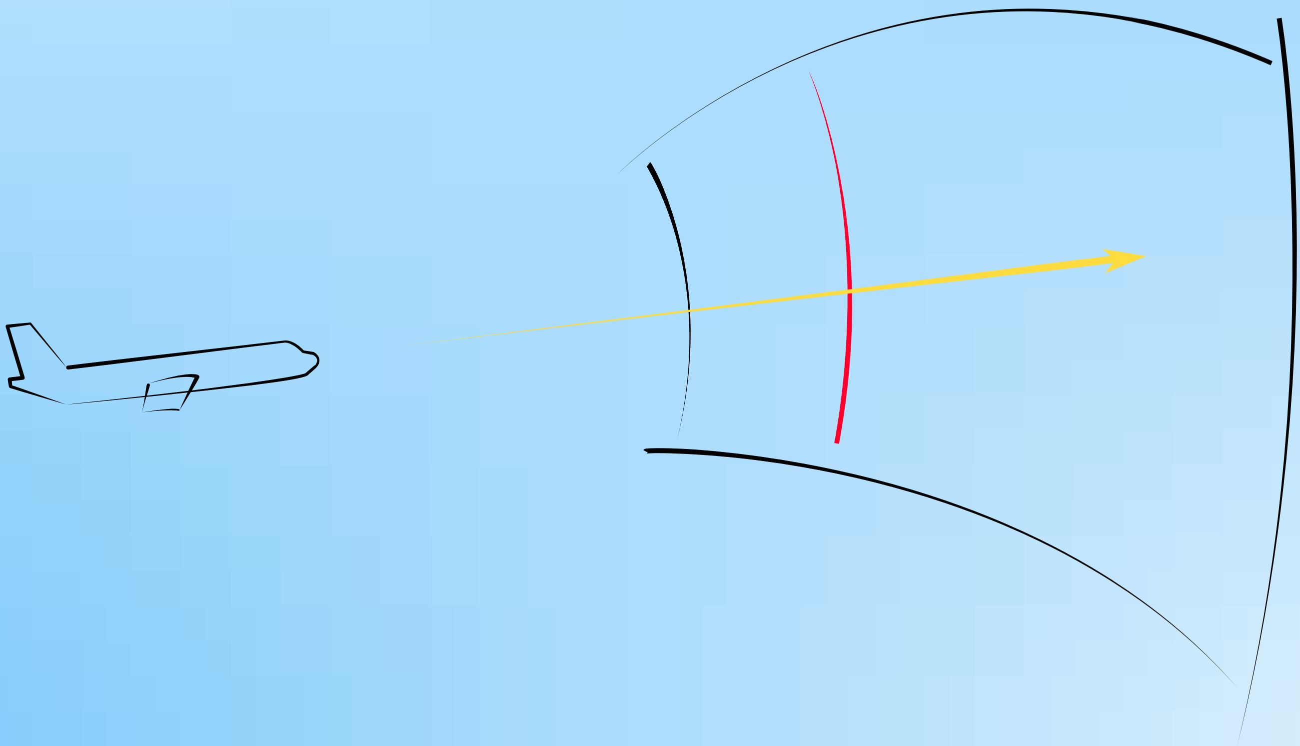
Master of Science Thesis

Design and Evaluation of an Ecological Interface Reflecting Configuration Changes in the Vertical Flight Performance Envelope

Preventing Flight Upset through Display Enhancement

A.F. van Geel

September 9, 2018



Faculty of Aerospace Engineering · Delft University of Technology

TU Delft Delft University of Technology

Challenge the future

Design and Evaluation of an Ecological Interface Reflecting Configuration Changes in the Vertical Flight Performance Envelope

Preventing Flight Upset through Display Enhancement

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering at Delft University of Technology

A.F. van Geel

September 9, 2018

Faculty of Aerospace Engineering · Delft University of Technology

Delft University Of Technology
Department Of
Control & Simulation

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Design and Evaluation of an Ecological Interface Reflecting Configuration Changes in the Vertical Flight Performance Envelope"** by **A.F. van Geel** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: September 9, 2018

Head of department: ______________________
Prof. Dr. ir. M. Mulder

Supervisor: ______________________
Dr. ir. C. Borst

Reader: ______________________
Dr. ir. M.M. van Paassen

Reader: ______________________
Dr. A. Gangoli Rao

Preface

This report is the final result of a long process towards finishing my MSc. The process was challenging at times, enjoyable at others, and has resulted in an experience that is both satisfactory and unique to me. I would like to thank my supervisors for their support, both in the technical details of coding a simulation and in the difficulties of doing a research project. Thanks especially to Clark, who managed to find a good balance between fun and productivity that made me look forward to the meetings we scheduled.

Although this thesis report was written by me, multiple others have contributed pieces of information or ideas throughout the process. During my preliminary thesis both Henk Hoogervorst from Aviation Performance Solutions and Hans-Albert Groothuis at CAE Flight Training / Ministry of Defense have shown me the practical side of upset prevention & recovery training, and speaking with them helped me get a better understanding of the issue aviation is facing. The experiment could not have been conducted without sixteen pilots offering up a few hours of their time, and frequent brainstorms with other students at the C&S faculty helped me resolve more difficult issues. Thank you to everyone who has offered their time to help me completing and raising the quality of this research.

I would like to thank my colleagues at Stichting Studiebegeleiding Leiden, co-board members at the Science and Technology Leadership Association and friends in SIM008 for making the last years of my time in Delft both memorable and valuable. I have learned a lot from working with such a greatly diverse group of people, and hope to run into each and every one of you at some point later in life. Thank you to my girlfriend Daphne, both for reading my thesis and for your talent of brightening up every day we spend together. Finally, a great thank you to my parents, who made my studies in Delft and abroad possible and supported me in my decisions. You have taught me to be proactive and ambitious, and your support has helped me a lot in getting where I am today.

Delft, The Netherlands — A.F. van Geel
September 9, 2018

Contents

List of Figures

List of Tables

Acronyms

AA	Adverse Aerodynamics
AOA	Angle of Attack
ATC	Air Traffic Control
DPC	Dynamic Pitch Control
DRC	Dynamic Roll Control
EID	Ecological Interface Design
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FL	Flight Level
FPV	Flight Path Vector
FSTD	Flight Simulation Training Device
GA	General Aviation
GAJSC	General Aviation Joint Steering Committee
HUD	Head-Up Display
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IRS	Inertial Reference System
IVSD	Improved Vertical Situation Display
LOC(-I)	Loss Of Control (In-flight)
NASA	National Aeronautics and Space Administration
NTSB	United States National Transportation Safety Board
PFD	Primary Flight Display
PIO	Pilot Induced Oscilation
QLC	Quantitative Loss-of-control Criteria
SA	Situational Awareness
SI	Structural Integrity
SIMONA	SImulation, MOtion and NAvigation flight research simulator
SOP	Standard Operating Procedure

SUPRA	Simulation of UPset Recovery in Aviation
TERP	Total Energy Reference Point
UA	Unusual Attitude
UPT	Upset Prevention Training
URT	Upset Prevention Training
UPRT	Upset Prevention and Recovery Training
VFR	Visual Flight Rules
VSD	Vertical Situation Display
VTE	Verified Training Envelope

List of Symbols

Latin Symbols

A	Aspect ratio
C_D	Drag coefficient
$C_{D,0}$	Zero-lift part of drag coefficient
$C_{D,i}$	Lift-induced part of drag coefficient
C_L	Lift coefficient
e	Oswald efficienty factor
g	gravitational acceleration
M	Mach number
M_{MO}	Maximum operating mach number
n	normal load factor
p	roll rate
q	pitch rate
r	yaw rate
T	Thrust
V	Indicated Airspeed
V_E	Equivalent airspeed
V_{MFE}	Maximum flaps extended speed
V_{MO}	Maximum operating speed
V_{SW}	Stall warning speed
W	Weight

Greek Symbols

α	Angle of attack
α_{Norm}	Normalized angle of attack
α_{stall}	Stall angle of attack
β	Sideslip angle
β_{MDXW}	Maximum demonstrated sideslip for crosswind landing
β_{Norm}	Normalized sideslip angle
γ	Flight path angle
θ	Pitch attitude
ϕ	Bank angle
ρ	Atmospheric density

Part I

Paper

Design and Evaluation of an Ecological Interface Reflecting Configuration Changes in the Vertical Flight Performance Envelope

A. F. van Geel (MSc Student)
Supervisors: dr. ir. C. Borst, dr. ir. M. M. van Paassen, Prof. dr. ir. M. Mulder
Section Control & Simulation, Department Control and Operations, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands

Abstract—**Loss of control is the largest contributor to the yearly aviation death toll, with energy mismanagement in low-energy conditions as one of its main causal factors. This has led to a large emphasis from both scientific and aviation safety communities on the prevention of aircraft upset conditions. Changes in aircraft configuration largely impact performance, and improved insight therein should allow pilots to better predict potentially dangerous situations, maintain suitable safety margins and more effectively react to unforeseen events. This paper presents the design and experimental evaluation of a Vertical Situation Display (VSD) with ecological enhancements visualizing changes in the flight performance envelope. Sixteen pilots were tasked to fly approach and go-around scenarios with both a baseline and an ecological VSD, some of the scenarios containing flight control failures. Results show that the new display makes pilots maintain larger margins in velocity, thus spending less time below the advised minimum speed limit in final approach. However, these larger velocity margins also led to larger errors with respect to target velocities. Flight control failures were more often and more quickly discovered, and pilots reported feeling better able to predict dangerous situations. No significant differences in workload were recorded. These results conclude that the new VSD design enhances safety performance, but simultaneously raise the question whether the effect of enlarged safety margins is desirable if it causes a reduction in velocity tracking.**

Index Terms—**Vertical Situation Display (VSD), Ecological Interface Design (EID), Flight Envelope Visualization.**

I. Introduction

THE past 50 years have seen an exponential increase in flight safety. However, flying is still not free of risks, as is made clear by the news and yearly incident statistics. Both surprisingly and worryingly, the past 10 years have shown the same main cause of fatalities across all categories of civil aviation: Loss Of Control In-flight (LOC-I) [1], [2].

The NASA Langley Research Center reports that over three-quarters of LOC-I incidents are the result of flight outside the regular operational flight envelope, a condition better known as aircraft upset [3]. These upsets are caused by various human, system or environmental factors, and often include an element of startle or surprise. Energy mismanagement (e.g. aerodynamic stall) is among the top causal factors in both commercial and general aviation, most commonly occuring in low-energy flight phases such as take-off and approach [4].

