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An Experiment to Evaluate Transfer of Low-Cost Simulator-Based Upset-Recovery Training

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16. Abstract

Many air transport training programs provide simulator-based upset-recovery instruction for company pilots. However, apparently no prior research exists to demonstrate that such training transfers to an airplane in flight. We report on two-phase FAA-funded research experiment to evaluate upset-recovery training transfer.

In two separate training/testing evolutions involving two different general aviation aircraft, participant pilots were trained using low-cost desktop flight simulation, then subjected to serious in-flight upsets in an aerobatic airplane. Their performance in upset-recovery maneuvering was compared with the performance of control group pilots who received no upset-recovery training. Data collected during both flight testing periods suggest that simulator-based training improves a pilot's ability to recover an airplane from an upset. However, in the most important measure of upset maneuvering skills—minimizing altitude loss—trained pilots fell well short of the performance routinely achieveable by pilots experienced in all-attitude manuevering.

We summarize prior related research, describe the experiments, present and analyze data collected during both flight testing periods, and advance recommendations for future upset maneuvering training. Although we conducted flight testing in a general aviation airplane, our research has important implications for heavy aircraft upset-recovery trainers.

17. Key Words
Airplane Upset-Recovery Training, Low-Cost Flight Simulation, Training Transfer

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CONTENTS

An Experiment to Evaluate Transfer of Low-Cost Simulator-Based Upset-Recovery Training

An upset occurs when an airplane enters an unexpected attitude that threatens loss of control (LOC) and subsequent ground impact. For the years 1998 – 2007 inclusive, LOC was the leading cause of hull losses and passenger fatalities in worldwide air transport operations, causing almost 25% of all crashes and nearly 40% of all fatalities.[1] During the years 1991 – 2000, statistics for general aviation (GA) accidents in the United States are similar, while in Australia LOC accounted for an even greater proportion of GA accidents and fatalities.[2]

Since LOC threatens both passengers and flight crews, as well as potential victims on the ground, many air transport training programs contain a module instructing pilots how to recover an airplane from an upset. However, the effectiveness of such training has not been demonstrated. We will report on a two-phase Federal Aviation Administration-funded research experiment designed to evaluate transfer of upset-recovery training conducted using low-cost flight simulation. We assess training effectiveness by means of in-flight upset-recovery testing in a general aviation airplane. In what follows, we:

1. Discuss prior research related to our experiment.
2. Describe the experiment.
3. Summarize previously reported results of Phase One flight testing.
4. Present and interpret results of Phase Two flight testing.
5. Construe the relevance of our results to air transport upset-recovery training.
6. Explain plans for future related research.

1. PRIOR RESEARCH[3]

We have found only a few research articles related to the transfer of simulator-based upset-recovery training. Several reports result from research at the Calspan In-Flight Upset Recovery Training Program in Roswell, N.M.[4] A second set of articles focuses on centrifuge-based flight simulators manufactured by the Environmental Tectonics Corporation. A third group discusses human factors considerations in upset-recovery training. Finally, we are aware of just one article related to training transfer when upset maneuvering is taught using low-cost simulation.

1.1 Calspan-Related Research

Calspan provides *in-flight* simulator-based upset-recovery training in a variable stability Learjet 25 modified to simulate the control characteristics of an air transport airplane. The Calspan Lear can simulate various accident scenarios that in the past have resulted in air transport upsets leading to uncontrolled crashes.

Gawron used Calspan's Learjet to test five groups of airline pilots with varying degrees of upset-recovery training and/or aerobatics experience on a series of eight upsets, hypothesizing that pilots with more training and/or experience would outperform those with less. However, she found no significant difference among the performances of the five groups.[5]

Kochan used the Calspan Lear to examine the roles of *domain knowledge* and *judgment* in upset-recovery proficiency. Domain knowledge is specific knowledge about upset-recovery procedures. Judgment is the ability to analyze and learn from an in-flight upset-recovery experience. She tested four groups of participants on a series of three in-flight upsets. Statistical analyses revealed that judgment was a significant factor in successful upset recovery, especially when a pilot has low domain knowledge, i.e., when a pilot is not trained to proficiency in upset recovery.[6]

Kochan and Priest studied the effect of upset-recovery training in the Lear. They measured pre- and post-training pilot performance in recovering from a series of upsets. Statistical analysis indicated "a strong positive influence of the [Calspan program] on a pilot's ability to respond to an in-flight upset."[7]

Kochan, Breiter, Hilscher, and Priest surveyed retention of knowledge in Calspan-trained pilots. Although participants in retrospect "rated their ability to recover from loss-of-control situations as being greatly improved by the training," most were unable to recall various specific details about upset-recovery maneuvering taught during their training.[8]

1.2 Centrifuge-Based Flight Simulation

The Calspan Learjet *in-flight* simulator allows pilots to experience upset maneuvering G forces that very few *ground-based* flight simulators can replicate. The

Environmental Tectonics Corporation (ETC) of Southampton, Pennsylvania, manufactures centrifuge-based flight simulators capable of generating continuous G forces. Such simulators bring to ground-based upset-recovery training a degree of realism unachievable even in Level- D simulators. Three ETC proprietary technical reports (available from Dick Leland at dletc@aol.com) detail the capabilities of the company's current generation of centrifugal simulators.[9,10,11] One drawback of such simulators, however, is that "if a pilot moves his head while under G in a centrifuge, strong feelings of disorientation (the Coriolis illusion) result because of the small rotation radius needed to create the G forces artificially."[12] In a related article on motion-based flight simulation, Szczepanski and Leland argue that "simulator data analysis suggests that motion cueing is necessary when training *ab initio* pilots or pilots who have limited or no experience in the particular flying task that is being trained."[13]

Since upset maneuvering involves generating high G forces than many pilots have never experienced, it seems reasonable to wonder if a centrifuge-based simulator might not be more effective that low-cost or Level-D flight simulators for upset-recovery training. We return to this subject later.

