrain as well as the changing energy state (potential and kinetic) of the aircraft.

Subject Matter Experts (SME), using information gained from Light Detection and Ranging (LIDAR) systems, have been able to develop models to predict potential wake vortex behavior based on the type of wake vortex producing aircraft[4]. Using the likelihood and levels of severity derived from this study, the Wake Turbulence Chief Scientific and Technical Advisor intends to determine objective criteria for categorizing WVE severity and the total risk associated with a WVE for future flight operations.

Table 1-1: FAA Order 8040.4, SMS Risk Matrix[5]

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Red]	[Red]	[Red]
Remote C	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Extremely Remote D	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely Improbable E	[Green]	[Green]	[Green]	[Yellow]	[Red] * / [Yellow]

High Risk [Red]
Medium Risk [Yellow]
Low Risk [Green]

* High Risk with Single Point and/or Common Cause Failures

[3] Retman, Michelle. 2016. "Wake Turbulence ASRS Report Review." *Wakenet USA.* New York, NY: Federal Aviation Administration. 1-43.

[4] Cindy Engholm, Dave Clark, Dr. Vab Andleigh, Frank Pobansky, Margo Pawlak. 2016. *Forecast and Data Needs to Support future Wake Solutions.* Boston, MA: Lincoln Laboratory, MIT.

[5] Federal Aviation Administration. 2017. *Safety Risk Management Policy, FAA Order 8040.4B.*

1.1 Background

An interim report completed April 2014, *Evaluation and Scaling of Wake Vortex Encounters and Responses during the Approach Phase Flight Segment in the 737-800*[6], focused on WVE during the approach phase of flight. In that study, there were 12 five-day simulations conducted from June 2011 to September 2013. Each session exposed flight crews to simulated WVEs during predetermined scenarios. Objective, numerical flight simulator data was recorded and each crewmember completed a subjective questionnaire during each encounter. That study focused on finding correlation between the subjective WVE severity rating and the objective simulator data. The strongest correlation existed between pilot severity ratings and aircraft bank angle. Results of the 2014 interim report indicated the following:

- The subjective data were commonly agreeable between the two flight crewmembers;
- The Pilot Flying (PF) severity level ratings were commonly consistent with the magnitude of upset from the aircraft's pre-encounter state;
- The magnitude of the aircraft upset was consistent with the strength of the vortex encounter; and
- Crews tended to give a higher severity rating to WVEs that occurred closer to the ground.

1.2 Purpose

The purpose of this report is to help establish criteria for the definition of a WVE severity consistent with the current FAA SMS process. This will allow the FAA to determine the level of risk associated with a WVE for any new or modified flight procedure or operation. This phase of the program primarily studied WVE during the takeoff phase of flight.

[6] Doug Rodzon, Richard Greenhaw, Jeffrey Fierro, Paul Nelson, Larry Newman. 2014. *Evaluation and Scaling of Wake Vortex Encounters and Responses During the Approach Phase Flight Segment in the 737-800.* Oklahoma City, OK: Federal Aviation Administration.

2 Objectives and Scope

2.1 Objective 1

Determine which aircraft parameter(s) (e.g., roll, yaw, altitude, accelerations, etc.) subject pilots report using to rate the severity level of a wake vortex encounter.

2.2 Objective 2

Determine whether there is a significant relationship between the measured extrema of the aircraft parameter(s) determined in objective 1 during wake vortex encounters and subject pilot severity ratings.

2.3 Objective 3

Collect aircraft state and aerodynamic data for post-simulation analyses to be conducted by the FAA Wake Program.

3 Methodology

Pilots experienced a WVE at three preset strengths and altitudes during takeoff. The direction of wake vortex rotation was alternated throughout the session. Although the main focus of the study was WVE on departure, a small number of approach scenarios were also sampled. On approach, pilots experienced a WVE at three preset strengths at two different altitudes. The approach scenarios were used to compare pilot responses to the previous WVE approach tests completed in 2013, as well as provide some variation for the subject pilots. Appendix B contains two tables, one for departure and one for approach, which delineate the parameters for each run. The order of the runs were randomly generated for each session to guard against sequencing and learning effects.

3.1 Test Design and Scenarios

The experiment was conducted over 12 four-hour simulator periods in the Boeing 737-800 simulator. Each day, the four-hour sessions were divided into two, two-hour simulator blocks with a thirty-minute break in between each block. Each simulator block consisted of scenarios randomized from the condition matrix tables (Appendix B). The first simulator block consisted of 38 runs randomized from the departure and arrival scenario matrices (Table B-1 and Table B-2 respectively), and the second block consisted of the remaining 37 runs, for a total of 75 runs for the session. The departure scenarios consisted of 57 runs, three of which were baseline runs where a wake vortex was not encountered. The baseline runs were incorporated to help counter learning effect of the subject pilots.

All scenarios took place at San Francisco International Airport, San Francisco, CA. For each departure scenario, the simulator was positioned at the runway threshold on runway 28R and configured for takeoff. The departures were conducted in visual meteorological conditions (VMC). For the approach scenarios, the simulator was positioned on a three-nautical mile (NM) final to runway 28R, established on the Instrument Landing System (ILS) approach, on course and on glidepath. All approaches began in Instrument Meteorological Conditions (IMC), and transitioned to VMC. For both the departure and approach scenarios, the Flight Management System (FMS) was programmed with all relevant information and the simulator was configured appropriately. Prior to commencing the test, the Principal Inspector (PI) gave the current weather conditions and specified which pilot was to perform the duties of PF and Pilot Monitoring (PM) in accordance with the randomized condition matrix (Appendix B).

The PI began the test run when all aircrew and observers indicated they were ready. A wake vortex was introduced at the altitude, strength (gamma) and direction of rotation in accordance with the condition matrix. When the aircrew encountered the wake vortex, they were expected to maintain aircraft control and continue to fly the aircraft as they would for typical line operations. For departure scenarios, the simulation continued until the subject crew had regained positive control of the aircraft or climbed through 1500 ft AGL. The approach scenarios were terminated when a positive rate of climb had been achieved following a go-around maneuver or upon landing. After the termination of each run the PI stopped the simulation and directed the crewmembers to complete the subjective questionnaire (Appendix D) contained on the electronic flight bag (EFB).

When the simulation was complete, the PI along with the Pilot/Human Factor (HF) Observer guided the subject pilots through a Post Evaluation Debriefing (Appendix E). The de-brief used an open discussion format.

3.2 Test Assumptions

- Subject pilots respond to the simulated WVEs as they do to WVEs during revenue operations.
- There is no significant difference in pilot responses between a right vortex and a left vortex given reversed encounter angles.
- The simulator is capable of effectively replicating WVEs.

3.3 Independent Variables

The independent variables, gamma and altitude, were manipulated to determine any potential effects on subject classification of the WVE. The variables were counterbalanced within subject. The wake vortex circulation strength, gamma, was tested at three different levels for each encounter. Gamma values were selected so that the highest gammas generally resulted in full control input by the subject crews, the middle gamma yielded significant control input but rarely required full input, and the lowest wake vortex gamma usually only required minimal control input. Gamma values for WVE on departure were tested at $200m^2$/sec, $300m^2$/sec, and $400m^2$/sec. Gamma values for WVE on approach were tested at $100m^2$/sec, $200m^2$/sec, and $300m^2$/sec. WVE were also sampled at varying altitudes: departure encounters occurred at 112 ft AGL, 600 ft AGL, and 1200 ft AGL; approach encounters occurred at either 150 ft AGL or 500 ft AGL. The departure altitudes were selected so that all WVE occurred within the initial climb segments before 1500 ft AGL and far enough apart for the crew to be able to discern a difference. Approach altitudes were selected to correspond and thus be comparable to previous test results.

3.4 Dependent Variables

The dependent variables consist of the subjective responses including pilot post-run responses and responses recorded in the post-evaluation de-briefing. The objective dependent variables consist of the Simulator Data Collection Variables described in Appendix F.

3.5 Constants

All scenarios took place at San Francisco International Airport. The FMS had the appropriate flight plan, weights, and pertinent data recalled prior to every run. Furthermore, all departure scenarios were positioned on the same runway threshold in takeoff configuration, and all approach scenarios were positioned at 940 ft MSL and 4.9 Distance Measuring Equipment (DME) on the localizer and glideslope. The scenarios were during the day. All departure weather was clear with 15 statue mile (SM) visibility, with winds 270° at 5 knots. All arrival weather was in IMC (400 ft AGL overcast ceiling, 1 SM visibility, Runway Visual Range (RVR) 9500 ft below the ceiling, fog top of 25 ft) and the surface winds were calm. The simulation had no aircraft deferred items and all instrumentation and automation systems were functional. Subject crews were instructed to fly in accordance with their company policy; with the exception of the pilot flying was directed to hand fly (no autopilot) every scenario. The head-up display (HUD) was operational and Captains that were HUD qualified were directed to use it in accordance with company policy.

The wake vortex itself was a single vortex encountered only one time; the crew was not able to fly out of the wake vortex and then re-enter further along the departure or approach path. It existed for 8.0 seconds, remaining at full strength for 5.5 seconds and then linearly decreasing in strength to zero over the last 2.5 seconds.

The wake vortex model used in this experiment was the Burnham-Hallock Flow Field Model. The model had these characteristics for the departure encounter:

- Wake lateral distance (Lat Dist): +/- 10 feet from aircraft (same sign as circulation)
- Wake vertical distance (SW Vert): -10 feet (aircraft above the wake vortex)
- Wake core size (radius): 10 feet
- Wake lateral encounter angle: 0°
- Wake vortex will stay with the aircraft selected
- Aircraft relative pitch angle selected

The model had these characteristics for the approach encounter:

- Wake lateral distance (Lat Dist): +/- 5 or 10 feet from aircraft per table (same sign as circulation)
- Wake vertical distance (SW Vert): -5 or -10 feet per table (aircraft above the wake vortex)
- Wake core size (radius): 5 or 10 feet per table
- Wake lateral encounter angle: 0°
- Wake vortex will stay with the aircraft selected
- Aircraft relative pitch angle selected

4 Test Support Requirements

The experiment consisted of aircrew captain and first officer, 737-800 simulator, one Pilot/HF observer and the PI who also performed the Operator Station (IOS) operator duties. The PI generated and logged all test conditions listed in the condition matrix and provided subject pilots with sufficient information to respond to the post-run questionnaires (Appendix D).

4.1 Subject Pilots

The subject pilots were current and qualified in the Boeing 737 aircraft type and were familiar with the 737 next generation (NG) instrumentation. The pilots were Title 14, Code of Federal Regulations (14 CFR) part 121 air-carrier line pilots currently flying line operations. During the pre-brief, every subject pilot reported having had a WVE in his or her flying career. Most pilots categorized their WVE experiences as minimal or minor; however, two reported a violent encounter or momentary loss of control. All crews were comprised of pilots from the same company, except crew number 9. The PI, pilot observer, and crewmembers discussed differences in company callouts and procedures. The crewmembers worked together to adopt uniform callouts and procedures and were able to adapt to the minor adjustments without any noticeable effect during the study.