Research and industry are taking action at large to improve pilot training for LOC scenarios, such as the *Manual on Aeroplane Upset Prevention and Recovery Training* by the FAA, the project to create extended aircraft simulation envelopes by SUPRA, and over 130 companies offering upset prevention and recovery training worldwide [5] - [7]. These organizations agree that more focus should be placed on training pilots for situation awareness and manual skills in preventing upsets.

One way to create such awareness is through Ecological Interface Design (EID) [8]. Founded by Vincente and Rasmussen [9], this framework aims to make complex interactions in the work environment accessible to users through visualizing operation boundaries. EID has successfully been adapted to improve pilot awareness in terrain avoidance [10], vertical combined traffic and terrain avoidance [11] and horizontal self-separation [12]. Furthermore, in these experiments EID has allowed pilots to better cope with unforeseen circumstances. Managing failures at low-energy flight phases is critical, as shown by the British Airways Flight 38 incident [13]. Following an engine failure in final approach the pilot of the Boeing-777 changed flap settings to reduce drag, thus extending the glide and preventing a crash with the ILS antenna. This raises the question: how can EID be used to increase safety and performance for prevention of energy mismanagement in low-energy conditions, even after an unexpected event?

The objective of this research is to investigate an ecological interface for increasing pilot performance and safety in an approach & go-around. This display is an enhancement of the Intentional Vertical Situation Display (IVSD) by Comans [14], which in its turn was based on the Experimental VSD (EVSD) by Rijneveld et al. [11]. These VSDs yielded positive results in terms of pilot situation awareness and insight into maneuverability limits. The new version was tested by sixteen licensed pilots and compared to a baseline version without ecological cues. It was expected that by making aircraft safety margins more insightful, higher levels of performance and safety are facilitated at a lower workload. Moreover, if unforeseen circumstances do occur, EID-inspired displays should allow pilots to more timely diagnose the problem.

This article is structured as follows. Section II analyzes background on LOC incidents, the work domain, and earlier VSD versions. Section III then introduces the new interface enhancements. In Section IV the experiment design is outlined. The results obtained are presented in Section V, after which they are discussed in Section VI. Finally, Section VII concludes this report and offers recommendations for further research.

II. Background

A. LOC Incident Analysis

Although the root cause of an upset might vary greatly, analysis of previous incidents show that a LOC incident usually develops as follows: the aircraft experiences a failure (system) or encounters an external hazard (environmental) to which the crew may not have appropriately responded (human). A resulting upset occurs, which might then lead to a loss of control [15].

Comparing causes between aircraft categories shows that Part 121 operations are more likely to suffer from system errors, whereas general aviation is more prone to human piloting errors [16] - [18]. Nonetheless, both scenarios would benefit from insight in aircraft capabilities combined with manual piloting skill to prevent or resolve upsets.

Sorting upsets by flight phase shows that low-energy flight phases, such as take-off and landing, rank highest in terms of incident rates [16] - [18]. These phases often involve multiple procedures, limiting the pilots' available mental resources. An upset at lower altitude allows for less time to recover and less potential energy to use in recovery. Additionally, these flight phases often involve changing the aircraft configuration, thus altering its performance characteristics. Visualizing these dynamic performance boundaries can make potentially dangerous situations more apparent.

B. Upset Prevention and Recovery Training

Unlike basic stall training, Upset Prevention and Recovery Training (UPRT) is not mandatory for pilots. In this sense UPRT can be compared to skid training for cars: a non-compulsory course that teaches drivers to keep control over their vehicle in adverse conditions.

Various flight-safety organizations have advized structuring UPRT according to a specific multi-step process [5], [19] - [21]. First, the basic principles of aerodynamics relevant for LOC are taught in a classroom environment. These form the basis for both prevention techniques and recovery procedures, which are then practiced on Flight Simulator Training Devices (FSTDs). Unfortunately, current technology only allows limited simulation of LOC in FSTDs, as extended flight envelope models are still being developed [22] - [24]. Finally, on-aircraft training is used to practice recovery from full upset conditions, including effects of startle and disorientation.

Two theories regarding aircraft performance and aerodynamics form the base of UPRT: the altitude envelope (Figure 1a) and the load-factor envelope (Figure 1b). Both describe aircraft maneuverability limitations, and thereby define operational constraints which pilots must respect.

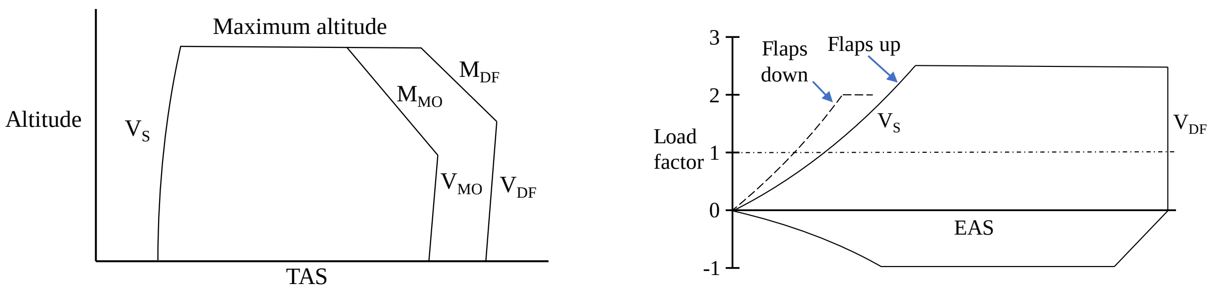
1) The Altitude Envelope: The altitude envelope shows the range of true airspeeds which can be achieved at each altitude. At greater altitudes the lower air density allows an aircraft to obtain a range of higher true airspeeds. This is true until the maximum speed exceeds the maximum Mach number. Changing configuration from clean will change envelope limits. Extended flaps or gear decrease velocity limits, thus shift the envelope to the left.

As airspeed and altitude are both measures of energy, the altitude-airspeed diagram represents a total energy diagram. When flying near the edges of the altitude envelope either the total energy contained by the aircraft must be adjusted or kinetic and potential energy must be exchanged. Exchanging energy is often faster than changing the total energy, making this the preferred option [5].

The most dangerous region of the altitude envelope is that for low altitude and low airspeed, as the combination indicates a low total energy state. Unintentionally approaching this region leaves pilots with reduced maneuverability, as there is a time delay for adding total energy through additional thrust.

2) The Load Factor Envelope: The load factor envelope, or V-n diagram, shows the interaction between load factor and equivalent airspeed. Use of equivalent airspeed allows using a single envelope rather than one for each altitude. The roof and floor of the V-n diagram in Figure 1b correspond to the common structural limits of +2.5 g and -1 g for general aviation aircraft, or +2 g and -1 g with flaps extended. These limits differ with aircraft type, and pilots should be aware of the maneuvering limits of the aircraft they are flying.

Excursions of the left side of the V-n envelope indicate a deficient airspeed, which will stall the wing. For maneuvering in (near-)upset conditions, an aircraft will most often find itself close to the left-most border for positive load factors. Stalls for negative load factors are uncommon, as achieving a negative load factor requires the aircraft to make a diving maneuver, which will allow the aircraft to gain airspeed and divert from the envelope border. Note that this does not hold true for inverted flight conditions.



(a) (b)

Fig. 1. The Altitude Envelope (a) and Load Factor Envelope (b), where V_{MO} and V_{DF} are the Maximum Operating and Design velocities respectively, M_{MO} and M_{DF} are the Maximum Operating and Design Mach numbers and V_S the stall speed. Adapted from [5].

C. Work Domain Analysis

The framework of designing an ecological interface is based on the foundations [9] and guidelines [25] by Vincente and Rasmussen. The display should show boundaries of the LOC work domain. This work domain is based on the theories described in Section II-B, and is to be structured in the form of an Abstraction Hierarchy (AH). The AH, shown in Figure 2, gives insight in the higher, more abstract orders of information present in the system. By showing the deeper structure underlying the control problem, the display should allow pilots to make more informed control decisions.

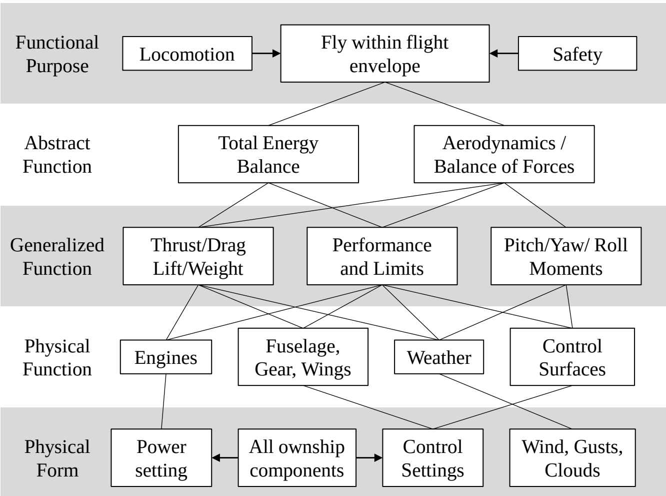


Fig. 2. Abstraction Hierarchy for the upset prevention work domain

Generally, elements on the physical level are most easily accessible for pilots, as they can be measured and displayed. The goal will be to display information of higher levels, which in this case means giving insight in the flight envelope and associated safety limits. To facilitate using this information effectively it is important to show how pilots can manipulate (their position in) the flight envelope, which is done through showing explicit 'means-ends' links [26]. These cues indicate how higher levels of abstraction can be influenced with direct control actions, and thus allow for better control of these higher levels to complement the insight gained in them.

D. Review of Earlier VSD Enhancements

1) Visualizing the Flight Envelope: The basis for both reference VSD designs is the flight envelope, which shows maneuverability space in the vertical plane. The envelope encompasses all steady state velocities which can be achieved with a certain aircraft configuration. The current position within the flight envelope is shown by the aircraft velocity vector. The angle this vector makes with respect to the horizon corresponds to the flight path vector, its length indicates the velocity of the aircraft.

Limiting factors for this envelope are the maximum and minimum thrust (T_{max} and T_{zero}) and the maximum operating and stall speeds (V_{MO} and V_S) These boundaries together form the performance envelope, shown in Figure 3. The steepest possible climb (V_X) is indicated by a green dot.

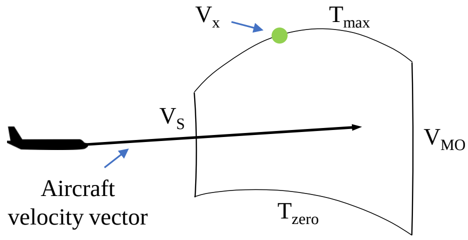


Fig. 3. The Vertical Performance Envelope.