1.3 Human Factors Considerations in Upset-recovery Training

A number of papers examine the "surprise" or "startle" factor in aviation, an effect that can hinder a pilot's ability to respond appropriately to an emergency situation such as an upset. Kochan, Breiter, and Jentsch (2004) found pilots often miss cues that might lead to avoiding an emergency that later arrives as a surprise.[14] In a follow-on paper, the same researchers develop "a conceptual framework for the study of unexpected events in aviation."[15] Kochan, Priest, and Moskal use a model for the "cognitive process of surprise"[16] to study "how an unexpected event can escalate to a loss-of-control situation." They conclude that in-flight (as opposed to ground-based) simulator training may be necessary to teach pilots to deal adequately with their perceptual *biases* in processing information during a surprise upset.[17,18] In a related paper, Kochan argues that a pilot's response to unexpected events can be improved through *cognitive flexibility training* (to discourage formulaic and encourage flexible responses to surprise events), *adaptive expertise training* (to reinforce modified or new responses to surprise based on responses learned in previous expert training), and *metacognitive training* (to teach pilots how to evaluate their mental processes in responding to surprise).[19]

1.4 Low-Cost Simulation

Roessingh (2005) studied training transfer from low-fidelity ground-based flight simulators to control of an actual airplane during aerobatic flight.[20] Two experimental groups received ground-based instruction in aerobatic maneuvering using desktop flight simulators. The simulator syllabus was the same for both groups, but one experimental group's simulator training was enhanced with a more "realistic layout of stick, rudder pedals, and throttle." Then the two experimental groups and a control group received five hours of in-flight aerobatic training. Data collected during subsequent testing revealed no significant difference in the aerobatic maneuvering of experimental and control group pilots.

2. THE RESEARCH EXPERIMENT

Our research seeks to determine if upset-recovery training in low-cost flight simulators develops flying skills that improve a pilot's ability to recover from a serious upset in a real airplane. We hypothesize that pilots trained in upset recovery will outperform untrained pilots. To test this hypothesis, we train a group of participant pilots in upset-recovery maneuvering using Microsoft Flight Simulator (MFS),[21] then subject both trained and untrained participants to a series of four upset situations in an actual airplane and collect data on their performance in recovering the airplane to straight-and-level flight. Participants in our experiment are student pilots at Embry-Riddle Aeronautical University (ERAU) in Daytona Beach, Florida. All participants hold a current instrument rating and have completed an academic course in basic aerodynamics for pilots. None has prior aerobatic experience or upset-recovery training beyond that required for FAA flight certificates and ratings.

As reflected in Table 1, our experiment is a 2 x 4 repeated measures factorial. The first independent variable is degree of training and has two levels—trained and untrained. Trained participants receive ten hours of classroom upset training and ten hours of MFS upset-recovery training.[22] Untrained participants—control group pilots—receive no classroom or simulator training. The second independent variable is upset attitude. It has four levels corresponding to the four upsets each participant is subjected to during flight testing. We categorize upset attitudes as nose-high or nose-low and as upright or inverted. An inverted attitude is one where the bank angle exceeds 90°.

Flight testing subjects participants to upsets intended to simulate an airplane in cruise flight suddenly disturbed by an external force such as severe wind shear or very strong wake turbulence. Participants close their eyes while the safety pilot induces an upset, then—when instructed to

Table 1. The 2 x 4 Factorial Design

2 x 4 Factorial		Upset Attitude (Repeated Measure)			
		Nose-high Upright	**Nose-low Upright**	**Nose-high Inverted**	**Nose-low Inverted**
Training	10 Hours Classroom / Simulator (Trained Group)	Trained pilots	Trained pilots	Trained pilots	Trained pilots
	None (Control Group)	Untrained pilots	Untrained pilots	Untrained pilots	Untrained pilots

do so—open their eyes and attempt to bring the airplane under control. If a participant pilot returns the aircraft to straight-and-level flight without verbal or physical assistance from the safety pilot, a recovery is successful; otherwise, it is unsuccessful.

We define a good upset recovery as one where a pilot respects aircraft operating limitations while returning the aircraft to straight-and-level flight with the minimum possible loss of altitude. Minimum altitude loss will result from:

- Prompt and correct control and throttle inputs in response to an upset situation.
- A high roll rate toward an upright attitude to orient the lift vector toward the sky.
- Use of appropriate G forces (unloaded during low-speed or inverted rolls; high Gs in dive pullouts while avoiding accelerated stalls) during upset maneuvering.

The dependent variables in our experiment are designed to measure these factors. Upset attitudes and dependent variables differ slightly between Phase One and Phase Two of our research because we used different test airplanes, with different instrumentation, in each of the two phases. This situation, however, does not constitute a design limitation: no data from Phase One testing were used in Phase Two analysis.

3. PHASE ONE FLIGHT TESTING[23]

3.1 Upset Attitudes and Dependent Variables

We conducted Phase One flight testing in a Beech Bonanza airplane provided by the Calspan Flight Research Group. Table 2 indicates the initial attitudes and airspeeds associated with each of the four upsets. Nose-high upset airspeeds were set at 10 KIAS above V_S, the Bonanza 1 G stall speed. Nose-low airspeeds were a maximum safe value taking into consideration the Bonanza never-exceed speed of 196 KIAS. Data values for dependent variables were derived from a flight data recorder and a video file produced from a camera focused on the Bonanza's instrument panel. Table 3 shows dependent variables used in statistical analysis.

3.2 Statistical Analysis

During flight testing, we experienced difficulties with data collection hardware that resulted in lost or inaccurate data. In addition, we discarded data for upsets where the initial aircraft attitude and airspeed varied significantly from target values show in Table 2. Finally, we omitted data for 14 unsuccessful upset recoveries, six by trained participants and eight by control group participants. As a consequence, although we tested 28 trained and 30 control group participants during 232 upsets, we produced reliable data for far fewer upsets, as shown in Table 4. Note that the table reflects the number of individual upsets with reliable data for each upset, not the number of participants with complete data sets for all four upsets.