Captains, who were HUD-qualified, were permitted to use the HUD installed in the 737-800 simulator. The HUD installed is the Rockwell Collins (RCI) 6700 and is the next version of the RCI 4000 currently installed on HUD-equipped 737 aircraft flying 14 CFR part 121 operations.

All of the Captains, that used the HUD in this study, were qualified on the RCI 4000 series HUD. There is a slight difference in the HUD symbology, but the overall functionality is very similar between the two

models. No HUD-qualified Captains reported any problems using the RCI 6700 HUD during this study. Eight of the 12 Captains used the HUD per company policy. One Captain (crew 5) used the HUD during approaches but stowed it on departure citing company policy for takeoff in VMC conditions.

4.2 Aircraft Simulator

The following simulator requirements applied to all data collection sessions:

- Auto-throttles (AT) were operational and utilized in accordance with aircrew company policy.
- Simulator provided suitable guidance for hand-flown operations using the flight director.
- Simulator conformed to Level D criteria.
- Simulator was configured to conduct either the departure or ILS Runway 28R approach at San Francisco International Airport.
- Simulator had no artificial errors introduced.
- Data parameters collected are listed in Appendix F.
- HUD was fully functional.

4.3 Video and Audio Recording

Commencing with subject pilot entry into the cockpit and ending not earlier than subject pilots departing the cockpit, video, and audio recordings were made of each simulator session. The crewmembers were made aware of this requirement during the pre-brief prior to commencing the study.

Video recordings were made primarily of the left forward panel, targeting specifically the left Primary Flight Display (PFD) and left Navigation Display (ND).

4.4 PI and Human Factors/Pilot Observers

The PI and a HF/Pilot Observer were stationed inside the simulator and were the only observers during the data collection. They took notes of events, activities, conditions, actions and communications that were considered significant to the data collection. They did not take an active role during the data collection sessions; however, the crewmembers were encouraged during the pre-brief to verbalize any comments they had during the test so that the observers could take notes for discussion during the post evaluation de-briefing.

5 Human Factors Analysis

This study was based upon human factor components, which were primarily assessed through a subjective questionnaire (Appendix D). Following each scenario, both crewmembers completed a post-run questionnaire, which was recorded electronically. The recorded subject pilot responses were used in conjunction with the simulator data to satisfy Objective 1 and Objective 2 described in section 2 of this report. During the pre-briefing, the crews were directed to select the severity rating of the WVE as it related to aircraft control input and flight path. They were asked to use the highest level (13) only in cases of a crash. There were no crashes during the 12-day data collections; however, six subject pilots selected level 13 as the severity level (two Captains and four First Officers). Therefore, to maintain consistency of pilot responses, the data points marked as level 13 were adjusted to severity level 12.

5.1 Realism

All crewmembers were able to use their flying experience and company procedures to effectively maintain or regain control of the simulator during each WVE. Crews 3-10 and 12 stated the WVE in the simulator seemed realistic and was an accurate replication of what they have encountered in the NAS. Crews 1, 2, and 11 felt the WVE in the simulator manifested as more severe and dramatic than any wake vortex they have encountered in their flying experience. The First Officer of crew 4 felt the onset of the wake encounter was not as rapid as has been his experience, and likewise, the Captain of crew 3 indicated the encounter felt more like a wind encounter than a wake encounter and the simulator model was missing the build-up or “burble” he has experienced in the airplane.

5.2 Wake Vortex Strength

Three different wake vortex gammas (strengths) were evaluated during departure and arrival scenarios. The highest gamma generally resulted in full control input by the subject crews. Several subject pilots noted that at full control input the yoke obscured the PFD, which resulted in increased workload. Some subject pilots reported their company policy, requiring pilots to keep one hand on the throttles below 2500 ft, made recovery from more severe WVE more difficult.

5.3 HUD

Seven of the 12 Captains (crew numbers 2, 3, 7, 8, 9, 11, and 12) were qualified and used the HUD throughout the course of the test. Crew numbers 1, 4, 6 and10 were not qualified and did not use the HUD. The majority of Captains that used the HUD found it very useful; however, one Captain (crew 5) noted that during extreme upsets he disregarded the HUD and relied on the PFD. The First Officers were not HUD qualified and did not utilize the HUD during this study. It may be useful to compare similar encounters between First Officers and Captains that used the HUD to see if any significant differences exist in the severity level ratings. This may be useful for WVE considerations in non-HUD equipped aircraft.

5.4 Use of Rudder

Rudder use during WVE recovery varied by subject pilot and by scenario. A significant number of pilots made rudder inputs during the more severe WVE. During the debriefing, pilots indicated, the ailerons did not feel as effective during those conditions. Over the course of the test, some pilots adjusted the amount of rudder use because they found less rudder input to be more efficient and effective. Subject pilots who did not make any rudder inputs or smoothly applied small rudder inputs appeared to have a more controlled

recovery from the WVE. It should be noted that the Aircraft Wake Turbulence Advisory Circular[7] states using the rudder to counter roll rate during a roll upset may lead to an undesirable aircraft response and pilots should exercise caution with pilot control inputs following wake encounters, especially avoiding abrupt reversal of aileron or rudder inputs.

5.5 Learning Effect

As expected, all subject pilots felt a learning effect played a part in their performance. The test was designed to help mitigate this effect by including approach WVE encounters, randomizing the scenarios for each crew and adding nominal (no event) runs throughout the test. Many subject pilots felt their reaction time improved and they became more comfortable with the required amount of control input over time. Throughout the simulations, many subject pilots made adjustments to the amount of rudder control input; however, no subject pilots opted to advance the throttles even though all takeoffs were reduced thrust takeoffs. Some crews indicated they became less operationally tolerant of WVE over the course of the study, while others said they became more tolerant.

5.6 Significant Aerodynamic Parameter(s)

During the post-simulation debriefing, a vast majority of subject pilots indicated that roll angle or roll rate was their most significant parameter in determining WVE severity rating. This was confirmed by analysis of question 2 on the Post-Run Questionnaire (Appendix D).

To determine which variables, if any, were cited as having a larger or smaller impact on the crew's perception of WVE severity level, two one-way Analysis of Variance (ANOVAs) were performed. If the null hypothesis of a one-way ANOVA is rejected it indicates that there is at least one category whose mean differed from the rest. The first was performed on just the Captain responses and the second was performed on just the First Officer responses. The ANOVA tables for both are below.

Table 5-1: ANOVA for Captain's Subjective Responses

Source	Sum of Squares	DF	Mean Square	F	Pr(>F)
Between Groups	583.54	5	116.708	407.848	<0.01
Within Groups	995.821	3480	0.286		
Total	1579.361				

Table 5-2: ANOVA for First Officer's Subjective Responses

Source	Sum of Squares	DF	Mean Square	F	Pr(>F)
Between Groups	642.646	5	128.529	445.121	<0.01
Within Groups	1004.854	3480	0.289		
Total	1647.5				

The critical value for an F-Test with degrees of freedom 5 and 3546 is 2.2167; thus, it is safe to reject the null hypotheses for both ANOVAs. This implies that there is a difference between the rankings of at least one category for both the Captains and First Officers subjective responses. To identify which of the subjective categories were ranked differently in both sets of responses, it is canonical to perform a

[7] Federal Aviation Administration. 2014. *Aircraft Wake Turbulence, AC 90-23G.*

Pairwise-Tukey test. The Pairwise-Tukey test summary for both Captain and First Officer subjective responses are described in the tables in Appendix G.

The Pairwise-Tukey test showed the two categories consistently cited as more impactful than the others were maximum roll rate and maximum roll angle. Figure 5-1 and Figure 5-2 below show the results for Captain and First Officer respectively. The x-axis represents how significant the pilots rated each parameter. One was not significant, two was significant, and three was very significant.

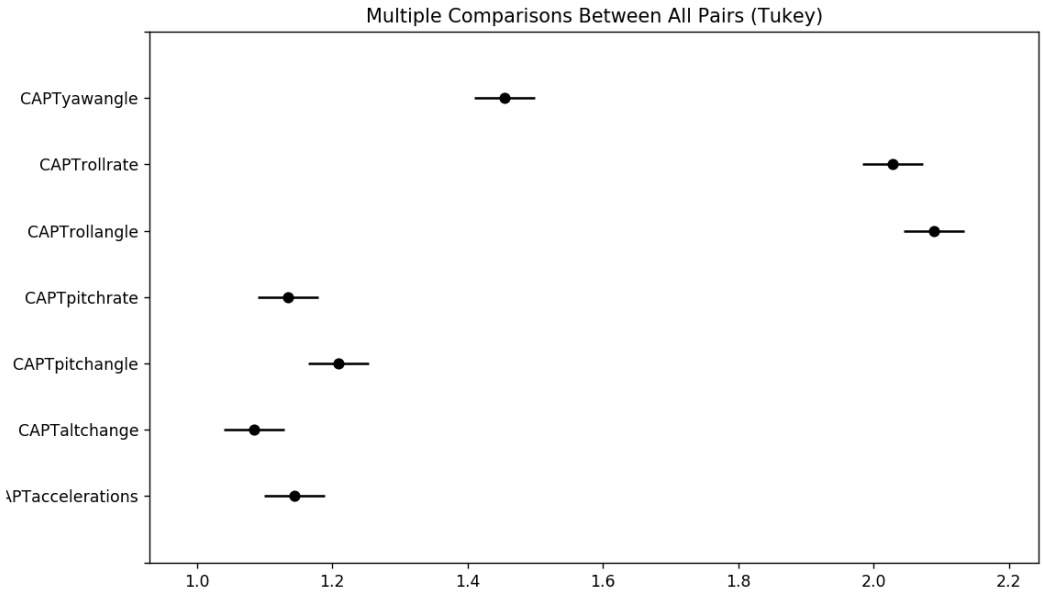

Figure 5-1: Tukey Test Results for Captain

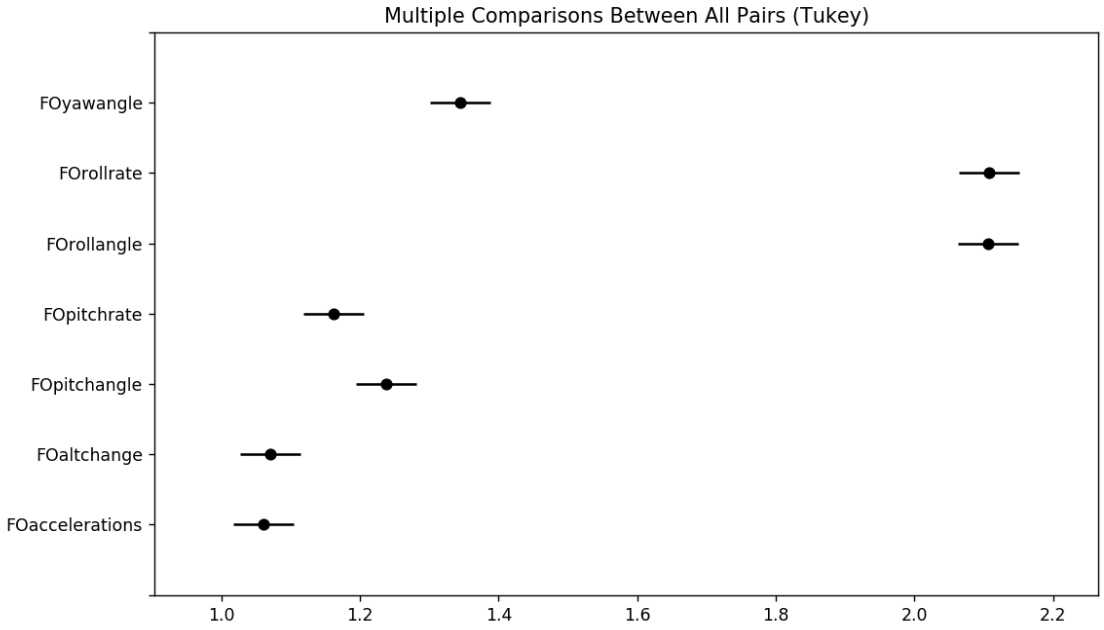

Figure 5-2: Tukey Test Results for First Officer

6 Statistical Results

The analysis performed for this test was primarily concerned with the second test objective, see section 2.