In some aircraft, such as the Boeing 737 and 787, VSD's are used to display terrain height and send ground proximity warnings [27]. To integrate the performance envelope with a terrain database the envelope is expressed in distances by multiplying all velocities with a certain lookahead time. For example, a lookahead time of 60 seconds will result in an envelope of all locations that can be reached in one minute with a constant steady state velocity. If any wind is present, the envelope can be shifted as a whole to account for effects wind has on ground speed.

2) The Experimental VSD (EVSD): Rijneveld et al. have added ecological cues to the VSD for purposes of traffic and terrain avoidance [11]. Areas within the flight envelope which would result in a loss of separation with another aircraft are colored red, and the peak in nearby terrain is indicated by a brown line. The resulting display is shown in Figure 4.

The upper axis shows the horizontal component of the velocity in Knots Indicated AirSpeed (KIAS), the right axis shows the vertical velocity component as the Rate Of Climb (ROC). Distance is expressed in nautical miles on the bottom horizontal Along Track Distance (ATD) axis, the left vertical axis shows Altitude (ALT) in feet.

As an additional ecological cue, the excess kinetic energy (more than is required for steepest climb) is expressed as a green bar on the velocity axis. This energy can be converted into a specific amount of potential energy, which is expressed as a green bar on the altitude axis. The total energy line within the flight envelope can be used to determine if the total amount of energy is increasing or decreasing.

Rijneveld et al. compared the EVSD to a VSD showing only climb and glide limitations in a pilot-in-the-loop experiment with 12 professional airline pilots. Although performance did not improve, pilots did report lower workload and increased situation awareness. Pilots noted that they did not often use the energy cues on velocity and altitude tapes. They also had longer reaction times using the EVSD but said to feel more confident in their decisions. The longer reaction time can be attributed to the greater amount of information needing to be processed, which also increases the certainty with which decisions can be made. It was recommended to explore integrating other types of information into the VSD such as intruder intent, aircraft configurations and malfunction scenarios.

3) The Intentional VSD (IVSD): The IVSD by Comans [14] is an adaption of the EVSD where constraints are split into two types: causal and intentional. Causal constraints are determined by physical limitations to operation, such as

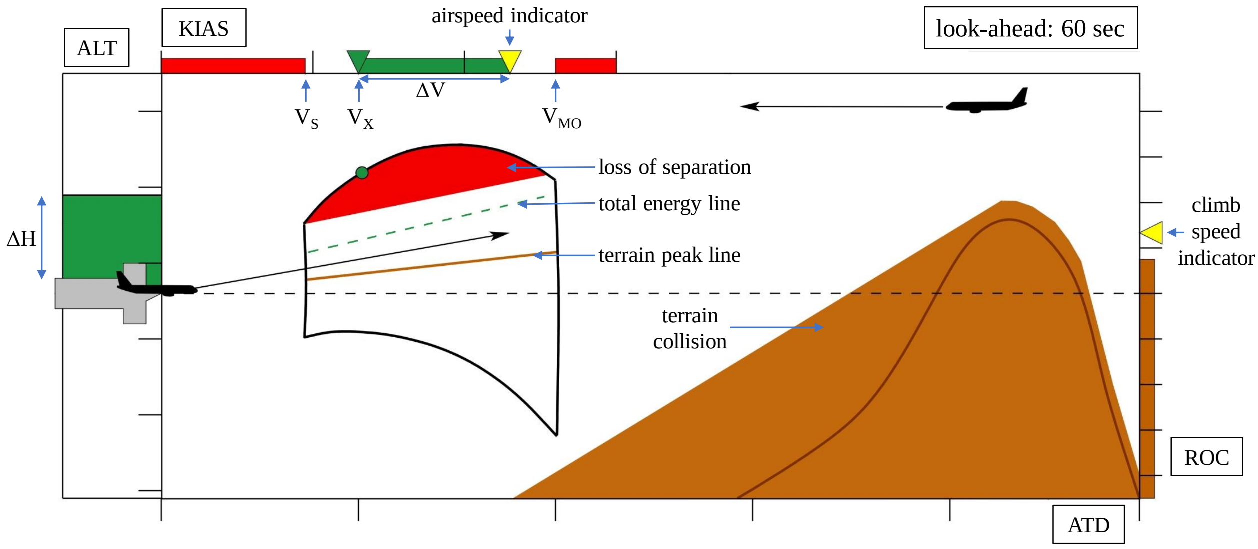


Fig. 4. Layout of the EVSD, adapted from [11].

the terrain or an intruder aircraft. The constraint around the intruder is approximated with a small cylinder to account for wake turbulence. Surrounding these are intentional constraints: the terrain clearance height and full intruder protected zone. Violating these boundaries will not directly cause an accident, but does put the aircraft in an increased state of risk.

Both types of constraints are represented by filled polygons; causal constraints are more opaque than intentional constraints to differentiate their severity. Since all areas of the flight envelope that would result in any type of conflict are fully colored, the task of evading conflicts is now simplified to keeping the aircraft velocity vector outside of colored areas.

An experimental evaluation of the IVSD by 8 novices and 8 licensed pilots showed no significant effect on safety or performance compared to the EVSD. The IVSD did reduce the spread in performance, suggesting that adding intentional constraint information makes pilots more aware of their position within safety boundaries, thus leading to more fine-tuned control strategies. The extent to which this effect holds is unknown, but it raises interest in further research into adding additional information to the VSD.

Both the experiment by Rijneveld et al. and by Comans used scenarios flown exclusively in clean configuration, which means the flight envelope only varied in shape with altitude. Aircraft configuration, however, has a large influence on the flight envelope. Reflecting these effects requires the flight envelope to be made dynamic, which will be a central feature of the VSD enhancements presented in this research.

III. The Configuration VSD

This section will propose a new enhancement of the VSD to aid pilots in low-energy flight maneuvering. First the adjustments to the performance envelope are discussed in Section III-A, after which the integration into the VSD is explained in Section III-B. As this design will show the pilot information based on current aircraft configuration, it is named the Configuration VSD (CVSD).

A. *Visualizing Configuration in the Performance Envelope*

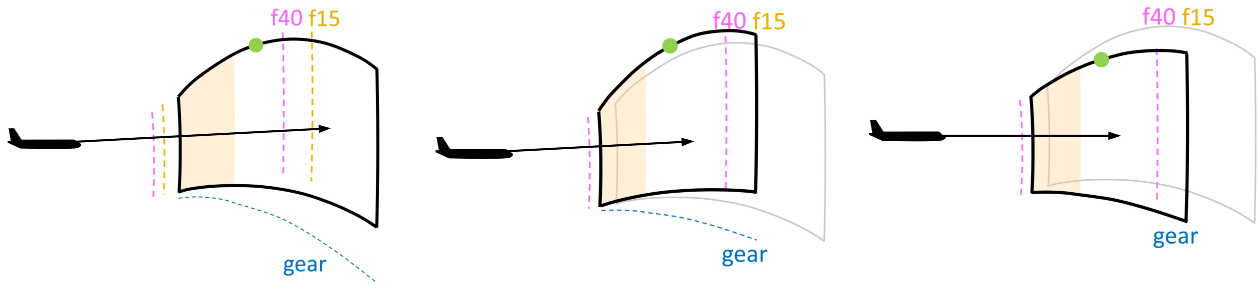
Changing aircraft configuration alters performance characteristics, which can be visualized using the flight envelope discussed in Section II-D. The flight envelope, however, is only able to reflect what velocities can be maintained with the current configuration. An ecological display shows the entire available work domain, so extra cues are added to give insight to what would happen when flap or gear state is altered. This envelope is shown in Figure 5.

The most prominent features of the visualization are the current velocity vector and current flight envelope. Together they represent information from the top level of the AH (Figure 2): the velocity arrow must point inside the lines to be flying within flight envelope bounds, and if the arrow points close to the envelope edge it indicates a heightened risk of envelope excursions. Low velocities are dangerous for risk of aerodynamic stall, made apparent by a transparent orange area.

To keep the velocity arrow inside the envelope, both the vector and the envelope limits can be controlled. The velocity is controlled through changing thrust force and pitching moment, which in their turn depend on throttle and stick inputs. As pilots are assumed to know of these means-ends links and to limit the amount of cues presented simultaneously, no additional cues are dedicated to this interaction.

The envelope shape is prescribed by aircraft performance and limitations, which in their turn depend on configuration and aircraft specifications. Specifications, such as weight or maximum thrust, are mostly uncontrollable while airborne. The configuration, however, can be changed to alter the envelope shape. Means-ends links in the form of dotted lines are added to make this interaction explicit. Lines are grouped by color, and include congruent text indicating the configuration change corresponding to these limits.

Deploying flaps increases the lift and slightly increases drag, as well as decreasing stall and maximum operating speeds. This causes the flight envelope from Figure 5a to shift left



(a) (b) (c)

Fig. 5. Performance Envelopes for the CVSD with (a) clean configuration, (b) flaps 15, gear up (c) flaps 15, gear down.

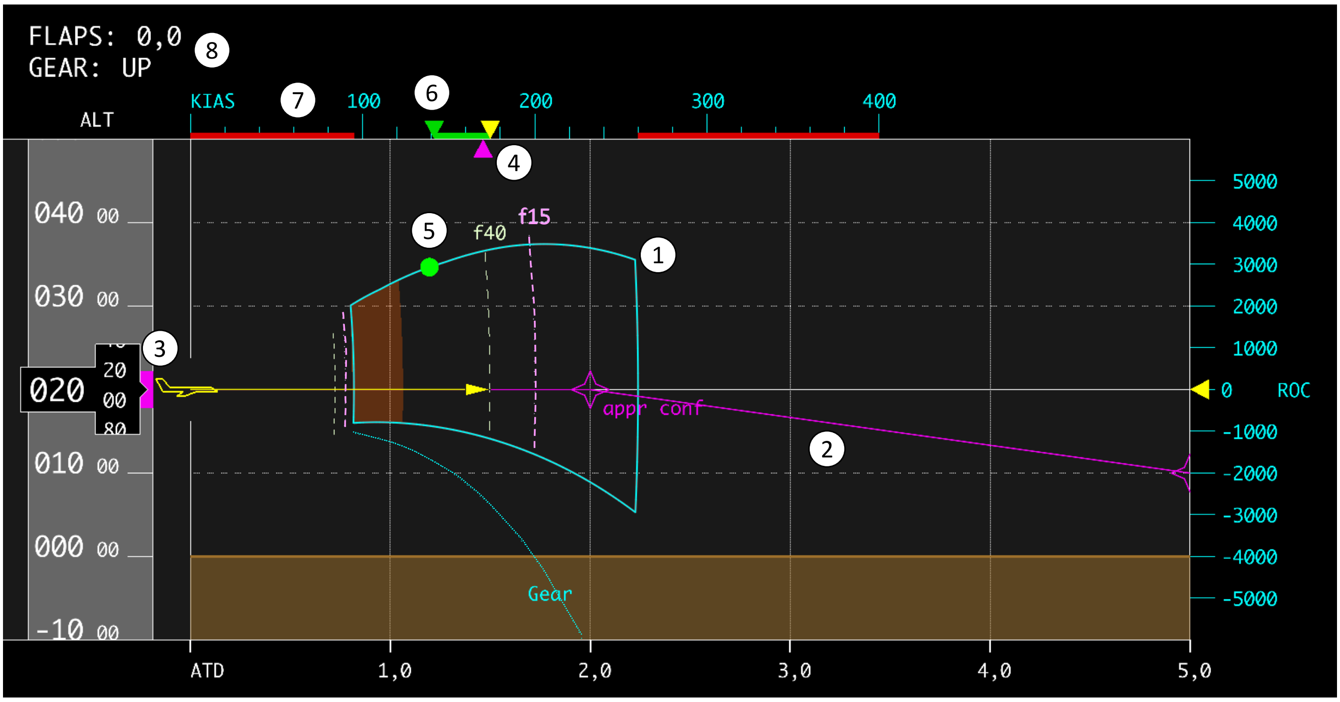


Fig. 6. Numbered Overview of the CVSD.