Because unusable data resulted in too few complete data sets, a two-group repeated measures Multivariate Analyses of Covariance (MANCOVA) proved infeasible. Thus, we decided to analyze each upset separately to preserve a reasonable sample size. For each upset in order, we calculated the Wilks' Lambda value. Since each analysis revealed a significant multivariate effect, we then used univariate ANOVAs employing the Bonferroni adjustment to assess the contribution of individual dependent measures. Table 5 records the mean and standard deviation (in italics) for each dependent measure. **Bolding** indicates a significant effect.

3.3. Interpretation

Statistical analysis implies a strong relationship between training in low-cost flight simulators and improved control responses during a serious upset situation in a real airplane. Trained pilots outperformed control group pilots in six of the nine dependent measures, reflecting a superior control of G forces during unloaded rolls and dive pullouts, an increased willingness to use large roll control inputs, and quicker throttle responses. The result was a tendency to return the aircraft to straight-and-level flight faster than control group pilots. In three dependent measures, however—seconds to first roll; rudder input; and, most notably, altitude loss—trained pilots never outperformed control group pilots.

Table 2. Levels of the Upset Attitude Independent Variable for Phase One Testing

Upset	Pitch	Bank	Airspeed	Thrust
Nose-high Upright	60° Nose-high	15° Left Wing Down	70 KIAS	Idle
Nose-low Upright	30° Nose-low	75° Left Wing Down	120 KIAS	Cruise
Nose-high Inverted	60° Nose-high	135° Right Wing Down	70 KIAS	Idle
Nose-low Inverted	20° Nose-low	135° Left Wing Down	100 KIAS	Cruise

Table 3. Dependent Variables Used in Phase One Statistical Analysis

Dependent Measures
G Force in Dive Pullout
Ratio of Available to Allowable G in Dive Pullout
G Force Unloading during Rolls
Recovery Altitude Loss in Feet†
Time to First Throttle Response in Seconds
Time to First Roll Response in Seconds
Time to Recover in Seconds
Use of Ailerons for Roll Authority in Degrees of Yoke Rotation
Use of Rudder for Roll Authority in Inches of Rudder Pedal Displacement

†Some nose-high upset recoveries resulted in small altitude gains, i.e., in negative altitude losses.

Table 4. Group Size for Each Upset

Group	Upset			
	Nose-High Upright	Nose-Low Upright	Nose-High Inverted	Nose-Low Inverted
Control	16	17	19	19
Experimental	23	23	22	21
Total	39	40	41	40

Table 5. Dependent Measures Means and *Standard Deviations* (**Bolding** = Significant Effect)

Upset	Nose-Low Upright		Nose-High Upright		Nose-Low Inverted		Nose-High Inverted	
	Trained	Control	Trained	Control	Trained	Control	Trained	Control
G Use in Dive Recovery	**3.13** ***0.50***	**2.50** ***0.38***	**1.88** ***0.29***	**1.36** ***0.20***	**3.49** ***0.59***	**2.92** ***0.58***	**2.56** ***0.82***	**2.00** ***0.57***
Average G / Target G	**0.79** ***0.13***	**0.63** ***0.09***	0.93 *0.14*	0.91 *0.12*	**0.87** ***0.15***	**0.75** ***0.20***	**0.84** ***0.15***	**0.64** ***0.16***
Unload G	**1.37** ***0.28***	**1.72** ***0.34***	0.34 *0.26*	0.23 *0.20*	**1.34** ***0.52***	**1.71** ***0.63***	0.52 *0.59*	0.66 *0.81*
Altitude Loss	918.26’ *225.70’*	1001.76’ *223.53’*	12.17’ *188.39’*	-119.38’ *226.41’*	1290.95’ *371.82’*	1243.68’ *338.68’*	563.18’ *481.43’*	538.95’ *380.63’*
Seconds to First Throttle	2.13 *1.10*	3.12 *2.34*	**1.91** ***0.51***	**4.38** ***5.25***	**1.57** ***.51***	**2.74** ***1.52***	**2.45** ***1.77***	**4.79** ***4.34***
Seconds to First Roll	2.00 *0.85*	2.18 *1.01*	2.30 *1.11*	2.06 *0.99*	1.76 *0.94*	2.11 *1.56*	2.36 *0.85*	2.58 *1.68*
Seconds to Recover	**5.96** ***1.07***	**8.18** ***2.21***	11.08 *2.86*	12.31 *1.77*	7.43 *1.69*	8.32 *1.45*	**9.14** ***2.34***	**12.00** ***3.27***
Roll Input	**24.22°** ***13.73°***	**17.18°** ***4.79°***	**63.30°** ***18.16°***	**46.38°** ***13.77°***	25.67° *13.54 °*	23.16° *9.60°*	40.64° *20.44°*	40.00° *18.46°*
Rudder Input	0.18” *0.12”*	.20” *0.15”*	0.91” *0.28”*	.75” *0.58”*	0.33” *0.24”*	0.23” *0.20”*	1.05” *0.58”*	0.79” *0.76”*

While trained pilots applied larger roll imputs and controlled G forces better than untrained pilots, both groups used relatively small control inputs in comparison to those required for optimal recoveries. Minimum altitude loss results from high roll rates (achieved at low airspeeds by using both aileron and rudder) and from the prompt application of maximum available/allowable G during dive pullout. However, general aviation pilots are accustomed to the small control inputs required for straight-and-level flight or flight at small bank and pitch angles. Without prior aerobatic experience, pilots find it difficult to apply large control inputs during a high-stress upset situation. We term this tendency *general aviation syndrome*. An equally appropriate name for this hard-to-resist behavior would be *straight-and-level syndrome*, as it also appears to characterize professional pilots who lack aerobatic experience—most notably airline pilots undergoing upset-recovery training.[24] This behavior was exhibited by trained participants to only a slightly lesser degree than untrained participants. We believe general aviation syndrome, which our training moderated but failed to overcome, explains why the superior control manipulations by trained pilots did not result in smaller altitude losses. The magnitude of trained pilot control inputs, though statistically significant in comparison to untrained pilot control input, was not close enough to optimal to result in an altitude loss difference. Moreover, as explained in Subsection 3.4, in some cases our training methods likely increased (rather than decreased) the altitude losses experienced by trained pilots.