6.1 Data Processing

Following integration of subjective response data, simulator data was post-processed to identify the pitch angle, roll angle, yaw angle, and their respective first and second derivatives associated with an upset caused by the WVE. First, the analyst identified a candidate time interval for upset by adding a 0.5-second buffer following the time interval when the flight crew was subjected to the WVE. Then, the analyst found the maximum of the absolute value of the aforementioned angles and their derivatives during this candidate time interval.

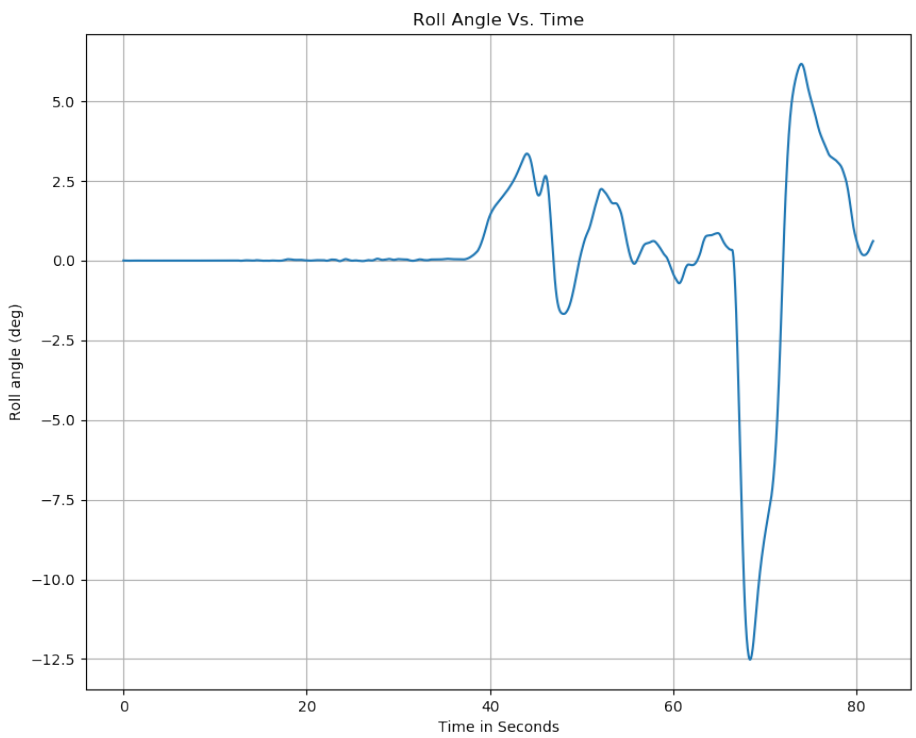

Figure 6-1: Example of Maximum Magnitude Finding

For example, Figure 6-1 shows the entire track worth of maximum roll angle values. We are only concerned with the section corresponding to the WVE. The data during the upset candidate time interval is shown in Figure 6-2.

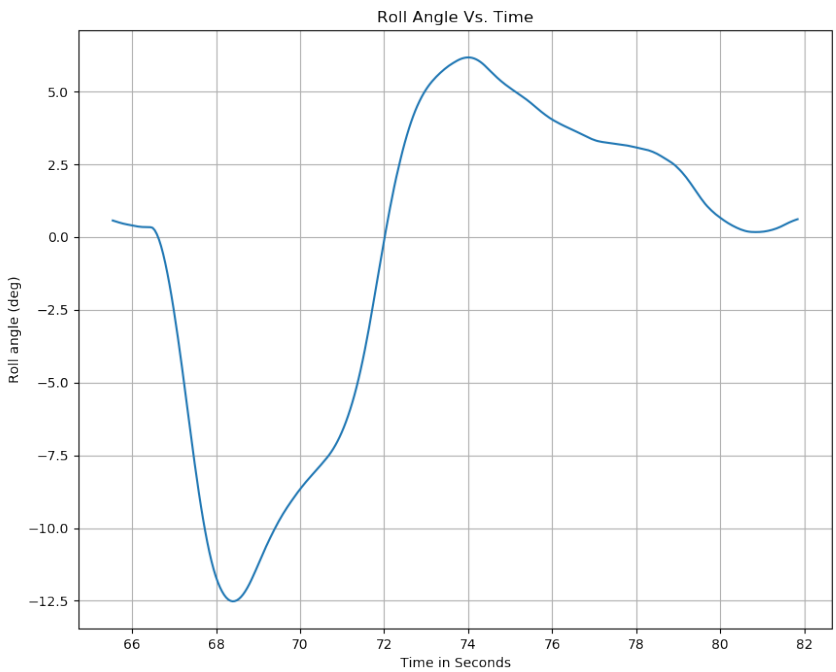

Figure 6-2: Pared Down Maximum Roll Angle

There was a sudden dip in roll angle beginning around the 68-second mark on the x-axis. Thus, to find the maximum magnitude, the maximum of the absolute values of the paired down of roll angle data was taken over this interval, yielding approximately 18 degrees. The same procedure was repeated for the all three angle variables: pitch, roll, yaw, and the respective derivatives.

6.2 Experimental Inputs Analysis

This analysis explored the variations caused by the input variables while removing the variability between different classes, or blocks, contained within the data using a random effects type ANOVA. The experimental variables, WVE strength (gamma in the WVE model), and the altitude were the ANOVA treatments.

Table 6-1: Two-Way ANOVA Table for Gamma and Encounter Altitude

Factor	Degrees of Freedom	Sum of Squared Errors	Mean Squared Errors	F Statistic	Pr(>F)
Encounter Altitude	2	30.088078	15.044039	3.653654	0.02649112
WVE Strength	2	1912.942062	956.471031	232.292262	<0.0001
Interaction Effects	4	7.378925	1.844731	1.844731	0.7738741
Residual	583	2400.521678	4.117533	4.117533	NaN

The interaction between wake vortex strength and encounter altitude was negligible (p-value = 0.77), meaning that the way flight crews rated severity based on WVE strength was nearly constant as altitude changed. Individually, however, both encounter altitude and WVE strength had a significant effect on flight crew perceived severity (p-value = 0.026, p-value < 0.001, respectively).

However, these factors have different relationships with the severity level. Figure 6-3 illustrates the number of runs with a given severity rating observed at each altitude, over all WVE strengths. Figure 6-4 illustrates the number of runs with a given severity rating observed at each WVE strength, over all altitudes.

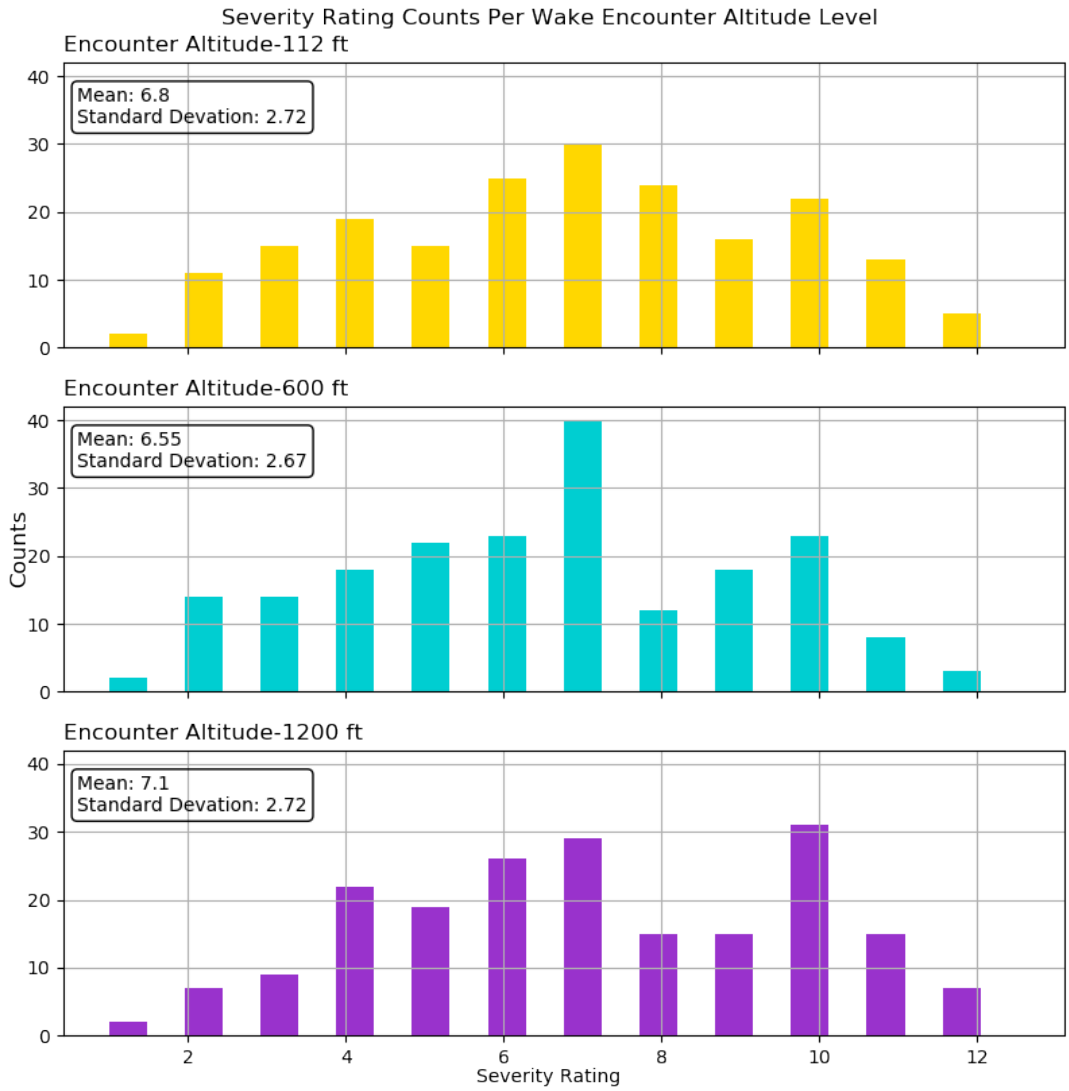

Figure 6-3: Severity Ratings for Each Level of the Independent Variable Encounter Altitude Histogram