towards lower speeds and slightly up towards higher rates of climb in Figure 5b. Lowering the gear greatly increases drag, causing the envelope to 'drop' in Figure 5c. Since drag increases with higher velocities, the effect is more significant on the far end of the envelope.

Additionally to adding configuration cues, an intentional cue is added regarding velocity. During approach the Final Approach Speed (V_{FAS}) is a safety constraint for pilots to abide to, which serves as a buffer in case any unexpected event occurs. Velocities below this threshold inside the flight envelope are indicated by a transparent orange area. The V_{FAS} in knots is typically determined by:

$$V_{\text{FAS}} = 1.3 \cdot V_S + \text{CF} \tag{1}$$

in which the Correction Factor (CF) depends on aircraft type and environmental conditions. For the Citation II, the model of which will be used in the experiment, this CF ranges from 0 to 20 kts.

B. Integration with VSD Design

As the display does not concern terrain avoidance the EVSD terrain peak line is removed for the CVSD. The total energy cues are also removed because their similar appearance to the newly added configuration cues might be confusing.

The CVSD includes all other features from the EVSD and IVSD. The performance envelope ① is updated as explained in Section III-A. A magenta line ② shows the two-dimensional flight path, which includes waypoints indicating desired actions. The altitude and velocity goal for the next waypoint are indicated with magenta markers on the altitude ③ and velocity ④ axes.

The envelope still shows the steepest climb by a green dot ⑤, and the corresponding velocity is indicated in green on the velocity strip ⑥. The red bars for stall and maximum speeds ⑦ are made dynamic to reflect speed limits for the current configuration. Finally a direct readout for the current flap angle and gear status is included ⑧.

IV. Experiment Design

The CVSD was evaluated in a pilot-in-the-loop experiment. This experiment was designed to test the effectiveness of the CVSD in improving performance, detecting failures and adapting to unforeseen circumstances by comparing it to a Baseline VSD (BVSD) without ecological cues.

A. Participants

Sixteen licensed pilots took part in the experiment. All participants flew two similar sets of scenarios with both displays. Their task was to fly a scenario as best they could within safety limits. The order of the displays was varied to control for learning and fatigue effects; the first group of eight pilots started by using the BVSD (avg flight experience 2261 hours, *SD* = 3198), the second group of eight pilots started by using the CVSD (avg flight experience 2003 hours, *SD* = 2588). After completing a set of runs, participants took a break and flew a second set with the other of the two displays. In previous EID research, this method prevented display order from having significant effects on dependent measures [28].

Both groups comprised four PPL pilots, three CPL pilots and one military pilot. All types of licenses require training to perform basic low-energy flight maneuvers, so license type is assumed not to make a difference in performance. Participants had different levels of experience with glass cockpit displays, and therefore they were able to provide a wide range of feedback after the experiment.

B. Independent Variables

The experiment was set up as a within-subjects repeated measures design, meaning that all participants flew using both the CVSD and BVSD displays. The former is described in Section III, the latter is exactly the same but without the velocity envelope and configuration cues.

The experiment comprises two sub-experiments: one concerning nominal operation and one concerning failure conditions. For both VSD variants a set of five runs was flown, four of which are nominal runs and one containing a flight control failure. The failure occurred once as the third and once as the fourth run in a set. As flight control failure, either the gear does not retract or the flaps get stuck at 15° during the go-around procedure. The order of these failures and combinations with displays were distributed evenly over the participants. Using a Latin-square design with 16 participants, each combination of display and failure occurred 8 times.

C. Apparatus

The experiment was conducted in a fixed base flight simulator at Delft University of Technology. A non-linear six degree of freedom model of a Cessna 550 Citation II was loaded on the simulator. Throttle inputs were controlled by a thrust lever, control surface inputs were given through a hydraulic side stick with trim buttons. The aircraft model was locked in the vertical plane, therefore yaw pedals and lateral side stick motions were frozen. A gear lever and flaps switch were used to change the configuration of the aircraft. International

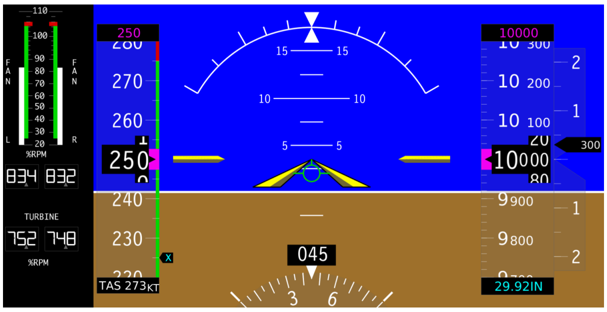


Fig. 7. The PFD as Used in the Experiment

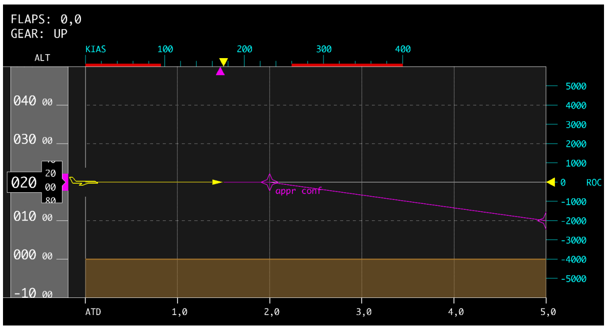


Fig. 8. The Baseline VSD as Used in the Experiment

Standard Atmospheric conditions were used with zero wind, but all scenarios did include a mild turbulence using a Dryden model to increase the difficulty of the task.

D. Experiment Displays

During each part of the experiment participants used a Primary Flight Display (PFD) and one of two VSD variants. No other flight displays were used.

1) Primary Flight Display: A generic PFD based on a Garmin G1000 was used to give participants a familiar reference for their basic flight parameters (Figure 7).

The PFD shows a pitch ladder and green flight path vector over a virtual horizon. An altitude tape is shown on the right, a velocity tape showing indicated airspeed on the left. Both include a magenta marker corresponding to the desired altitude and velocity at the next waypoint. The optimal climb speed V_X is marked by an X on the velocity tape. The bank angle indicator at the top and compass at the bottom were frozen due to lateral inputs being disabled.

Engine information is included on the far left side. Two bars indicate engine fan speeds with numerical readouts below. The bottom two numbers are the turbine speeds for both engines.

2) Vertical Situation Display: Two versions of the VSD were used: the CVSD (Figure 6) and the BVSD (Figure 8).

Although the BVSD does not include the flight envelope visualization the aircraft velocity vector was still present, allowing horizontal and vertical speeds to be read out on the KIAS and ROC tapes. The current flight configuration can be read from cues such as the numerical readout, red V_S and V_{MO} indicator bars and the three green indicator lights on the control panel.

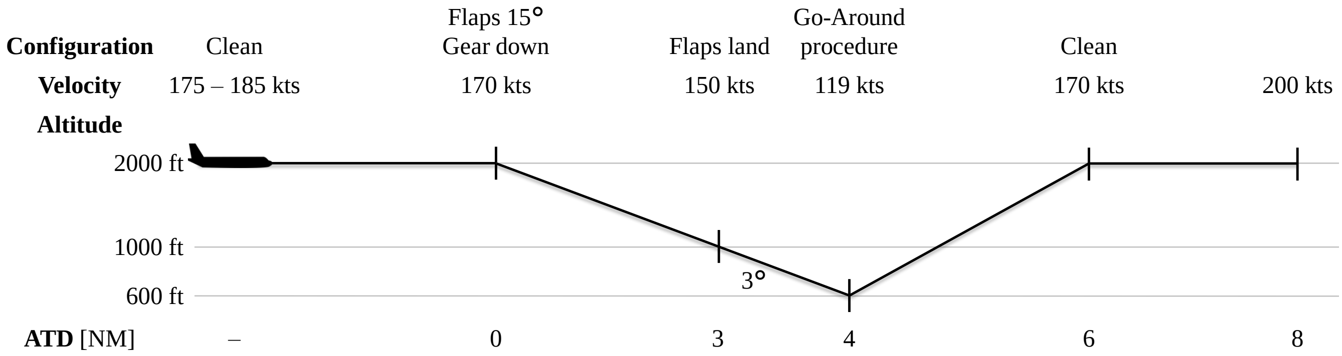


Fig. 9. Schematic Representation of the Experiment Scenario

E. Scenario

Participants were tasked to fly an approach and go-around procedure, as it allows combining multiple low-energy flight maneuvers in a single scenario. The scenario consisted of a standard non-precision approach using a 3° glideslope with a go-around at an altitude of 600 ft. The flight path and corresponding procedures were based on the Citation II Pilot Manual. An overview of the flight plan is shown in Figure 9.

Each run started in trimmed condition with an indicated airspeed between 175 and 185 knots at a distance of 1 to 3 nautical miles from the top of descent. From this point the participant had to follow the profile as closely as possible with intermittent velocity and configuration goals. All goals were allowed to be anticipated upon (such as configuring before a waypoint) except the go-around, which was not allowed to be initiated until after the go-around waypoint marker.