3.4 Potential for Improved Training

During Phase One flight testing, we identified areas where improved ground training might result in better pilot performance during flight testing. The first concerns the practice of leveling the wings before dive pullout, as opposed to performing a rolling pullout. If less than an optimal roll rate is employed to level the wings before applying high G, or if less than allowable G is applied during pullout, a rolling pullout will decrease altitude loss. Second, the "standard" recovery technique for nose-high upsets, which involves inducing a steep bank angle to allow the nose to fall toward the horizon before leveling the wings, is not optimal for high thrust-to-weight ratio airplanes. In high thrust-to-weight aerobatic airplanes, far less altitude loss results when a pilot rolls immediately toward a wings-level upright attitude while flying nose-high at full power "across the top" of a half-loop. This recovery technique mimics the final roll-out portion of an Immelman aerobatic maneuver. Third, more emphasis is required during training to help pilots overcome general aviation syndrome by using large control inputs. Simulator training should stress unloading fully during nose-low inverted rolls or when rolling at low airspeeds during nose-high upsets. It must also emphasize the use of large rudder as well as aileron inputs to increase roll rates at low airspeeds. Finally, it must stress the need to apply high G forces quickly during dive recovery once the lift vector is pointed toward the sky. In Phase One training, we were less than perfect in all four instructional areas.

4. PHASE TWO TESTING

4.1 Data Collection, Upset Attitudes, and Dependent Variables

After repeated failed efforts to find a suitably instrumented contract aircraft, we decided to use the Embry-Riddle Super Decathlon aerobatic trainer for Phase Two flight testing. To collect data, we installed a battery-operated video camera focused on the Decathlon's instrument panel. A high-resolution palm-size video recorder captured the camera's output and cockpit voice communications. Figure 1 presents a screen capture of a video recorded during flight testing. We also installed an Appareo AHARS data recorder, an inexpensive battery-operated GPS-based

Figure 1. Sample Decathlon Video Recorder Output

Table 6. Levels of the Upset Attitude Independent Variable for Phase Two Testing

Upset	Pitch	Bank	Airspeed	Thrust
Nose-high Upright	60° Nose-high	45° Left Wing Down	65 MPH	Idle
Nose-low Upright	45° Nose-low	70° Right Wing Down	130 MPH	Full
Nose-high Inverted	60° Nose-high	180° (Inverted, Wings Level)	65 MPH	Idle
Nose-low Inverted	20° Nose-low	180° (Inverted, Wings Level)	110 MPH	Full

Table 7. Dependent Variables Used in Phase Two Statistical Analysis

Dependent Measure
Maximum G Force in Dive Pullout
Minimum G Force Unloading during Rolls†
Recovery Altitude Loss in Feet: Negative Value = Altitude Gain
Time to First Throttle Response in Seconds
Time to First Roll Response in Seconds
Time to Recover in Seconds

†Not applicable to the nose low upright upset, since trained pilots were taught to use rolling pullouts during dive recovery.

Table 8. Flight Hour Data for 50 Flight-Tested Participants

Group	Group Size	Mean Flight Hours	Standard Deviation
Control	26	160.5	54.0
Experimental	25	201.2	85.9
Combined	51	180.5	73.8

system capable of recording aircraft position, altitude, airspeed, attitude (pitch and bank), G forces (x, y, and z), yaw angles (β), and similar parameters. However, this unit proved unreliable in aerobatic attitudes. As a consequence, we were able to obtain only G force data from it. Two factors prevented our installing a more sophisticated data recording system. One was the significant cost. The other is a prohibition against invasive instrumentation in an ERAU training aircraft.

Because we used the Decathlon rather than the Bonanza for Phase Two testing, we modified upset initial attitudes and airspeeds slightly from those used in Phase One. Table 6 reflects upset attitudes and airspeeds for Phase Two flight testing. Nose-high initial airspeeds were set 12 MPH above V_S for the Decathlon, while nose-low airspeeds reflect a maximum safe value based on the Decathlon's red line speed V_{NE} of 200 mph. The principal change in attitudes is that we used 180° of bank (inverted wings-level attitude) for both of the inverted upsets. This change made it easier for the safety pilot to position the airplane in the prescribed attitudes, a challenging task significantly complicated by the fact that the Decathlon rear cockpit, where the safety pilot sits, has no flight instruments. The change was prudent, given the difficulty we experienced during Phase One in positioning the Bonanza accurately.

Table 7 details the six dependent measures we used to conduct Phase Two statistical analyses. Lacking a reliable flight data recorder, we were unable to collect data on rudder and aileron input that we obtained during Phase One.[25] We consider the absence of these data points inconsequential, because rudder and aileron input are responsible for roll rate, and Phase One results established training transfer in using roll authority. In Phase Two, our main objective was to determine if improved training would result in significantly smaller altitude losses for trained pilots, compared with control group pilots.

4.2 Statistical Analysis

As a result of careful safety pilot training, we were able to position the Decathlon accurately for upsets and to collect complete data sets for 24 of 25 trained participants and for 25 of 26 control group participants. Average flight time for each group is shown in Table 8. Six trained pilots and eight control group pilots experienced unsuccessful recoveries during the nose-low inverted upset. In every case, the safety pilot took control in dive pullout to avoid exceeding the Decathlon's red line speed. Data for these upsets are not included in our statistical analysis.