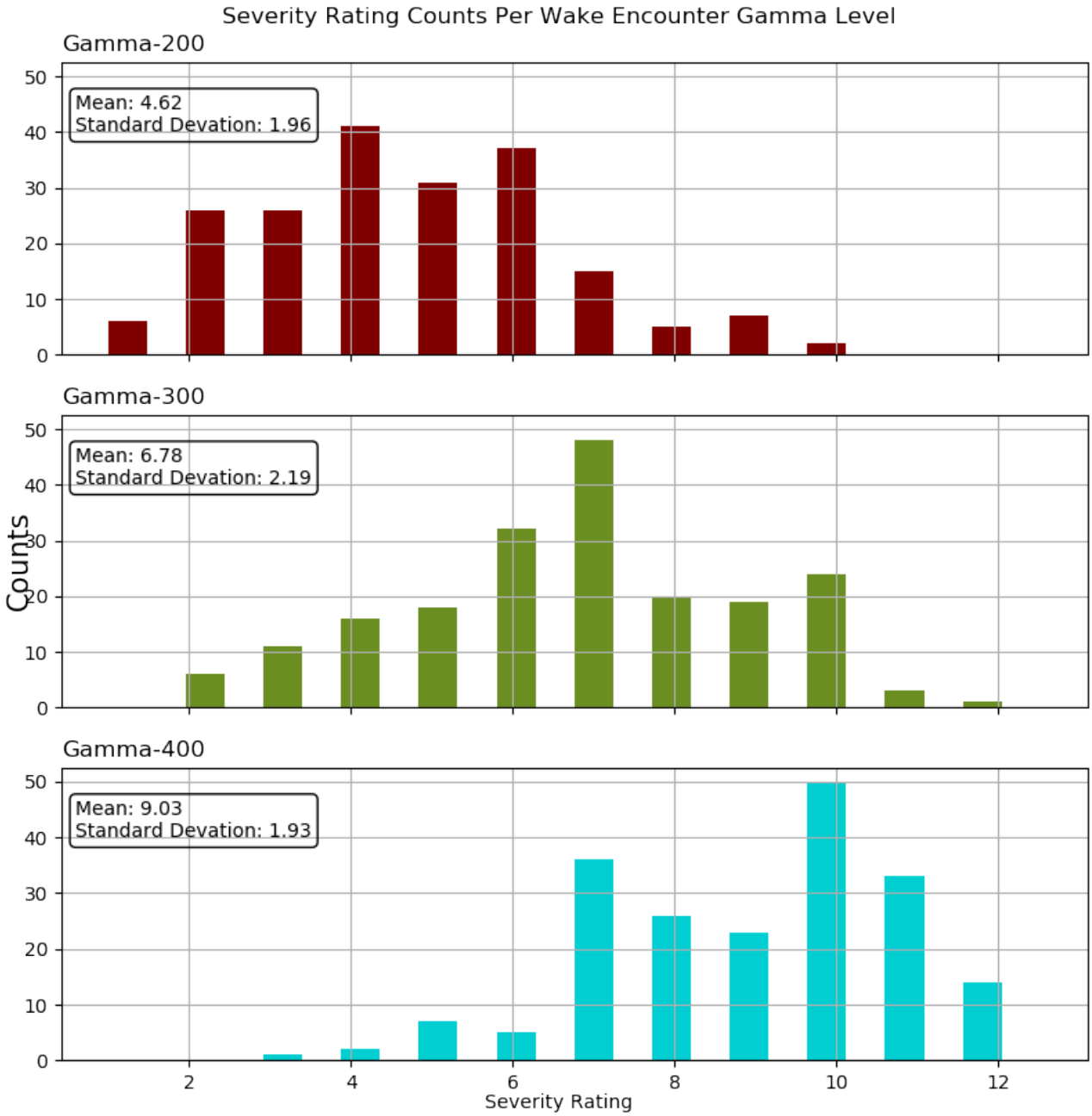

Figure 6-4: Severity Ratings for Each Level of the Independent Variable WVE Gamma Histogram

It is clear from Figure 6-3 that there was not a noticeable relationship between the levels of the WVE altitude and the severity rating of the WVE. However, a relationship between levels of gamma and the severity rating is apparent. That is, as WVE strength increased, the average crew severity rating also increased.

6.3 Upset Aerodynamics and Severity Rating Correlation

The correlation coefficients between severity and maximum magnitude values for pitch, roll, yaw and their respective derivatives describes how much each angle or derivative describes the variance in the

severity ratings. The maximum angle or derivative value in question was used as the independent variable and the severity rating was the dependent variable. A t-test was used to assess the significance of the calculated R-Squared value. An R-Squared (measure of correlation) value of 0 indicates no correlation, where an R-squared value of one indicates perfect correlation. The table below contains a summary of the R-squared values and their significance values.

Table 6-2: Aircraft parameters R-Squared Values

Aircraft parameters	R-Squared	T-Value	Pr(>|t|)
Max Pitch Angle	0.001	0.847	0.398
Max Pitch Rate	0.128	9.322	<0.0001
Max Pitch Acceleration	0.109	8.527	<0.0001
Max Roll Angle	0.307	16.163	<0.0001
Max Roll Rate	0.422	20.743	<0.0001
Max Roll Acceleration	0.445	21.729	<0.0001
Max Yaw Angle	0.061	6.180	<0.0001
Max Yaw Rate	0.174	11.138	<0.0001
Max Yaw Acceleration	0.187	11.639	<0.0001

The three variables with the highest R-Squared values were maximum roll acceleration, maximum roll rate, and maximum roll angle. All R-Squared values were statistically significant, with p-values < 0.05, results except for maximum pitch angle (p-value = 0.398).

The Figure 6-5 illustrates the relationship between maximum roll acceleration and severity rating.

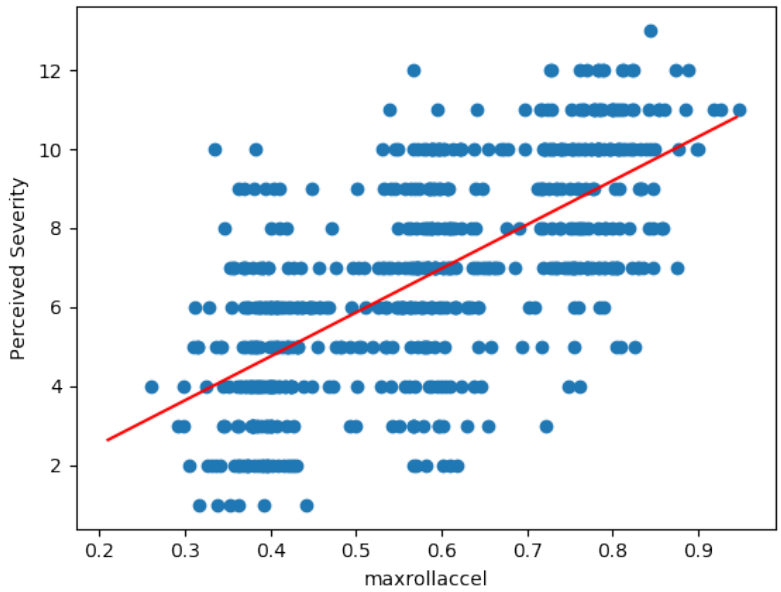

Figure 6-5: Maximum Roll and Severity Rating Scatter Plot

6.4 SMS Severity Scale vs. Bank Angle

The 13 level severity scale used by the subject pilots was grouped by color to correspond to the SMS severity levels. Levels 1, 2, and 3 equate to no safety effect; levels 4, 5, and 6 are minor, levels 7, 8 and 9 as major; levels 10, 11, and 12 as hazardous and 13 as catastrophic. Figure 6-6 uses all of the departure data, regardless of the WVE altitude, to illustrate the overall correlation between SMS severity level ratings and initial angles of bank that were achieved by the aircraft at the time of the encounter. The figure shows the higher the severity level rating the higher the expected bank angle.