All participants reviewed the standard go-around procedure before the start of the experiment:

1) Gain velocity by giving full throttle
2) Simultaneously pull stick back to stop losing altitude
3) At V_{REF}+5 kts, reduce drag by setting flaps to 15°
4) With positive ROC, retract gear
5) Clean up configuration to 0° flaps

Additionally, participants were told that they were free to deviate from standard procedure if they thought it would be in the interest of safety.

F. Procedure

The experiment started with a general briefing on the flight simulator, scenario and pilot objectives. Additionally, the briefing explained the information shown on their first VSD variant, which was then put into practice through multiple training runs. Finally, five measurement runs were made. Just before the measurement runs started, participants were alerted to the possibility of a flight failure as follows: *"Unexpected events might take place. In such an event, the main goal will stay the same: to best execute the approach and go-around maneuver within safety limits."*

After a break, participants were briefed on the second VSD variant. This briefing and training runs were slightly shortened since the participant was already familiar with the flight controls, dynamics and procedures. The experiment is concluded by a questionnaire and debrief. The complete experiment procedure is shown in Table I.

TABLE I
EXPERIMENT PROCEDURE

15 min	Briefing	
30 min	Training	**VSD variant 1**
20 min	Measurements	
20 min	Break	
5 min	Briefing	
25 min	Training	**VSD variant 2**
20 min	Measurements	
15 min	Questionnaire and Debrief	

G. Dependent Variables

Measures for safety, performance and workload include both objective and subjective variables. From the simulation data, the Root Mean Squared Deviation (RMSD) of both altitude and velocity were used to assess participant performance. Safety is measured by the amount of envelope excursions, the minimum velocity obtained during a run and the cumulative time spent at velocities below V_{FAS}. Control activity is taken as an objective measure of workload. Participants' procedures were qualitatively analyzed to find differences in control strategies between displays. During scenarios in which a failure occurs, the time it took for the participant to diagnose the failure is measured. To obtain this information participants were requested to think aloud during the experiment, and timestamps were deduced from the audio recordings.

After each run participants were requested to submit a workload score on the Rating Scale Mental Effort (RSME), which was used as a subjective workload measure. A post-experiment questionnaire was used to collect further data on safety and workload that participants experienced, as well as general comments on their preferences and suggestions.

H. Hypothesis

It is hypothesized that using the CVSD will increase performance, as the V_{FAS} constraint assists pilots in velocity tracking when their workload is largest and the steepest climb indicator shows the quickest method to recover altitude at the start of go-around. Similarly, it is expected that the participants using the CVSD will fly more safely since velocity limits and V_{FAS} boundary are made more explicit. Third, workload metrics are expected to be lower using the CVSD due to the mapping of higher level information in EID. Finally, as the CVSD includes ecological cues regarding aircraft configuration, it is hypothesized that detection and diagnosis of control failures will be faster than using the BVSD.

V. Results

This section presents the results of the experiment described in Section IV. The results are split into five parts corresponding to the categories of metrics used: performance, safety, workload, failure runs analysis and pilot feedback.

Each participant flew two runs which included a type of failure, one with each display variant. These failure runs are excluded from nominal performance and safety metrics, since a gear or flap failure impairs the performance characteristics of the aircraft. These runs are analyzed separately instead.

Runs which did not include a flight failure were effectively the same scenario with a random starting velocity and distance offset. These runs were aligned by disregarding data until 0.5 nautical miles before the top of descent. Test statistics were computed for each run and then averaged per pilot, resulting in fewer yet more reliable data. No runs were found eligible to be removed as outliers.

A. *Performance*

Generally altitude RMSD scores were similar between displays, and velocity RSMD scores showed better performance using the BVSD. Visualization of the data through box plots in Figure 10 shows a smaller spread in altitude error using the CVSD. The total range is however still similar.

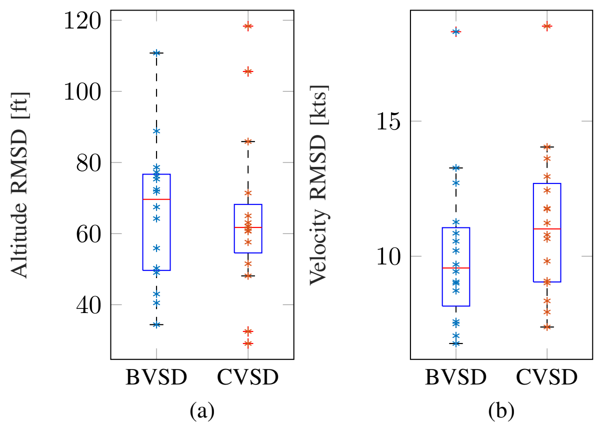


Fig. 10. RMSD for Altitude (a) and Velocitiy (b)

No significant difference in altitude performance was found using Wilcoxon-Signed-Rank test ($Z = 0.362$, $p > 0.05$). Velocity RMSDs were compared using paired t-test, which showed a significant better velocity tracking performance using the BVSD ($t(15) = -2.19$, $p < 0.05$).

An improved velocity tracking performance using the BVSD is contrary to the hypothesis, which stated that this improvement would be found for the CVSD. Further analysis into the origin of this result is done by creating a running 95% confidence interval of the velocity profile along the length of the approach and go-around. Intervals for both displays are superimposed in Figure 11, showing similar trends at all velocity targets except at 4 NM. At this point the velocity goal is equal to V_{FAS}, which is explicitly shown by the intentional constraint on the CVSD. Participants using the CVSD more actively prevented their velocity from violating this intentional constraint, often keeping some margin to account for the randomness of turbulence. The variance in velocity during go-around was also decreased, but this effect is not reflected in performance metrics as no velocity targets are present in this section of the experiment scenario.

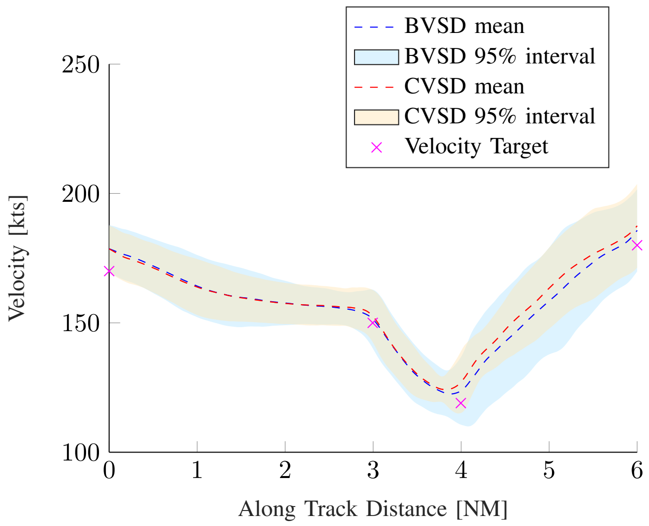


Fig. 11. Mean and Running 95% Confidence Interval for Velocity Profile.

To further analyze strategies participants used, the two performance metrics are compared to each other. Pearson's correlation coefficient shows that for both displays a relationship between the two performance metrics exists ($r = -0.637$, $p < 0.01$ and $r = -0.715$, $p < 0.01$ for BVSD and CVSD respectively). This is visualized by plotting both performance metrics against one another in Figure 12.

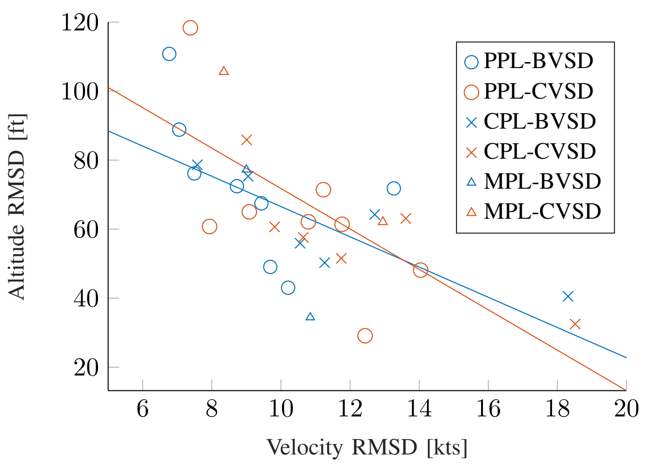


Fig. 12. Velocity versus Altitude RMSD's for Both Displays, Including Regression Lines. Participants Visually Distinguishable by Pilot License Type.

Trend lines for BVSD and CVSD are of comparable slope, and show that participants must chose between optimizing altitude or velocity tracking performance. Furthermore, Figure 12 can be used to confirm that pilot license seems to have no effect on performance, as no type of pilot is consistently above or below the trend line. This is confirmed by multi-variate ANOVA tests, varying license type for altitude RMSD ($F(2,15) = 0.376$, $p = 0.694$) and license type for velocity RMSD ($F(2,15) = 1.066$, $p = 0.373$). Similarly, MANOVA tests showed display order not have a significant effect on performance metrics.

B. Safety

One of the goals of the CVSD is to make pilots more aware of causal and intentional velocity limits. No envelope excursions occurred during the experiment, so only intrusions of the intentional constraint are analyzed. This is done by looking at intrusion depth and total intrusion time, which translates to the minimum obtained velocity and the total time spent below V_{FAS}. These metrics are represented by box plots in Figure 13a and 13b respectively.

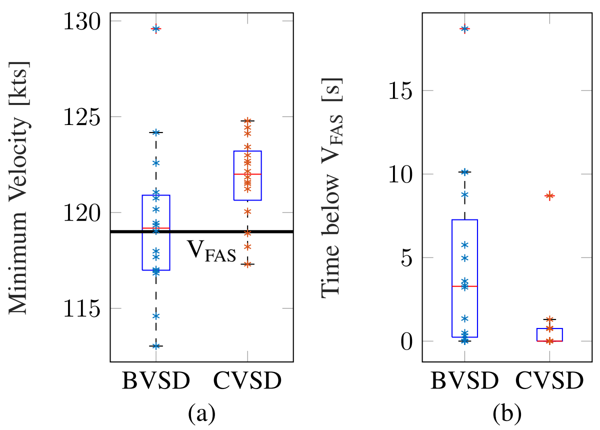


Fig. 13. Minimum Velocity (a) and Time Spent Below V_{FAS} (b).

The large difference in minimum velocity is confirmed by a *t*-test ($t(15) = -2.71$, $p < 0.05$). This is in agreement with the results found in Section V-A, in which performance metrics were in favor of the BVSD. Since the target velocity at go-around and the velocity safety limit coincide, the BVSD median minimum velocity being approximately V_{FAS} means that half the minimum velocities violated the intentional constraint. The CVSD minimum speeds are generally above the V_{FAS} mark, trading performance achieved by the BVSD for better performance regarding safety.