To compare trained and control group pilot performance, we conducted one-way MANOVAs for each of the four upsets using the dependent measures in Table 7. The resulting

Table 9. Multivariate Wilks' Lambda Values and Group Sizes for Each Upset

Upset	Nose-Low Upright	Nose-High Upright	Nose-Low Inverted	Nose-High Inverted
Trained Group Size	n=25	n=25	n=19	n=24
Control Group Size	n=26	n=26	n=17	n=26
Combined Group Size	n=51	n=51	n=36	n=50
Wilks Lambda Value	F (5,45) =9.59 p = .0001 η^2 = .0.52	F(6,44) = 4.47 p = .001 η^2 = .38	F (6,29) =9.11 p = .0001 η^2 = .653	F (6,43) =10.26 p = .0001 η^2 = .60

Table 10. Dependent Measures Means and *Standard Deviations* (**Bolding** = Significant Difference

Upset	Nose-Low Upright		Nose-High Upright		Nose-Low Inverted		Nose-High Inverted	
	Trained	Control	Trained	Control	Trained	Control	Trained	Control
Altitude Loss In Feet	**565.20** ***75.28***	**728.46** ***169.51***	331.20 *225.56*	340.38 *184.75*	382.08 *200.65*	464.62 *169.59*	**948.95** ***167.03***	**1069.41** ***139.08***
Min Unload G in Rolls	Not Applicable†		0.93 *0.14*	0.00 *0.12*	-0.47 *.28*	-0.43 *.26*	**0.84** ***0.15***	0.99 *0.86*
Max G in Dive Pullout	**3.70** ***0.64***	**2.90** ***0.49***	**2.41** ***0.90***	**1.82** ***0.30***	**2.34** ***0.45***	**2.34** ***0.45***	**4.74** ***0.62***	**3.98** ***0.50***
Seconds to First Throttle	**3.0** ***1.66***	**5.19** ***2.43***	2.12 *1.62*	3.27 *2.97*	**3.31** ***3.21***	**3.31** ***3.21***	**2.79** ***1.78***	**4.41** ***2.81***
Seconds to First Roll	**1.28** ***.46***	**1.85** ***.68***	**2.28** ***.89***	**3.15** ***1.38***	**6.15** ***2.98***	**6.15** ***2.98***	**1.68** ***.67***	**4.88** ***3.30***
Seconds to Recover	**5.40** ***1.38***	**7.04** ***1.64***	**11.16** ***1.43***	**12.88** ***2.98***	**15.23** ***2.27***	**15.23** ***2.27***	7.11 *1.29*	7.88 *.99*

† Not applicable to nose-low upright upset because trained pilots were taught to use rolling pullouts from dives.

Wilks' Lambda values shown in Table 9 reflect a significant difference between the two groups in all four upsets. We then conducted ANOVAs with the Bonferroni adjustment for each of the dependent variables. Table 10 reports mean and standard deviation data for the post hoc analyses. **Bolding** in Table 10 indicates a significant difference. Figure 2 presents information from Table 10 in graphical format. Table 12, which follows in Subsection 4.3, presents F values associated with significant effects in Table 10.

Two factors motivated our decisions to forego a more traditional 2 x 4 mixed-model analysis. First, because we eliminated data from unsuccessfully recoveries in the nose-low inverted upset, a mixed-model analysis would have substantially reduced the sample size (cf. Table 9). This approach maintains consistency with our Phase One approach, where each upset was analyzed separately because data collection problems, as well as unsuccessfully recoveries, resulted in a small number of complete data sets (cf. Table 4). Second, the nature of the upset data themselves argues against the direct comparisons that characterize a repeated measures MANOVA. For example, a nose-high recovery may lead to an altitude gain, whereas nose-low recoveries invariably result in significant altitude losses. Rather than compare "apples to oranges," we opted for a more direct and operationally more relevant approach to data analysis.

4.3. Effect of Improved Training

As in Phase One, Phase Two statistical analysis confirms our hypothesis that low-cost simulator-based upset-recovery training improves pilot performance in recovering an airplane from a serious upset. However, Phase Two statistical results reflect a far more comprehensive training transfer than we detected in Phase One. Phase Two-trained pilots lost less altitude than control group pilots in all four upsets, and two of the four altitude differences were statistically significant. This result stands in vivid contrast to Phase One testing outcomes, where trained pilots actually lost *more* altitude than control group pilots in three of four upsets.[26] We attribute this result to improved participant training, as described in Subsection 3.4 above.

The improved performance in altitude loss occurred because trained pilots initiated rolls toward a wings-level upright attitude sooner and applied more Gs in dive pullouts than untrained pilots, both critical factors in minimizing altitude loss. In addition, trained pilots also applied throttle more promptly than untrained pilots. These differences in turn resulted in a quicker return to straight-and-level flight. Excluding altitude loss, trained pilots were statistically superior to control group pilots in 14 of 19 categories, or 73.7 % of the time. Including altitude loss, trained pilot performance exceeded untrained pilot performance in 16 of