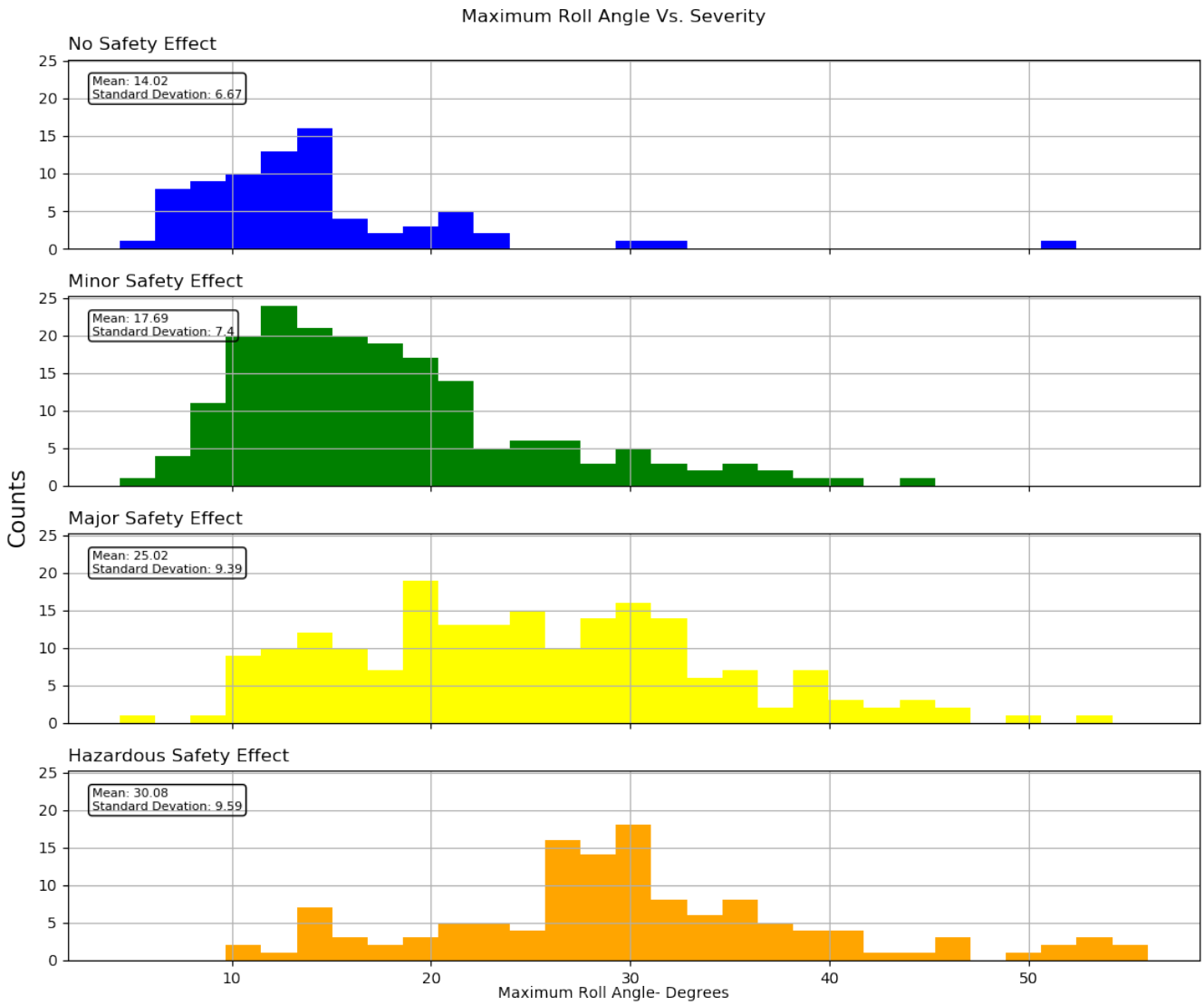

Figure 6-6: Departure SMS Severity Level vs Roll Angle

Figure 6-7 uses all of the departure data, segregated by WVE altitude, to illustrate the overall correlation between SMS severity level ratings and the initial angles of bank that were achieved by the aircraft at the time of the encounter. The analysis shows that altitude did not have a significant effect on subject pilot severity rating.

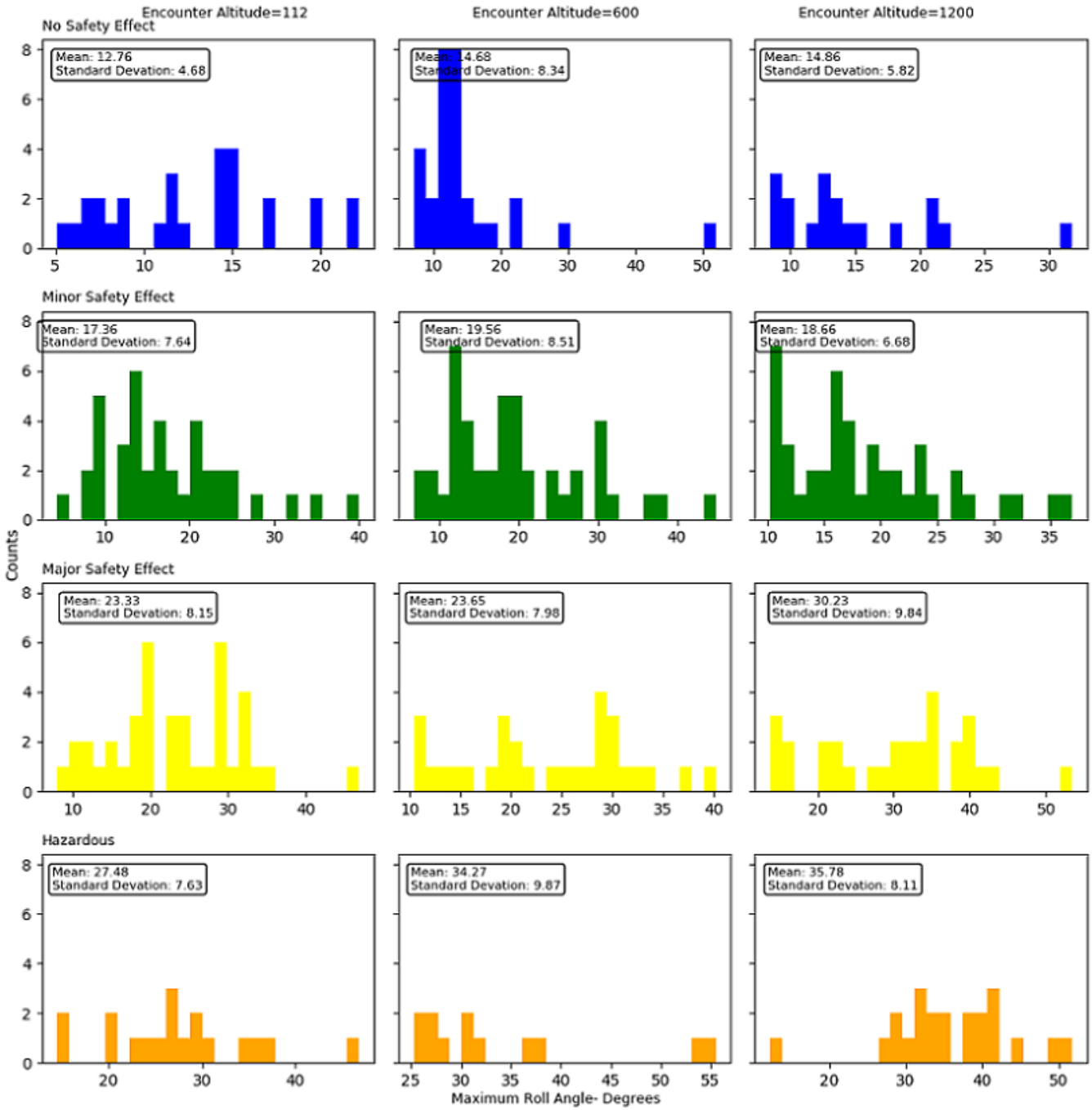

Figure 6-7: Departure SMS Severity Level vs Roll Angle by Altitude Encounter

6.5 Comparison with Arrival Results

The experiment included several scenarios where flight crews were asked to fly an approach. See section 3.1 to compare the results from previous arrival WVE studies[8] to the arrivals performed during this study. The results from the arrival procedures were similar to the previous arrival studies' results and the results for the departures in this study. In the previous study, the two aircraft parameters with the highest R-squared values were roll acceleration and roll angle; with values of 0.57 and 0.62 respectively. In the departure portion study, those same aircraft parameters constituted two of the three highest R-squared values in the test. Over the course of the prior arrival studies, the R-squared values for roll acceleration ranged from 0.14 during the June/August 2011 test to 0.57 for the September 2013 test. Similarly, the R-squared values for roll angle ranged from 0.19 during the first round of testing to 0.62 during the final round of testing. These changes may be attributed to testing procedures and questionnaire design. However, the general trend of the maximum roll angle, and maximum roll rate were consistently the aircraft parameters with the highest R-squared values; similar to what was observed in the current study.

The altitude that the subject aircraft encountered the wake vortex played a far larger role in the severity ratings in the last arrival study than in the arrivals in this study. Looking at the arrival procedures flown in this study, it can be seen that a mean shift does occur in the chart below; however, the number of runs were limited, and there is not enough to conclude that the means actually did shift. During the post-simulation de-brief several subject pilots compared WVE on approach to WVE on departure. The general consensus was that they rated the severity level higher and had far less operational tolerance for WVE on approach than they did for WVE on departure. Reasons included:

- During approach, they are aiming for a defined spot, the runway, as opposed to departure where they have "a whole sky" and were more tolerant of lateral displacement.
- The downward velocity vector on approach
- The thrust is at a lower setting on approach as opposed to already having a higher thrust setting.
- They were more aware of the aircraft altitude above the ground during approach. (They were more inclusive of radio altimeter in their scan on approach and visually looking out the window and seeing the ground as opposed to the sky.)

[8] Doug Rodzon, Richard Greenhaw, Jeffrey Fierro, Paul Nelson, Larry Newman. 2014. *Evaluation and Scaling of Wake Vortex Encounters and Responses During the Approach Phase Flight Segment in the 737-800.* Oklahoma City, OK: Federal Aviation Administration.

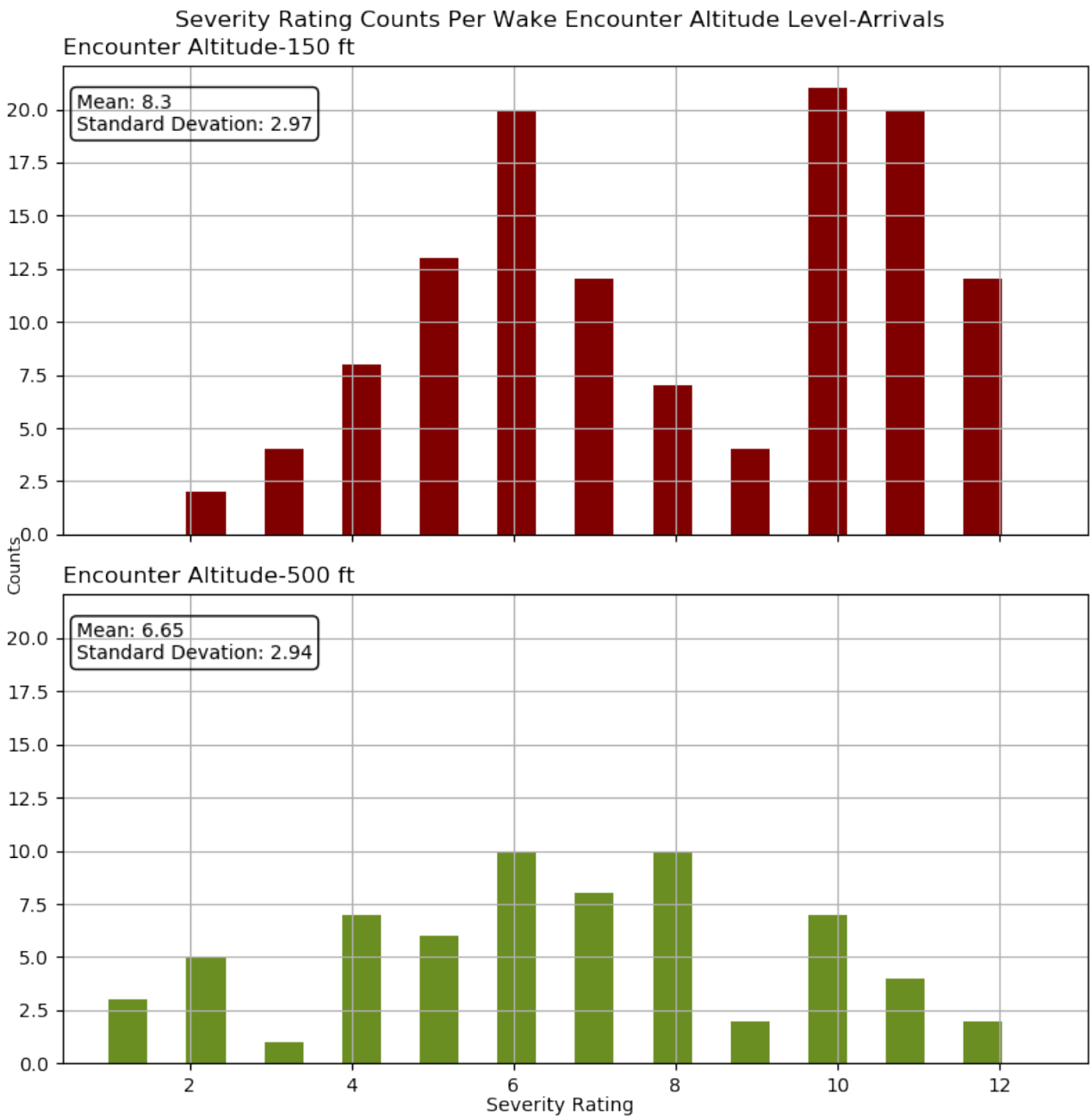

Figure 6-8: Severity Rating by Altitude Level Histogram

Figure 6-9 uses all of the approach data, regardless of the WVE altitude, to illustrate the overall correlation between SMS severity level ratings and the initial angles of bank that were achieved by the aircraft at the time of the encounter. The figure shows the higher the severity level rating the higher the expected bank angle.