Since minimum velocities for the CVSD generally did not drop below V_{FAS}, it is no surprise that most participants averaged 0 seconds below V_{FAS} in this condition, as can be seen in Figure 13b. Eleven out of sixteen participants didn't exceed V_{FAS} in any of their four nominal runs, bringing the median and bottom quartile both to zero. The single CVSD outlier whith a mean time of 8.7 seconds often pitched up too quickly during go-around in order to follow the reference height, thus neglecting their velocity for a brief moment. As data for time below V_{FAS} did not pass the Shapiro-Wilk test, a Wilcoxon-Signed-Rank test was used to confirm significance ($Z = -2.29$, $p < 0.05$). As both safety metrics are in favor of the CVSD, the hypothesis that CVSD will allow pilots to fly more safely is considered confirmed.

C. Workload

Workload was analyzed objectively through control input variation and subjectively through self-reported RSME ratings. Control inputs used were side stick deflection and thrust setting. Using the control rates rather than deflections eliminates the effect a different trim position might have, thus allows comparing results of participants using varying amounts of trim.

At least one large peak in both control inputs is expected each run at the start of the go-around. Since this input is present for all runs it introduces the same bias in all results, and thus does not prove a problem for this analysis. Boxplots with deviation of control input rates are shown in Figure 14.

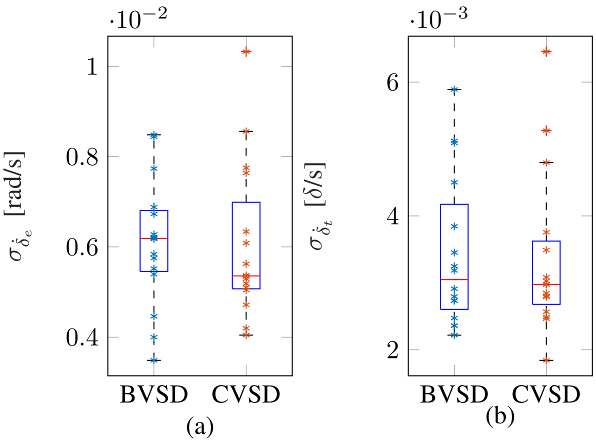


Fig. 14. Standard deviation of elevator input rate (a) and throttle deflection rate (b).

A decrease in rate variability is visible, especially for elevator inputs in Figure 14a. This might be explained by participants being able to see that their aircraft is not flying close to any safety limits, thus relaxing the need to correct higher frequency errors introduced turbulence.

Wilcoxon-Signed-Rank tests found no difference for standard deviation in elevator input rates ($Z = -0.958$, $p > 0.05$) or throttle deflection rates ($Z = -0.675$, $p > 0.05$). These results are replicated by self-reported workload ratings, showing no improvement in reported subjective workload scores ($t(15) = -0.798$, $p > 0.05$)). These metrics provide evidence that there is no difference in workload between displays.

D. Failure Run Analysis

It was expected that flight control failures would always be discovered, but this did not end up being the case. Failures were diagnosed in half of the BVSD failure runs and three-quarters of the CVSD failure runs, shown in Table II. Possible reasons for missed detection are discussed in Section VI.

TABLE II
AMOUNT OF DIAGNOSED FAILURES

	BVSD	CVSD
Gear Failures Diagnosed	4 / 8	6 / 8
Flap Failures Diagnosed	4 / 8	6 / 8
Total Failures Diagnosed	8 / 16	12 / 16

Although diagnosis rate is in favor of the CVSD, not enough data were generated to confirm this with a reliable test statistic. Five participants did not notice the flight control failure with the BVSD but did with the CVSD, whereas the reverse result occurred only once. For all failures successfully diagnosed, the time it took for the participant to do so is shown in Figure 15. Times are measured from the moment a rejected input is given until the start of an audible diagnosis by the participant. No boxplots are drawn because of the limited amount of data.

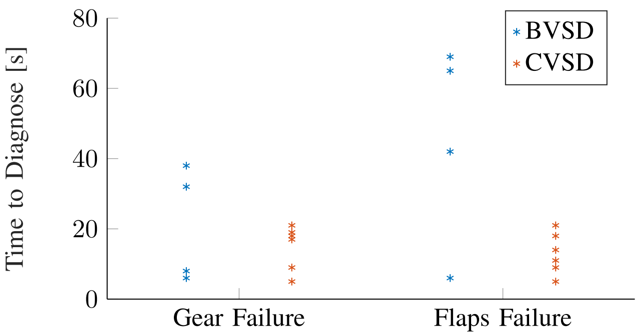


Fig. 15. Time to Diagnose Flight Control Failure.

Diagnosis times for the CVSD are generally shorter than for the BVSD. This was expected, as the CVSD flight envelope visualization offers an additional cue for detection and diagnosis. Several failures were diagnosed within seconds of being introduced, but most required some additional event to take place. Diagnosis times for both gear and flap failures that initially went undetected seem grouped at certain time intervals. This grouping is correlated with specific moments in the go-around occurring which facilitate diagnosis.

For gear failures, this specific moment was either the participant going through a self-directed post-go-around checklist when using the BVSD, or when extending the flaps to 0 with the CVSD. The latter often led to immediate detection by the participant, as having the gear deployed without flaps results in a downward pointing shape of the performance envelope which is easily distinguishable (Figure 16).

CVSD flap failures were often noticed shortly after the rejected input had been given. Using the BVSD generally caused these failures only to be noticed by the end of the go-around after the speed goal changed to 200 knots. This corresponds to V_{MO} for the Citation II with flaps 15^o, and pilots noticed something was wrong as their velocity indicator on the VSD horizontal speed tape approached the red area.

Although no reliable statistical analysis is possible, trends in data show the CVSD having a positive effect on both diagnosis rate and diagnosis time of flight control failures.

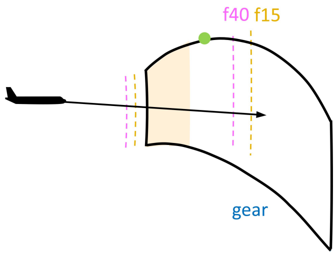


Fig. 16. Performance Envelopes with Zero Flaps and Gear Deployed.

Not all failures were discovered however, for which potential reasons are discussed in Section VI.

After detection and diagnosis, participants generally slightly adjusted their control strategy for that run. Flying an aircraft with the gear deployed adds drag, which participants accounted for by setting a higher throttle. Having flaps at 15^o adds both drag and lift, but more noticeably reduces V_{MO} to 200 knots. Participants originally gave more throttle, but later reduced to keep their velocity around 190 knots, again sacrificing performance for safety. These adjustments were similar for both displays after the failure was diagnosed.

Failure runs have also been analyzed using the performance, safety and workload metrics, and showed similar trends to the nominal conditions. The CVSD has not lead to different control strategies such as changes in configuration schedule.

E. Pilot Feedback

Two forms of feedback were collected from participants at the end of the experiment. Firstly, a questionnaire asked participants to compare both displays, and participants were requested to elaborate on their answers. Secondly, participants were asked for feedback on the displays, simulator or any other aspect of the research in an open format.

1) Questionnaire: Each of the ten questions in the questionnaire presented participants with a scale showing the BVSD on the left, CVSD on the right and a small mark in the middle for neutral/equal. Participants ticked a location on the scale to indicate for which display they found the statement to be most true, as well as the weight they gave to their opinion. This was used to construct a box plot for each question, which are shown in Figure 17.

Participants mostly indicated that the CVSD allowed them to better handle failures, fly safer and better predict dangerous situations. Even pilots who did not notice either of the two failures reasoned that additional information on the CVSD must make failure detection and diagnosis easier, although they submitted less positive scores than those who successfully diagnosed the flight control failures. Two out of sixteen pilots disliked the CVSD, and noted that the flight envelope visualization sometimes caused cluttering of the display.

Generally, pilots indicated experiencing the CVSD ecological cues as useful additions to the VSD. They say to have experienced lower workload, although this claim is not supported by objective nor subjective metrics analyzed in Section V-C. Additionally, multiple participants said the CVSD was more difficult to work with (Question 1), yet

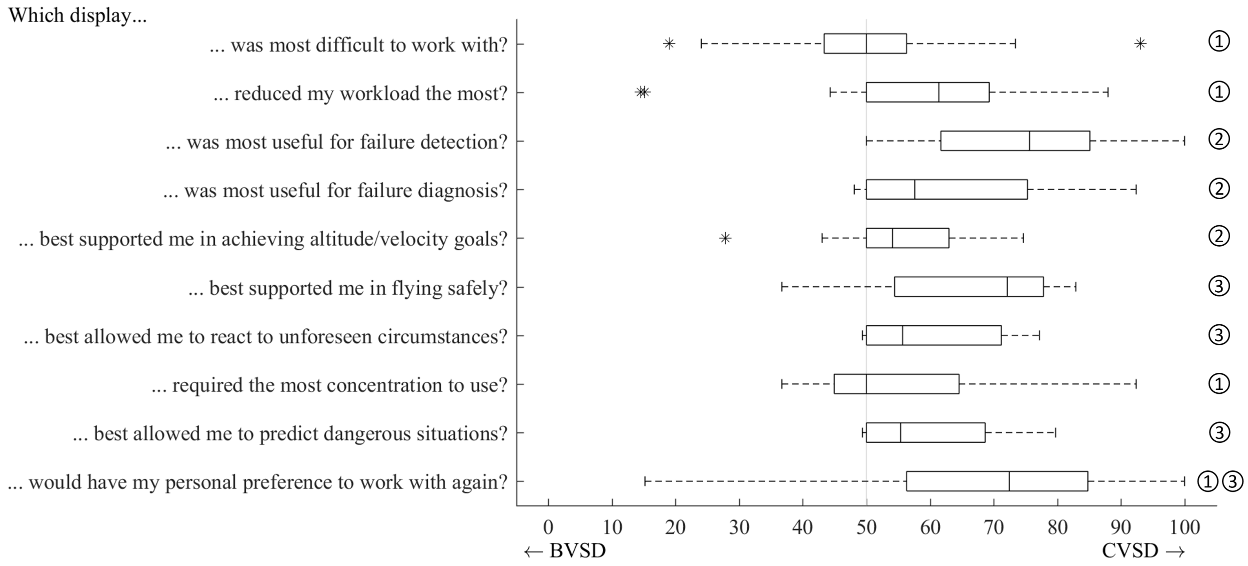


Fig. 17. Box plots of Questionnaire Results with Numbers Indicating Principle Component Categories

still rated their workload in favor of the CVSD. When asked about this seeming inconsistency, a participant explained: *"The CVSD wasn't easy to learn and requires more of my attention, but it offers me peace of mind knowing I'm not near the limits of my aircraft."* This is confirmed by the answers to question 8 on 'most concentration to use'.