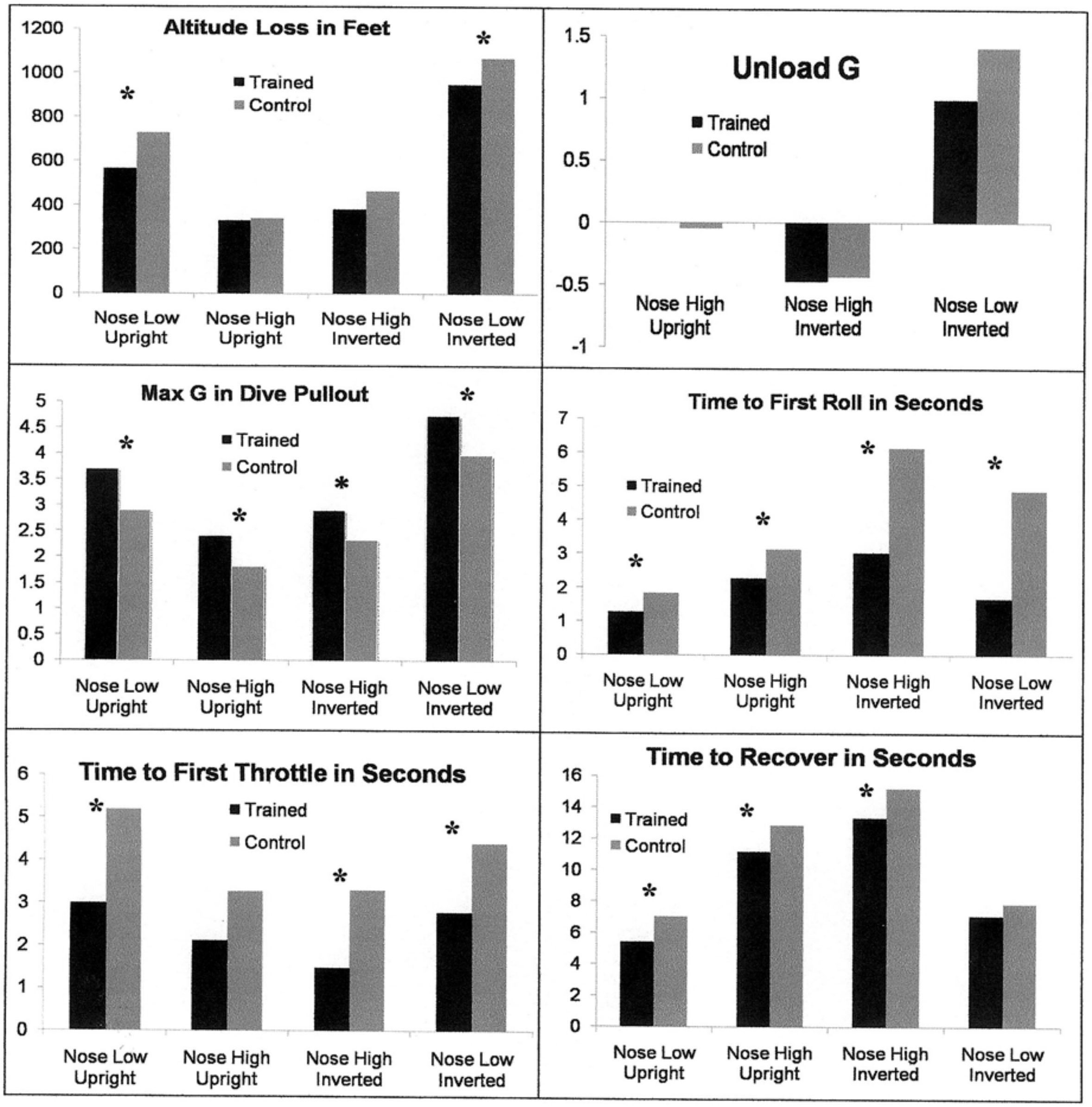

Figure 2. Phase Two ANOVA Results in Graphical format (* = Significant Effect)

23 categories, or 69.6% of the time. This is in opposition to 16 out of 36 categories, or 44.4% of the time, in Phase One testing. These contrasts are presented in Tables 11 and 12, where an "X" or an "F" value, respectively, indicates a significant effect.

4.4. Possible Effect of Reduced Sample Size in the Nose-low Inverted Upset Results

As previously explained, all 14 unsuccessful recoveries occurred during the nose-low inverted upset. Eliminating data from these unsuccessful upsets results in a sample size of 36, as opposed to a sample size of 50 when unsuccessful recoveries are included. Moreover, when data from the unsuccessful recoveries are included in an analysis of the nose-low inverted upset, the MANOVA and all six univariate Fs are significant. When it is excluded, the univariate differences for *Minimum Unload G in Rolls* and *Seconds to Recover* are no longer significant.

In Table 13, Ratio-A (**A**ll) is the ratio of a dependent measure control group average to the corresponding trained group average with data from all recoveries included. Ratio-S (**S**uccessful) is the same quotient computed for successful recoveries only. Eliminating data from unsuccessful recoveries has little effect on relative differences between the two groups, as reflected in the fact that Ratio-A divided by Ratio-S is in every case close to 1.0, and extremely close to 1.0 in the two categories where loss of statistical significance occurs when unsuccessful recoveries are eliminated. We believe the information in Table 13 suggests that the loss of significance in *Unload G* and *Time to Recover* differences when unsuccessful recoveries are eliminated may be due primarily to the resulting reduced sample size.

Table 11. Phase One Flight Testing Significant Effects (**X**) as Determined by Univariate Analysis (Rogers et al. [2007], p. 11)

Dependent Measure	Upset			
	Nose-Low Upright	Nose-High Upright	Nose-Low Inverted	Nose-High Inverted
G Use in Dive Recovery	X	X	X	X
Average G / Target G	X		X	X
Unload G	X		X	
Altitude Loss				
Seconds to First Throttle		X	X	X
Seconds to First Roll				
Seconds to Recover	X			X
Roll Input	X	X		
Rudder Input				

Table 12. Phase Two Flight Testing Significant Effect F Values as Determined by Univariate Analysis

Dependent Measure	Upset			
	Nose-Low Upright	Nose-High Upright	Nose-Low Inverted	Nose-High Inverted
Altitude Loss	F(1,49) = 19.48 p = .0001		F(1,34) = 5.45 p = .03	
Minimum Unload G in Rolls	Not Applicable†			
Maximum G Load in Dive Pullout	F(1,49) = 25.52 p = .0001	F(1,49) = 10.11 p = .003	F(1,34) = 16.02 p = .0001	F (1, 48) = 8.912 p = .004
Seconds to First Throttle	F(1,49) = 14.02 p = .0001		F(1,34) = 4.38 p = .04	F(1,48) = 7.46 p = .009
Seconds to First Roll	F(1,49) = 12.19 p = .001	F(1,49) = 7.18 p = .01	F(1,34) = 17.16 p = .0001	F(1,48) = 22.29 p = .0001
Seconds to Recover	F(1,49) = 14.82 p = .0001	F(1,49) = 6.83 p = .012		F(1,48) = 10.90 p = .002

†Not applicable to nose-low upright upset because trained pilots were taught to use rolling pullouts from dives.