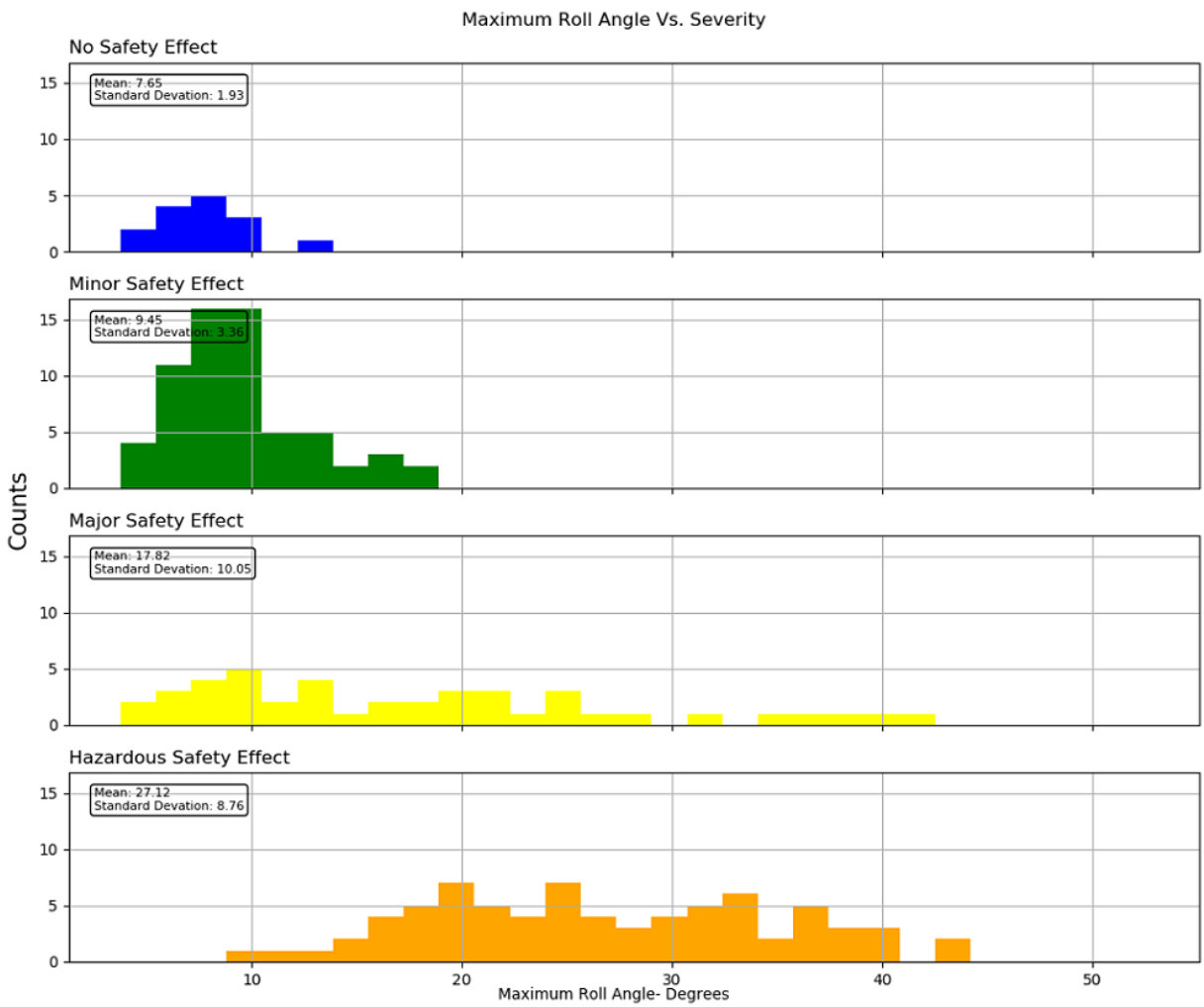

Figure 6-9: Arrival SMS Severity Level vs Roll Angle

Figure 6-10 uses all of the approach data, segregated by WVE altitude, to illustrate the overall correlation between severity level ratings and the initial angles of bank that were achieved by the aircraft at the time of the encounter. The relatively small sample size of the approach scenarios does not meet our threshold of alpha = 0.05; however, from the figure below we can infer that a relationship does exist between subject pilot severity level ratings and the proximity to the ground. The subject pilots tended to have less tolerance for aircraft upset closer to the ground. For example from the chart below, a severity level of major has a mean bank angle of 15 degrees at 150 ft AGL as compared to 21 degrees mean bank angle at 500 ft AGL.

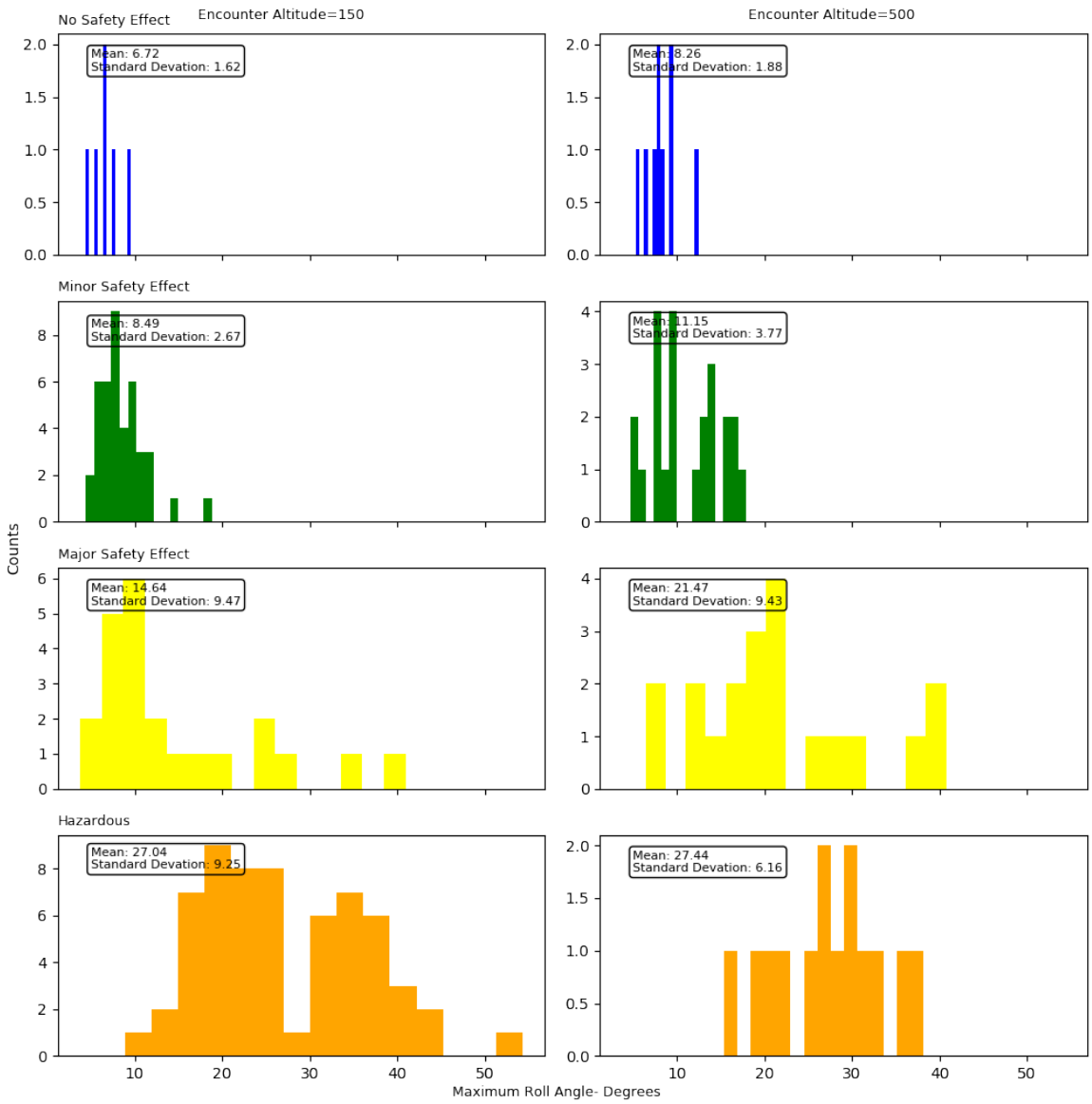

Figure 6-10: Arrival SMS Severity Level vs Roll Angle by Altitude Encounter

7 Conclusions

The purpose of this report is to help establish criteria for the definition of a WVE level of severity consistent with the current FAA SMS process. This study examined the severity aspect of the SMS risk matrix; the likelihood aspect of a WVE is the subject of other government and industry research, documents and models. The conclusions outlined below indicate that a relationship does exist between pilot severity ratings and the maximum aircraft extrema measured during a WVE.

7.1 Findings for Objective 1

Determine which aircraft parameter(s) (e.g., roll, yaw, altitude, accelerations, etc.) subject pilots report using to rate the severity level of a wake vortex encounter. This objective was met through the application of Post-Run Question #2. (Appendix D)

The analysis described in section 5.6 indicated the vast majority of subject pilots classified roll angle or roll rate as the significant parameter in determining their WVE rating.

7.2 Findings for Objective 2

Determine whether there is a significant relationship between the measured extrema of the aircraft parameter(s) determined in Objective 1 during wake vortex encounters and subject pilot severity ratings. This objective was met by analyzing the objective simulator recorded data and Post-Run Question #1. (Appendix D)

Question #1 presented the subject pilots a color-coded scale with 13 choices (levels). Each aircraft parameter and the respective pilot severity rating from the question above had a correlation coefficient computed. The results showed that the aircraft parameters with the three highest correlations were maximum bank angle acceleration, maximum bank angle rate, and the maximum bank angle.

The 13 level rating scale used by the subject pilots in question #1 can be grouped by color to correspond to the SMS severity levels.