Further correlations in the questionnaire results were found by means of a principle component analysis. Three significant categories (with eigenvalues greater than 1) were created, cumulatively capturing 80% of variance in the answers given. The categories are marked with numbers ① to ③ in Figure 17 based on overlapping topics of the questions:

1) Workload
2) Performance
3) Situation Awareness

Whereas questions on failure detection and diagnosis seem to belong under the 'Situation Awareness' topic, a larger correlation was found with the question on achieving altitude/velocity goals, placing this question in the 'Performance' category. This can be explained by the nature of the display and scenario design: multiple flight control failures have happened during the experiment, which impeded aircraft performance. Flight envelope visualization gave insight in performance limits after a failure, thus timely detection and diagnosis allowed pilots to consciously account for these adjusted performance limits in controlling the aircraft.

Questions regarding failure detection and diagnosis were heavily in favor of the CVSD, a result which was expected due to the increased amount of cues a pilot can observe when a failure occurs. Interestingly, the CVSD scores higher on failure detection than on diagnosis. Various reasons along the same lines were given, best articulated by a participant as: *"After a few runs you know how the envelope is supposed to move, thus when it doesn't [move as expected] you know to start a search for the underlying reason"*.

Interestingly, personal preference correlates with both workload and situation awareness, although correlations are less strong than commonly found within categories (with correlation weights of 0.71 and 0.63 respectively). This result gives insight in what factors might effect pilot preference in working with one display over another, with workload as one of the highest priorities.

2) Further Pilot Comments: Since the pilot comments had an open format, topics varied among pilots. Still various themes could be distinguished, within which one or two common opinions were held by groups of participants.

Pilots often mentioned the usefulness of the green dot indicating the steepest climb on the CVSD. Reasons given include its clear purpose, good visibility and ease of use by simply moving the velocity vector there. Especially at the workload-intensive time during go-around when the steepest climb is commonly used, these aspects are amplified in their importance and thus perceived usefulness.

Several suggestions were done to expand on display features, such as having the aircraft icon rotate according to the current aircraft pitch angle and providing a cue to indicate the current trend of the velocity vector. The most requested display feature was some form of direct feedback for the effect of control inputs on the velocity vector. For a successor to the CVSD, some form of acceleration vector might be considered to more closely link inputs to the effect they have, thus giving operators more insight in system dynamics.

Critique of the display mostly focused on display elements which, in their current state, are not easy to use. Since most cues are centered around the left of the VSD, the ROC tape on the right is difficult to include in a natural-feeling crosscheck. Additionally, the scale of the vertical velocity tape is too small for some readouts, and participants rather used the numerical velocity readout on the PFD. Two participants disliked the CVSD in general, as they said it makes the situation unnecessarily complex.

VI. Discussion

This research aimed to investigate the effects of an ecological VSD enhancement on the ability of pilots to perform a safe and accurate approach and go-around maneuver with potential flight control failures. An analysis of flight paths and control inputs shows that pilots were better able to abide by safety constraints when using the ecological CVSD then when using the more basic BVSD. However, this did come at the price of reduced velocity tracking performance, indicating that the CVSD caused pilots to place a higher emphasis on maintaining safety margins than on optimizing their performance. The desirability of this effect can be questioned when it would become too large, as the marginal gain of larger safety buffers might not outweigh significant decreases in performance.

A turbulence of medium intensity was simulated throughout all of the experiment runs, which caused small random movements of the velocity vector. This uncertainty might be a reason for pilots to maintain an additional velocity margin to the CVSD V_{FAS} boundary, thus decreasing CVSD performance metrics. Previous research by Comans has shown EID to cause a reduced spread in flight path traces [14], an effect which can also be seen in the velocity traces for the CVSD (Figure 11). Reducing the turbulence might cause pilots to reduce the velocity buffer size they maintain. This would result in flight consistently close to but rarely under V_{FAS}, thus optimizing both safety and performance.

Objective workload measures do not indicate any significant difference between displays, and neither do subjective post-run workload scores. However, comparing the two displays in the post-experiment questionnaire, pilots did indicate experiencing a workload reduction when using the CVSD. This does come at the cost of more concentration required to interpret the cues it gives, especially in early phases of using the display. Pilots believed that more training and experience in using the CVSD would allow them to retain their workload reduction without the concentration penalty. In conclusion, the hypothesis stating that the CVSD leads to a workload reduction cannot be accepted, as the results are conflicting and inconclusive.

The CVSD did increase flight control failure detection rates and reduce diagnosis times. Multiple failures went undetected, and a reduction in the amount of data available rendered producing a reliable statistic impossible. Visual analysis of the data supports the hypothesis, but more tests will be necessary for a full confirmation.

Although pilot license did not effect performance metrics, recent experience with FSTDs might have affected metrics for failure diagnosis. Three participants had frequent simulator experiences during the past six months: two during CPL training and one as FSTD instructor. These participants consistently diagnosed failures within 10 seconds regardless of flight display, and achieved all diagnosis times below 10 seconds for the BVSD. This would indicate that recent FSTD training outweighs the effect EID might have on handling certain types of unforeseen circumstances. Whereas the CVSD might not play a significant role for well-trained pilots, its use as diagnosis aid for participants who have not had recent simulator training is strengthened when these data points are accounted for.

It was assumed pilots would always detect failures after they occurred, and the question would be how quickly they would be able to diagnose them. However, the experiment has shown that with neither VSD all failures were detected. Reasons for unnoticed failures are suspected to lie in their non-critical consequences and the limited amount of cues they can be detected by. Participants were only presented with visual cues during the experiment, whereas something as an extended gear would usually also have audible and haptic cues. Including these in the simulation is expected to reduce detection times considerably, whereas diagnostic times are expected still to be in favor of the CVSD. This is to be confirmed by future research, investing more effort into increasing simulation fidelity for better failure simulation.

Throughout the experiment, a few issues arose regarding the simulator and simulation that might have affected the results. When using the simulator for multiple experimental trails on a single day, the hydraulic side-stick could overheat which caused the simulator to stop operating. This has forced to restart a handful of scenarios, and on two occasions forced to take a second, small recess during the experiment. The effect of the extra experience, rest and/or fatigue which some participants accumulated this way is unclear. However, the effect is brought to a minimum when analyzing the results by averaging metrics for all runs a participant flew. No individual runs qualified to be removed as outliers.

Some participants commented on the highly sensitive pitch response of the simulation model. This may be due to poor tuning of the aircraft model, but is more likely related to the experience these participants had flying mostly larger aircraft. Participants experienced flying the Cessna Citation II had no objections on simulation fidelity.

VII. Conclusion & Recommendations

In this research, two versions of a VSD were evaluated by 16 pilots to test their effect on the performance of an approach and go-around maneuver. Some scenarios included a gear or flap failure which pilots had to diagnose. The CVSD showed pilots their flight envelope, which was variable with configuration and included a V_{FAS} indication. Compared to a baseline VSD, the CVSD increased safety at the cost of tracking performance, as pilots avoided violating safety constraints by maintaining an additional velocity buffer. Participants said the CVSD reduced their workload, although this statement is not backed by objective metrics. Flight control failures were more often detected and diagnosed more quickly. However, not all failures were detected and pilots said the CVSD required more concentration, indicating more training might be necessary for the display to be optimally used.

For future research, it is recommended to look into redesigning parts of the CVSD, as well as testing its use in other scenarios. Various small yet valuable suggestions were made by pilots participating in the experiment, such as pitching the ownship visualization and including a velocity trend vector, but also more prominent aspects such as the effect of a constant wind should be considered. This would allow for a wider variety of more realistic scenarios to be flown and tested.

Failures tested in this experiment were limited in variety and cues. Future experiments could aim to add others failures such as windshear, microburst or engine failures. Previous versions of the VSD were used as tools for traffic and terrain awareness, incorporating these in scenario design will lead to a more varied experiment and potentially to a more versatile display.

Finally, it is recommended to further explore the effect turbulence has on strategies employed by pilots. If introducing random variance to a controlled system with an ecological display causes pilots to change their control strategy, this may have unintentional consequences. Understanding these consequences is paramount to adapting ecological displays for use in the real, turbulent outside world.

References

[1] Boeing Commercial Airplanes. Statistical Summary of Commercial Jet Airplane Accidents. *Boeing Commercial Airplanes*, 2016.

[2] E. F. Weener. General Aviation LOC and the NTSB Most Wanted List. *National Transportation Safety Board*, 2016.

[3] S. R. Jacobson. Aircraft Loss of Control Causal Factors and Mitigation Challenges. In *AIAA Guidance, Navigation, and Control Conference*, pages 1–59, 2010.

[4] A. Lambregts, G. Nesemeier, R. Newman, and J. Wilborn. Airplane Upsets: Old Problem, New Issues. *AIAA Modeling and Simulation Technologies Conference and Exhibit*, (August):1–10, 2008.

[5] Federal Aviation Administration. *Manual on Aeroplane Upset Prevention and Recovery Training*. FAA, Montreal, Quebec, first edition, 2014.

[6] E. Groen, W. Ledegang, J. Field, H. Smaili, M. Roza, L. Fucke, S. Nooij, M. Goman, M. Mayrhofer, L. Zaichik, M. Grigoryev, and V. Biryukov. SUPRA - Enhanced Upset Recovery Simulation. *AIAA Modeling and Simulation Technologies Conference*, (August):1–14, 2012.

[7] J. Croft. Reconsidering Upset Recovery Training. *Aviation Week & Space Technology*.

[8] C. Borst, J. M. Flach, and J. Ellerbroek. Beyond ecological interface design: Lessons from concerns and misconceptions. *IEEE Transactions on Human-Machine Systems*, 45(2):164–175, 2015.

[9] K. J. Vicente and J. Rasmussen. Ecological interface design: theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(4):589–606, 1992.

[10] C. Borst, F. A. Sjer, M. Mulder, M. M. Van Paassen, and J. A. Mulder. Ecological Approach to Support Pilot Terrain Awareness After Total Engine Failure. *Journal of Aircraft*, 45(1):159–171, 2008.

[11] P. Rijneveld, C. Borst, M. Mulder, and M. M. Van Paassen. Towards Integrating Traffic and Terrain Constraints. In *AIAA Guidance, Navigation, and Control Conference*, Toronto, Ontario, 2010.

[12] S. B. J. van Dam, M. Mulder, and M. M. van Paassen. Ecological Interface Design of a Tactical Airborne Separation Assistance Tool. *IEEE Transactions on Systems, Man, and Cybernetics*, 38(6):1221–1233, 2008.