Table 13. Comparison of Nose-low Inverted Upset Data with Unsuccessful Recoveries Included and Excluded (**Bolding** = Significant Difference)

Dependent Measure	Successful + Unsuccessful			Successful Recoveries Only			Ratio-A / Ratio-S
	Trained	Control	Ratio-A	Trained	Control	Ratio-S	
Altitude Loss	**973.2** **158.9**	**1088.1** **139.9**	1.118	**948.9** **167.0**	**1069.4** **139.1**	1.127	0.992
Minimum Unload G in Rolls†	**0.86** **0.90**	**1.33** **0.60**	1.547	0.99 0.86	1.41 0.63	1.424	1.086
Maximum G Load in Dive Pullout	**4.20** **1.17**	**3.40** **0.99**	0.810	**4.74** **0.61**	**3.98** **0.50**	0.840	0.964
Seconds to First Throttle	**3.08** **1.96**	**4.76** **2.85**	1.545	**2.79** **1.78**	**4.41** **2.81**	1.581	0.978
Seconds to First Roll	**1.96** **1.40**	**5.24** **3.29**	2.673	**1.68** **0.67**	**4.88** **3.30**	2.905	0.920
Seconds to Recover†	**7.08** **1.15**	**8.08** **0.95**	1.141	7.11 1.29	7.88 0.99	1.108	1.030

†Indicates that the difference is significant when data from unsuccessful recoveries are included but loses significance when data from unsuccessful recoveries are eliminated.

If *Unload G* and *Seconds to Recover* were significant in the nose-low inverted upset recovery, then trained pilots would have been statistically superior to untrained pilots in 18 of 23 dependent measure categories, or 78.3% of the time.

4.5. Limitations of Ground-Based Simulator Training

Our research results also suggest the limitations of low-cost simulator training in developing upset-recovery maneuvering skills. MFS responses to control stick inputs are realistic near the middle of the Decathlon flight envelope (V-n diagram). Near the envelope's available G line [α_{CRIT}, $(C_L)_{MAX}$], however, responses to control inputs tend to differ from the Decathlon's behavior in actual flight situations. For example, if a Decathlon pilot inadvertently stalls the airplane with an aileron down, a departure from controlled flight may result. However, MFS does not simulate departures from controlled flight realistically. MFS also responds inaccurately during accelerated stalls in low-speed dive pullouts. To recover the actual airplane from such a stall, it suffices to momentarily relax back stick pressure a small amount, resulting in a slightly reduced G force. To recover the simulated Decathlon from the same accelerated stall situation, a pilot must unload completely to 0 Gs for a second or two. In such scenarios, the potential for negative training is significant.

During flight testing, imperfect participant pilot control inputs frequently resulted in a nose-high upset progressing into low-speed nose-low upset. Whenever this occurred, accelerated stalls and departures from controlled flight were common. MFS limitations may explain why these post-stall departures occurred so frequently and why there was a significant difference between trained and control group pilot altitude losses in nose-low upsets but not in nose-high upsets. Maneuvering during high energy nose-low upsets occurs near the middle of the Decathlon flight envelope, where MFS control responses are reasonably accurate. By contrast, nose-high and low-speed nose-low maneuvering occurs near α_{CRIT} and $(C_L)_{MAX}$, where MFS control responses tend to be inaccurate. Moreover, required control inputs when maneuvering in high-speed nose-low upsets differ in degree, but not in kind, from control inputs general aviation pilots routinely use in non-aerobatic upright maneuvering. During nose-high upset maneuvering, by contrast, the proper control inputs differ radically from what general aviation pilots typically are accustomed to. As an example, efficient rolling in nose-high upsets requires a pilot to use large aileron and rudder inputs at maximum thrust while maintaining zero G at airspeeds approaching 0 mph. If any significant positive or negative G force is applied, a stall and departure from controlled flight may result. However, using elevator to maintain 0 G while applying large rudder and aileron inputs is something general aviation pilots never experience. As a second example, minimizing altitude loss in low-speed dive recovery by pulling out at the stall buffet (i.e., at or very slightly above α_{CRIT}) is again an experience unfamiliar to general aviation pilots. Training in a flight simulator that responds inaccurately to control inputs in these and similar situations makes it difficult to prepare pilots to handle them adequately in a real airplane. It is conceivable that the pilot behaviors necessary to perform nose-high low airspeed precision aerobatic maneuvers can be rehearsed using MFS and similar low-cost flight simulators but can only be perfected in a real airplane.

Moreover, even when trained pilots significantly bettered control group pilots in altitude loss, their performance was far from optimal. For each of the four upsets, Table 14 presents Phase Two average altitude losses for trained and control group pilots. The bottom row of Table 14 reflects the minimum altitude losses that we observed for each upset during safety pilot training.[27] There is a large disparity between research participant altitude losses and the far smaller altitude losses achievable by experienced pilots. Low-cost flight simulator training clearly improves a pilot's ability to recover an airplane from a serious upset. Just as clearly, however, it is prelude and complement to, not a substitute for, aerobatic experience in a real airplane. Whether a better flight simulator would produce a different result during flight-testing is an open question.

Table 14. Altitude Losses to Nearest Foot for the Four Upsets (**Bolding** = Significant Effect)

Data Source	Altitude Loss in Feet			
	Nose-Low Upright	Nose-High Upright	Nose-Low Inverted	Nose-High Inverted
Trained Pilot Average	**565**	331	**949**	382
Control Group Pilot Average	**728**	340	**1069**	465
Observed Minimums during Safety Pilot Training	220	-50	350	-30

5. Implications for Transport Type Airplanes[28]

Phase Two flight-test data reflect only a modest difference in performance between trained and untrained participants. It may well be the case that simulator-trained pilots need all-attitude flight experience in a real airplane to hone simulator-taught upset-recovery skills to an acceptably high level. It appears that during an initial upset-recovery experience, low-cost simulator training can help pilots overcome *General Aviation Syndrome* only to a limited extent. Simulator shortcomings—for example, unrealistic control feedback, inaccurate accelerated stall responses, and the inability to replicate the positive and negative G forces that characterize all-attitude flight—limit a trainer's ability to prepare a pilot mentally and emotionally for a real-world upset. As a result, any subsequent initial experience in a real upsets may appear strange and disquieting. In such a circumstance, a pilot easily loses situational awareness and instinctively resorts to old control input habits. Long-reinforced patterns of behavior and the significant stress of a serious upset tend to inhibit the application of new and relatively unfamiliar piloting skills developed during simulator training.