Table 7-1: SMS Severity Level Color Groupings

Severity Level	Equivalent SMS Severity Level
Level 1,2,3	No Safety Effect
Level 4,5,6	Minor
Level 7,8,9	Major
Level 10,11,12	Hazardous
Level 13	Catastrophic

The data analysis in section 6 (Figure 6-6) shows the subject pilot severity rating and corresponding aircraft angle of bank resulting from a WVE during takeoff. The data, with alpha = 0.05 shows when pilots categorized a WVE as No Safety Effect (NSE) the expected bank angle range is between 0.68° and 27.36°, a WVE encounter categorized as Minor the expected bank angle range is 2.89° to 32.49°, Major ranged from 6.38° to 43.66°, and Hazardous from 10.9° to 49.26°. It is important to note that the bank angles were not programmed into the wake vortex model. Instead, the model used programmed gammas to achieve a desired aircraft displacement.

7.3 Objective 3

This objective did not require analysis by the Flight Research and Analysis Group. All data collected from the study including subject pilot responses and simulator variables was uploaded electronically to a shared drive and made accessible to the sponsor.

7.4 Future Studies

The FAA continually strives to modernize the National Airspace System by increasing capacity and efficiency while improving safety. A wake vortex risk matrix could play an important role as NextGen operational improvements are implemented. It is recommended this study continue to explore wake vortex encounters during departure and approach in a platform categorized as heavy.

References

Cindy Engholm, Dave Clark, Dr. Vab Andleigh, Frank Pobansky, Margo Pawlak. 2016. *Forecast and Data Needs to Support future Wake Solutions.* Boston, MA: Lincoln Laboratory, MIT.

Doug Rodzon, Richard Greenhaw, Jeffrey Fierro, Paul Nelson, Larry Newman. 2014. *Evaluation and Scaling of Wake Vortex Encounters and Responses During the Approach Phase Flight Segment in the 737-800.* Oklahoma City, OK: Federal Aviation Administration.

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Retman, Michelle. 2016. "Wake Turbulence ASRS Report Review." *Wakenet USA.* New York, NY: Federal Aviation Administration. 1-43.

Acknowledgments

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Appendix A: Pilot Demographic Questionnaire

DATE:_____ CREW #_____ CP / FO_____

1. Are you current and qualified (having landing currency) in the B737NG? YES / NO

2. Do you currently fly line operations for your company? YES / NO

3. Approximately how many hours do you have in this aircraft? _____

4. Have you experienced Wake Turbulence during your normal duties? YES / NO
   If so, please characterize your Wake Vortex Encounter(s) (WVE).

   _____

   _____

   _____

Appendix B: Condition Matrix

Table B-1: Departure Matrix

Scenario	Pilot Flying	Altitude	Gamma	Rotation	Core Size	SW Vert	Lat Dist
1	CPT	1200'	200	CC	10	-10	-10
2	CPT	1200'	200	CW	10	-10	10
3	CPT	1200'	200	CC	10	-10	-10
4	CPT	1200'	300	CW	10	-10	10
5	CPT	1200'	300	CC	10	-10	-10
6	CPT	1200'	300	CW	10	-10	10
7	CPT	1200'	400	CC	10	-10	-10
8	CPT	1200'	400	CW	10	-10	10
9	CPT	1200'	400	CC	10	-10	-10
10	CPT	600'	200	CW	10	-10	10
11	CPT	600'	200	CC	10	-10	-10
12	CPT	600'	200	CW	10	-10	10
13	CPT	600'	300	CC	10	-10	-10
14	CPT	600'	300	CW	10	-10	10
15	CPT	600'	300	CC	10	-10	-10
16	CPT	600'	400	CW	10	-10	10
17	CPT	600'	400	CC	10	-10	-10
18	CPT	600'	400	CW	10	-10	10
19	CPT	112'	200	CC	10	-10	-10
20	CPT	112'	200	CW	10	-10	10
21	CPT	112'	200	CC	10	-10	-10
22	CPT	112'	300	CW	10	-10	10
23	CPT	112'	300	CC	10	-10	-10
24	CPT	112'	300	CW	10	-10	10
25	CPT	112'	400	CC	10	-10	-10
26	CPT	112'	400	CW	10	-10	10
27	CPT	112'	400	CC	10	-10	-10
28	FO	1200'	200	CW	10	-10	10
29	FO	1200'	200	CC	10	-10	-10
30	FO	1200'	200	CW	10	-10	10
31	FO	1200'	300	CC	10	-10	-10
32	FO	1200'	300	CW	10	-10	10
33	FO	1200'	300	CC	10	-10	-10
34	FO	1200'	400	CW	10	-10	10
35	FO	1200'	400	CC	10	-10	-10
36	FO	1200'	400	CW	10	-10	10

Scenario	Pilot Flying	Altitude	Gamma	Rotation	Core Size	SW Vert	Lat Dist
37	FO	600'	200	CC	10	-10	-10
38	FO	600'	200	CW	10	-10	10
39	FO	600'	200	CC	10	-10	-10
40	FO	600'	300	CW	10	-10	10
41	FO	600'	300	CC	10	-10	-10
42	FO	600'	300	CW	10	-10	10
43	FO	600'	400	CC	10	-10	-10
44	FO	600'	400	CW	10	-10	10
45	FO	600'	400	CC	10	-10	-10
46	FO	112'	200	CW	10	-10	10
47	FO	112'	200	CC	10	-10	-10
48	FO	112'	200	CW	10	-10	10
49	FO	112'	300	CC	10	-10	-10
50	FO	112'	300	CW	10	-10	10
51	FO	112'	300	CC	10	-10	-10
52	FO	112'	400	CW	10	-10	10
53	FO	112'	400	CC	10	-10	-10
54	FO	112'	400	CW	10	-10	10
55	CPT	NA	0	NA	NA	NA	NA
56	CPT	NA	0	NA	NA	NA	NA
57	FO	NA	0	NA	NA	NA	NA

Table B-2: Approach Matrix

Scenario	Pilot Flying	Altitude	Gamma	Rotation	Core Size	SW Vert	Lat Dist
58	CPT	500	300	CW	10	-10	10
59	CPT	500	200	CC	10	-10	-10
60	CPT	500	100	CW	10	-10	10
61	CPT	150	300	CC	5	-5	-5
62	CPT	150	200	CW	5	-5	5
63	CPT	150	100	CC	5	-5	-5
64	CPT	150	300	CW	10	-10	10
65	CPT	150	200	CC	10	-10	-10
66	CPT	150	100	CW	10	-10	10
67	FO	500	300	CC	10	-10	-10
68	FO	500	200	CW	10	-10	10
69	FO	500	100	CC	10	-10	-10
70	FO	150	300	CW	5	-5	5
71	FO	150	200	CC	5	-5	-5
72	FO	150	100	CW	5	-5	5
73	FO	150	300	CC	10	-10	-10
74	FO	150	200	CW	10	-10	10
75	FO	150	100	CC	10	-10	-10

Appendix C: Pilot Scenarios

Takeoff Scenario

Routing
San Francisco International Airport (KSFO) to Los Angeles International Airport (KLAX)
Clearance will be: Runway Heading to 3000'

Environmental Conditions
The weather will be VMC
ATIS: KSFO 302153Z 27005KT 15SM CLR 15/10 A2992 RMK A02 SLP128 T01520103
Turbulence level: 25%

Wake Vortex Specifications
Burnham-Hallock Flow Field Model
Main Vortex selected

Lateral Distance:	+/- 10 feet from aircraft (same sign as circulation)
Vertical Distance:	-10 feet (aircraft above the wake)
Core size:	10 feet
Wake lateral encounter angle:	0°

Stays with aircraft selected
Aircraft relative pitch angle selected

Simulator Configuration
The simulator will be configured prior to each departure run as follows:
Gross Weight (GW) = 130,000# Zero Fuel Weight (ZFW) = 110,000#
Fuel Weight = 20,000# Center of Gravity (CG) = 26% CI:30
Positioned at the threshold of Runway 28R at KSFO.
FMS preprogrammed for the route of flight and all other pertinent data included.
Flaps 5, Bleeds ON takeoff.
An assumed temperature of 54°C will be used for reduced thrust takeoff.
Acceleration height will be set to 1000'AGL and climb thrust set to 1500ft AGL
The Flight Director, HUD and Auto Throttles will be fully functional and the crew may use at their discretion in accordance with company policy.

Scenario
The crews will have been briefed to hand fly all runs (no Auto Pilot).
The crew will be briefed to assume a Boeing 747 Heavy has departed RWY 28R and the required separations have been achieved.
The PI will inform the crew of the current weather and indicate who is the PF and PM.
When the crew indicates they are ready the scenario will begin. They will be cleared for takeoff and instructed to fly runway heading and to climb and maintain 3000 ft.

A WVE will occur at a preset altitude, strength, and rotation.
The subject crew will react to the encounter as required to maintain aircraft control.
The simulation will terminate when the subject crew has regained positive control of the aircraft, climbing through 1500 ft AGL or impact with the ground, whichever occurs first.

Approach Scenario

Routing
San Diego International Airport (KSAN) to San Francisco International Airport (KSFO)
Cleared for the ILS or LOC RWY 28R

Environmental Conditions
Approaches will be flown in IMC until breakout at 400 ft MSL. Visibility below the ceiling will be 9500 feet Runway Visual Range (RVR) and fog top of 25'. Surface winds will be calm.
ATIS: KSFO 302153Z CALM 1SM OVC004 BR 15/13 A2992 RMK A02 SLP128 P0005 T01500136
Turbulence level: 25%

Wake Vortex Specifications
Burnham-Hallock Flow Field Model
Main Vortex selected

Lateral Distance:	+/- 5 or 10 feet per Table 7 (same sign as circulation)
Vertical Distance:	+/- 5 or 10 feet per Table 7 (aircraft above the wake)
Core size:	5 or 10 feet per Table 7
Wake lateral encounter angle:	0°

Stays with aircraft selected
Aircraft relative pitch angle selected

Simulator Configuration
The simulator will be configured prior to each approach as follows:
Gross Weight (GW) = 110,000# Zero Fuel Weight (ZFW) = 100,000#
Fuel Weight = 10,000# Center of Gravity (CG) = 26% CI: 30
Positioned on a 4.9 DME final, 940 ft MSL and speed 134 knots indicated airspeed (VREF+5) on the ILS Runway 28R at KSFO.
The FMS will be preprogrammed for the route of flight and have all other pertinent data included.
The VHF radio's set to the appropriate ILS navigation frequencies.
The Localizer and Glideslope will be captured.
The aircraft will have the gear down and Flaps 30 selected and indicated.
The Flight Director, HUD and Auto Throttles will be fully functional and the crew may use at their discretion in accordance with company policy.

Scenario
The crews will have been briefed to hand fly all runs (no Auto Pilot).
The crew will be briefed to assume a Boeing 747 Heavy has landed RWY 28R and the required separation has been provided.
The PI will inform the crew of the current weather and indicate who is the PF and PM

When the crew indicates they are ready, the scenario will begin. The crew will be cleared to land.
A WVE will occur at a preset altitude, strength, and rotation.
The subject crew will react to the encounter as required to maintain aircraft control.
The simulation will terminate when the subject crew has regained positive control of the aircraft, during roll out on landing or impact with the ground, whichever occurs first.

Appendix D: Post-Run Questionnaire

Date _____ Position (CAPT or F/O) Crew # _____

1. Please rate the encounter (1 – 13) severity level you just experienced, using the following qualifiers/examples:

Severity Level	Qualifiers/Examples
Level 1,2,3	Flight path easily maintained
Level 4,5,6	Minimal control input required to maintain desired flight path
Level 7,8,9	Considerable control input required to ***maintain desired flight path*** or avoid ground impact
Level 10,11,12	Significant or maximum control input required to ***maintain controlled flight*** or avoid ground impact
Level 13	Crash/potential hull loss

1	2	3	4	5	6	7	8	9	10	11	12	13

2. As a result of the WVE, what was the significance of the following parameters in determining your rating of the WVE?

	Not Significant	Significant	Very Significant
Roll Angle	☐	☐	☐
Roll Rate	☐	☐	☐
Pitch Angle	☐	☐	☐
Pitch Rate	☐	☐	☐
Yaw	☐	☐	☐
Accelerations	☐	☐	☐
Change of altitude	☐	☐	☐

3. Please classify the frequency you would tolerate encountering such a wake (Assume 10-40 Landings / Month) "If it occurs no more often than:"
   - ☐ Once or more per week
   - ☐ Once per year
   - ☐ Several times in a career
   - ☐ To make an occurrence unlikely but possible in a career
   - ☐ To make an occurrence so unlikely it would never happen in a career

   Operationally Tolerable: Based on your flying experience, an event where on approach you could safely land or execute a go around or on departure you can maintain or regain the flight path by using normal (day to day) flying skills and not have to exercise extraordinary flying skills or fly the aircraft to its design limits.

4. If this encounter happened on the line, I would classify it as:

   ☐ Operationally Tolerable

   ☐ Not Operationally Tolerable

Appendix E: Post Evaluation De-briefing – Pilots

DATE:_____ CREW #_____ CP / FO_____

1. Did the wake vortices you encountered today seem realistic? YES NO
   If no, please explain:
   _____
   _____
   _____
2. What aspect(s) of the wake encounters seemed the most significant to you?
   _____
   _____
   _____
3. Did your habit patterns change as a result of repetition or "learning effect" YES NO
   If yes, please explain:
   _____
   _____
   _____
4. If you have encountered wake turbulence during line flying, is there one location and/or phase of flight that stands out as the most likely location to encounter one (e.g., Airport(s), Departures, Arrivals etc.)
   _____
   _____
   _____
5. Are there any other concerns or issues you would like us to be aware of? YES NO
   If yes, please explain:
   _____
   _____
   _____

Appendix F: Simulation Data Collection Variables

The following was recorded for each run:

- Identification of the simulator
- Simulation time
- Audio and Video recording of the simulator cockpits
- The following data description parameters at a rate equal or greater than 20 Hz:

Table F-1: Simulator Data Collection Variables

Simulator Data Description Parameters	Simulator Data Description Parameters
Wake Vortex Activation	AGL (Ft) (Aircraft CG AGL)
Second Wake Gamma (ft^2/sec)	Pressure Altitude (in hg)
Main Wake Gamma (ft^2/sec)	MSL (Ft)
Wake Lateral offset (ft)	Radio Altitude
Wake Vertical offset (ft)	Main Gear Squat (-1 = On ground)
Wake Vortex Spacing (ft)	Indicated Airspeed (knots)
second core radius(ft)	MACH
main core radius(ft)	Calibrated Airspeed (knots)
Wake HDG (deg)	ADC True Airspeed (knots)
Wake model 2=atsi	True Airspeed (ft/sec)
Aircraft Latitude (DEGS)	Ground Speed (knots)
Aircraft Longitude (DEGS)	Roll Acceleration (body axis) (rad/sec^2)
Aircraft distance to runway C/L (ft)	Roll angle [deg]
A/C altitude above Ref Rwy Threshold (ft)	Heading angle [deg]
A/C distance to Ref Rwy Threshold (ft)	Pitch Acceleration (body axis)(rad/sec^2)
Yaw Acceleration (body axis)(rad/sec^2)	Elevator Position (degs)
Pitch angle [deg]	Pedal Position (in)
Angle of Attack [deg]	Rudder Position (degs)
XX Moment of Inertia (slug-ft^2)	Horizontal Stab Position (degrees)
Dynamic pressure (lbs/ft^2)	Horizontal Stab Position (units)
Aerodynamic body axis roll moment (lbs-in)	Leading Edge Surface ave position (deg)
Rate of Climb (ft/min)	Trailing Edge Surface ave position (deg)
Roll Rate (body axis) (rad/sec)	Landing Gear Handle Position (1 = down)
Pitch Rate (body axis) (rad/sec)	Flap handle position (degs)
Yaw Rate (body axis) (rad/sec)	Landing Gear Position (1=dn)
X-Body Velocity WRT ground	Average Flap Position (degs)
Y-Body Velocity WRT ground	Wind direction at aircraft (degs relative to A/C position)
Z-Body Velocity WRT ground	Wind speed at aircraft (kts)
X-Body Axis Accerleration (ft/sec^2)	Left N1 (%RPM)
Y-Body Axis Accerleration (ft/sec^2)	Right N1 (%RPM)
Z-Body Axis Accerleration (ft/sec^2)	Left Throttle Level Angle (degs)

Simulator Data Description Parameters	Simulator Data Description Parameters
body axis roll moment coef	Right Throttle Level Angle (degs)
Capts Wheel Force (lb)	AutoThrottle (1=engaged)
Capts Wheel Position (deg)	Autopilot A (1=engaged)
F/Os Wheel Force (lb)	Autopilot B (1=engaged)
Left Aileron Position (degs)	Capts F/D (1=engaged)
Right Aileron Position (degs)	F/Os F/D (1=engaged)
Aileron Trim (degs)	TOGA Switch (1=activated)
Capts Column Position (in)	LNAV (1=engaged)
VNAV (1=engaged)	Magnetic variation (degs)
VIS RWY LAT	VIS RWY LON
VIS RWY HDG	Accel FWD Pitch (g's)
Accel AFT Pitch (g's)	Accel STBD Roll (g's)
Accel PORT Roll (g's)	Accel STBD Yaw (g's)
Accel PORT Yaw (g's)	TIMER
Left FMC Vertical Deviation (ft)	Left FMC Crosstrack Deviation (ft)
ILS G/S Deviaiton [Degs]	ILS Loc Deviation [Degs]
Left FMC distance to go (nm)	Left FMC RNP readout
Left FMC ANP readout	Yaw Aircraft parameters (deg)

Appendix G: Detailed Technical Analysis

Table G-1: Pairwise Tukey HSD for First Officer

Multiple Comparison of Means - Tukey HSD,FWER=0.05

group1	group2	meandiff	lower	upper	reject
FOaccelerations	FOaltchange	0.0155	-0.0719	0.1029	FALSE
FOaccelerations	FOpitchangle	0.179	0.0916	0.2664	TRUE
FOaccelerations	FOpitchrate	0.1033	0.0158	0.1907	TRUE
FOaccelerations	FOrollangle	1.0413	0.9539	1.1287	TRUE
FOaccelerations	FOrollrate	1.0379	0.9504	1.1253	TRUE
FOaccelerations	FOyawangle	0.2806	0.1931	0.368	TRUE
FOaltchange	FOpitchangle	0.1635	0.0761	0.2509	TRUE
FOaltchange	FOpitchrate	0.0878	0.0004	0.1752	TRUE
FOaltchange	FOrollangle	1.0258	0.9384	1.1132	TRUE
FOaltchange	FOrollrate	1.0224	0.935	1.1098	TRUE
FOaltchange	FOyawangle	0.2651	0.1776	0.3525	TRUE
FOpitchangle	FOpitchrate	-0.0757	-0.1632	0.0117	FALSE
FOpitchangle	FOrollangle	0.8623	0.7749	0.9497	TRUE
FOpitchangle	FOrollrate	0.8589	0.7714	0.9463	TRUE
FOpitchangle	FOyawangle	0.1015	0.0141	0.189	TRUE
FOpitchrate	FOrollangle	0.938	0.8506	1.0255	TRUE
FOpitchrate	FOrollrate	0.9346	0.8472	1.022	TRUE
FOpitchrate	FOyawangle	0.1773	0.0899	0.2647	TRUE
FOrollangle	FOrollrate	-0.0034	-0.0909	0.084	FALSE
FOrollangle	FOyawangle	-0.7608	-0.8482	-0.6733	TRUE
FOrollrate	FOyawangle	-0.7573	-0.8447	-0.6699	TRUE

Table G-2: Pairwise Tukey HSD for Captain

Multiple Comparison of Means - Tukey HSD,FWER=0.05

group1	group2	meandiff	lower	upper	reject
CAPTaccelerations	CAPTaltchange	-0.0568	-0.1464	0.0328	False
CAPTaccelerations	CAPTpitchangle	0.0671	-0.0225	0.1568	False
CAPTaccelerations	CAPTpitchrate	-0.0069	-0.0965	0.0827	False
CAPTaccelerations	CAPTrollangle	0.9415	0.8519	1.0311	True
CAPTaccelerations	CAPTrollrate	0.8795	0.7899	0.9691	True
CAPTaccelerations	CAPTyawangle	0.3115	0.2219	0.4012	True
CAPTaltchange	CAPTpitchangle	0.1239	0.0343	0.2135	True
CAPTaltchange	CAPTpitchrate	0.0499	-0.0397	0.1395	False
CAPTaltchange	CAPTrollangle	0.9983	0.9087	1.0879	True
CAPTaltchange	CAPTrollrate	0.9363	0.8467	1.0259	True
CAPTaltchange	CAPTyawangle	0.3683	0.2787	0.458	True
CAPTpitchangle	CAPTpitchrate	-0.074	-0.1636	0.0156	False
CAPTpitchangle	CAPTrollangle	0.8744	0.7847	0.964	True
CAPTpitchangle	CAPTrollrate	0.8124	0.7228	0.902	True
CAPTpitchangle	CAPTyawangle	0.2444	0.1548	0.334	True
CAPTpitchrate	CAPTrollangle	0.9484	0.8587	1.038	True
CAPTpitchrate	CAPTrollrate	0.8864	0.7968	0.976	True
CAPTpitchrate	CAPTyawangle	0.3184	0.2288	0.408	True
CAPTrollangle	CAPTrollrate	-0.062	-0.1516	0.0277	False
CAPTrollangle	CAPTyawangle	-0.6299	-0.7196	-0.5403	True
CAPTrollrate	CAPTyawangle	-0.568	-0.6576	-0.4784	True