Our research findings seem to call in question the implicit assumption that airline simulator-based upset-recovery training programs impart flying skills sufficient to make it probable that typical line pilots can recover an airliner from a serious upset. It is true that airline pilots, on average, are considerably more experienced than our research participants, hence may benefit more from upset-recovery training. However, air transport pilots' experience consists of hours of flying straight and level, punctuated by occasional excursions into very small bank and pitch angles. In addition, airline pilots typically receive only about four hours of classroom-based upset-recovery training and perhaps an hour of simulator training, in comparison to ten hours of each for our trained participants. Moreover, the primary advantage of a Level-D simulator over low-cost desktop flight simulation is limited to cockpit verisimilitude and realistic control forces. Typically, the motion of a Level-D simulator is disabled to avoid stressing the mechanism unnecessarily in upset-recovery maneuver. In any event, Level-D simulator motion is in no way realistic in all-attitude maneuvering, and neither Level-D nor low-cost desktop simulators can replicate the G forces that characterize upset-recovery maneuvering in a real airplane.

Thirty years ago, U.S. airline pilots typically came from military flight backgrounds where training afforded them extensive opportunity to perform aerobatic flight maneuvers. These pilots were routinely accustomed to all-attitude flight. For them, there were no *unusual* attitudes, only *unexpected* attitudes. By contrast, most air transport pilots flying today lack a military background and have never experienced the extreme pitch and bank angles and high G forces associated with severe airplane upsets. Indeed, most have never even been upside-down in an airplane. Informal conversations with current airline pilots suggest that while virtually all regard the upset training they receive as useful, a significant number also perceive it as a *pro forma* approach to a serious safety problem—better than nothing but far from what would be desirable if training costs were not a paramount consideration. In short, it seems unlikely that airline upset training is a completely acceptable substitute for all-altitude manuevering experience in a real airplane.

Upsets are known to be a primary cause of fatal commercial air transport accidents. Passenger and air crew safety considerations mandate that air transport pilots be able to recover from the infrequent but potentially catastrophic upsets, which inevitably will occur from time to time in air transport operations. Our research implies that aerobatic experience in a real airplane may be required to make recovery probable with minimum altitude loss. Since aerobatic experience cannot be obtained legally in transport type aircraft, perhaps the FAA should consider making aerobatic experience in a light airplane part of the requirement for a commercial pilot license and/or an ATP rating.

6. Follow-On Research

In August 2008, we commenced follow-on upset-recovery research in partnership with Dick Leland of ETC, lead researcher and financial sponsor of the project under an FAA grant. Twenty-five Embry-Riddle flight students received the same ten hours of classroom training that Phase Two trained-participants received. They received five hours of MFS training, then traveled in small groups to Pennsylvania to receive five hours of weekend upset-recovery training in ETC's proprietary centrifuge-based GyroLab-2000 flight simulator. ETC modified the GyroLab-2000 to give it the flight characteristics of a Super Decathlon airplane and to make its basic flight instruments replicate the layout on a Decathlon's instrument panel.

When their GyroLab training was complete, in early November 2008, the 25 follow-on research participants underwent Decathlon flight testing identical to that received by Phase Two participants. Their performance in recovering from the four upsets will be compared with the performance of Phase Two-trained and control group pilots. The follow-on research is designed to determine

Table 15. The 3 x 4 Repeated Measures Factorial Design of the Follow-On Research Experiment

3 x 4 Factorial		Upset Attitude (Repeated Measure)			
		Nose-high Upright	Nose-low Upright	Nose-high Inverted	Nose-low Inverted
Training	10 Hours Classroom / 5 Hours MFS +5 Hours GyroLab-2000	GyroLab/MFS Trained Pilots	GyroLab/MFS Trained Pilots	GyroLab/MFS Trained Pilots	GyroLab/MFS Trained Pilots
	10 Hours Classroom / 10 Hours MFS Training	MFS Trained Pilots	MFS Trained Pilots	MFS Trained Pilots	MFS Trained Pilots
	None Control Group Pilots	Untrained Pilots	Untrained Pilots	Untrained Pilots	Untrained Pilots

the added value of upset training in a motion-based flight simulator capable of generating continuous G forces. We hypothesize that pilots trained in the sophisticated Gyro-Lab-2000 simulator will outperform Phase Two-trained and untrained pilots in upset-recovery maneuvering. Table 15 reflects the fact that the experimental design of the follow-on research is a 3x4 repeated measures factorial.

7. ENDNOTES

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21. The United States Navy uses Microsoft Flight Simulator in both basic and advanced flight training of student Naval aviators.

22. Training materials may be viewed at http://faculty.erau.edu/rogersr/as471.

23. Rogers et al. (2007). pp. 8-14.

24. Two authors of this paper—Rogers and Howell—have attended upset training at four legacy airline companies. At each, trainers remarked of the difficulties they experienced in persuading line pilots to use full-yoke deflection when rolling a Level-D simulator in an inverted upset to an upright, wings-level attitude.

25. In addition, we did not compute use of available G in dive pullout, since this information indirectly reflects the maximum G force applied in the recovery.

26. Compare the altitude loss data in Table 10 with the altitude loss data in Table 5.

27. The values in the last row of Table 14 are not losses produced by optimal recoveries, a subject we have not pursued systematically. They merely reflect the minimum altitude losses we recorded during Phase Two safety pilot training with experienced pilots maneuvering the Decathlon out of an upset.

28. Portions of this section are closely paraphrased or transcribed verbatim from Rogers et al. (2007), p. 16.

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