[13] P. A. Sleight and R. D. G. Carter. Report on the accident to Boeing 777-236ER, G-YMMM, at London Heathrow Airport on 17 January 2008. Technical Report Aircraft Accident Report 1/2010, British Department for Transport, London, 2010.

[14] J. Comans. *Visualizing Rules, Regulations, and Procedures in Ecological Information Systems*. PhD thesis, Delft University of Technology, 2017.

[15] C. M. Belcastro and J. V. Foster. Aircraft Loss-of-Control Accident Analysis. In *AIAA Guidance, Navigation, and Control Conference*, Toronto, Ontario, 2010.

[16] International Air Transport Association. Safety Report 2015 Edition. Technical report, International Air Transport Association, Montreal, Quebec.

[17] S. J. Houston, R. O. Walton, and B. A. Conway. Analysis of General Aviation Instructional Loss of Control Accidents. *Journal of Aviation/Aerospace Education & Research*, 22(1), 2012.

[18] B. N. Branham. *Analysis of Fatal General Aviation Accidents Occurring from Loss of Control on Approach and Landing*. PhD thesis, Embry-Riddle Aeronautical University, 2013.

[19] D. Carbaugh, L. Rockliff, and B. Vandel. *Airplane Upset Recovery Training Aid*. Number 2. Washington DC, 2nd edition, 2008.

[20] International Air Transport Association. Guidance Material and Best Practices for the Implementation of Upset Prevention and Recovery Training. Technical Report June, International Air Transport Association, Montreal, Quebec, 2015.

[21] J. Barbagallo. Advisory Circular: Upset Prevention and Recovery Training. Technical report, Federal Aviation Administration, Washington DC, 2015.

[22] S. K. Advani, J. A. Schroeder, and B. Burks. What Really Can Be Done in Simulation to Improve Upset Training? In *AIAA Modeling and Simulation Technologies Conference*, Toronto, Ontario, 2010.

[23] N. B. Sbramov, M. G. Goman, A. N. Khrabov, E. N. Kolesnikov, L. Fucke, B. Boemarwoto, and H. Smaili. Pushing Ahead - SUPRA Airplane Model for Upset Recovery. In *AIAA Modeling and Simulation Technologies Conference*, Minneapolis, Minnesota, 2012.

[24] S. A. E. Nooij, M. Wentink, H. Smaili, L. Zaichik, and E. L. Groen. Motion Simulation of Transport Aircraft in Extended Envelopes: Test Pilot Assessment. *Journal of Guidance, Control, and Dynamics*, 40(4):776–788, 2017.

[25] K. J. Vicente. *Cognitive Work Analysis - Toward Safe, Productive, and Healthy Computer-Based Work*. Lawrence Erlbaum Associates, Mahwah, New Jersey, 1 edition, 1999.

[26] C. Borst, V. A. Bijsterbosch, M. M. van Paassen, and M. Mulder. Ecological interface design: supporting fault diagnosis of automated advice in a supervisory air traffic control task. *Cognition, Technology and Work*, 19(4):545–560, 2017.

[27] M. J. Tucker, S. S. Chen, J. Wiedemann, and J. L. Hammack. United States Patent - Enhanced Vertical Situation Display, 2010.

[28] C. Borst, M. Mulder, and M. M. Van Paassen. Design and Simulator Evaluation of an Ecological Synthetic Vision Display. *Journal of Guidance, Control, and Dynamics*, 33(5):1577–1591, 2010.

Part II

Preliminary Report

Previously graded under AE4020

Abstract

Design and Evaluation of an Ecological Interface Reflecting Configuration Changes in the Vertical Flight Performance Envelope

For the past 10 years consecutively, loss of control has been the largest contributor to the yearly fatalities count across all categories of aviation. Unlike basic stall training, Upset Prevention and Recovery Training (UPRT) is available to pilots but not mandatory. In this sense UPRT can be compared to skid training for drivers: a non-compulsory course that teaches to keep control over your vehicle in adverse conditions. This calls for a more accessible alternative for pilots to practice and learn upset prevention.

This preliminary thesis consists of two parts. The first is an analysis of the loss of control epidemic, identifying the most common causal factors and current efforts to mitigate this problem. This includes looking at both incident statistics and accident reports, as well as methodologies that are being used in UPRT courses. Using these sources the root of the problem is isolated.

The second part proposes a design for an ecological display. This Configuration awareness Vertical Situation Display (ConfVSD) is aimed at giving the pilot insight in maneuverability limitations of the aircraft, thus more awareness of when these limits are approached. These limits are made dynamic to reflect changes in altitude and configuration, which affect the aircraft performance capabilities. Finally an experiment is proposed to test the effectiveness of the ConfVSD for pilot performance in preventing aircraft upset.

Chapter 1

Introduction

This introduction will make the reader familiar with the concept of this thesis, both in terms of contents as in buildup. First, a background is given in which both a motivation and global status surrounding the thesis topic are explained. From this, a problem statement is derived. The problem statement is later refined after the literature survey is concluded in chapter 5. Finally in this introduction, the structure of the report is elaborated upon.

1.1 Background

Over the past 50 years, private and commercial aviation have gone from an exclusive privilege to commonplace. Thankfully this has gone hand in hand with an exponential increase in flight safety. However, flying is still not free of risks, as is made clear by the news and yearly incident statistics. Both surprisingly and worryingly, the past 10 years have shown the same main cause of fatalities across all categories of civil aviation: loss of control in-flight (LOC-I) [1].

The NASA Langley Research Center reports that over three-quarters of LOC-I incidents are the result of flight outside the regular operational flight envelope, a condition better known as aircraft upset [2]. These upsets are caused by various human, system or environmental factors, and often include an element of startle or surprise [3]. Unlike basic stall recovery training, Upset Prevention and Recovery Training (UPRT) is not mandatory for any piloting license. In this sense UPRT can be compared to skid training for drivers: a non-compulsory course that teaches to keep control over your vehicle in adverse conditions.

Many actions are being taken to improve pilot training for loss of control scenarios, such as the Simulation of UPset Recovery in Aviation (SUPRA) research project in Europe, projects by the General Aviation Joint Steering Committee (GAJSC) in the United States over 130 companies offering Upset Prevention and Recovery Training (UPRT) worldwide [4]. Unfortunately upset *recovery* in Full Flight Simulator (FFS) environments is currently not possible due to simulation limits, as simulation fidelity decreases when flying outside the Verified Training Envelope (VTE) [5][6]. However, effective ground-based training of upset *prevention* is possible with modern simulation fidelity near the edges of the VTE.

Only some pilots and airliners choose to invest in current aircraft-based UPRT. Adapting FFS's to play a more effective role in UPRT would make it cheaper and more accessible, thus help in mitigating the yearly death toll of LOC-I. This research will take a step into this direction by attempting to enhance upset prevention in FFS's within the bounds of current flight simulation technology by using ecological interface design.

1.2 Problem Statement

Despite the recent focus of research and industry on UPRT, upsets and LOC-I incidents still prevail among aviation fatalities. In near-upset conditions, high levels of stress often cause pilots to act in accordance with their basic intuition rather than thinking adaptively. This was shown for example in research by Schroeder and Bürki-Cohen: while testing stall models with UPRT-trained pilots, less than one-quarter of the 45 B737 pilots applied the correct recovery procedure when approaching an upset [7]. This means the instinctive mental model pilots have of their aircraft might be inconsistent with the true model they are tasked to control, and thus they apply the wrong recovery strategy.

A promising field of study for making complex systems more insightful is Ecological Interface Design (EID). This interface design methodology focuses on showing the dynamic constraints of the work domain a system is operating in, thus enhancing the Situational Awareness (SA) of the operator [8]. At present EID has been applied to various aspects of aviation including terrain awareness, airborne separation assistance and even air traffic control [9][10][11][12]. These applications, as well as notable longitudinal studies by Christofferson et al. [13][14], have shown that EID does indeed support knowledge-based decision making and thus allow for more resilient performance.

Regarding performance after training with EID, research by Visser [11] suggests that in ATC, EID-trained novices indeed show higher levels of SA and performance than regular-trained novices, but at the cost of their response times. As aircraft upset is a fast and dynamic process, EID could induce risks by slowing down pilot decision making in time-crucial scenarios. Greater SA could, however, also allow a pilot to identify approaching safety-critical situations faster, mitigating the longer decision time. This leads to the following initial research question being posed:

How can addition of visual cues contribute to an increase in performance for preventing aircraft upset conditions?

In order to answer this question, a display based on the EID methodology will be developed. This display will then be evaluated by training participants with a piloting license in the SImulation, MOtion and NAvigation (SIMONA) research simulator using training scenarios according to FAA and IATA guidelines.

To answer the research question stated above, the following sub-questions are defined:

- What are the causes of aircraft upset and loss of control?
- How are air safety organizations currently addressing this problem?
- What research in interface design is done to increase pilot awareness?
- How can 'performance' be defined in terms of pilot control actions?
- What are desirable pilot control actions when approaching an aircraft upset?
- What information can aid pilots in preventing critical flight states?

After (parts of) these questions have been answered by an extensive literature review, the research question is updated and posed again in chapter 5.

1.3 Report Structure

Before the prototype display is designed and tested, a literature study into aircraft upset and current EID interfaces is conducted. Chapter 2 looks into the details and causes of aircraft upset, followed by Chapter 3 which discusses UPRT current practices and recommendations.

After a clear image of aircraft upset is sketched, Chapter 4 analyses the design of current ecological interfaces and proposes a new design to aid pilots in preventing flight upset conditions. Finally Chapter 5 proposes an experiment set-up, including training program lecture based on current UPRT methodology.

Chapter 2

Aircraft Upsets

The fact that aircraft upset is a dangerous condition that can lead to loss of control is well known in aviation safety, but a formal definition for both upset or LOC has not been set. The aim of this chapter is to analyze the process of aircraft upset, finding results relevant for chapter 3 on UPRT and drawing conclusions that are used in chapter 4 in designing an ecological flight display.

Section 2.1 discusses the process of aircraft upset and loss of control, and the difference between upset *prevention* and upset *recovery*. Section 2.2 continues by proposing a definition of aircraft upset, creating a formal framework for use in all other chapters. Finally, section 2.3 analyses the causal factors that lead to LOC-I within the different categories of aviation.

2.1 Aircraft Upset and Loss of Control Procedure

Adverse conditions during flight may result in an aircraft upset if they are not timely recognized by the pilot, which can escalate to a complete loss of control scenario. In this procedure there are multiple ways to regain control over the aircraft, which require different control strategies. The procedure of LOC-I development is shown in figure 2.1, adverse conditions are further discussed in section 2.3.

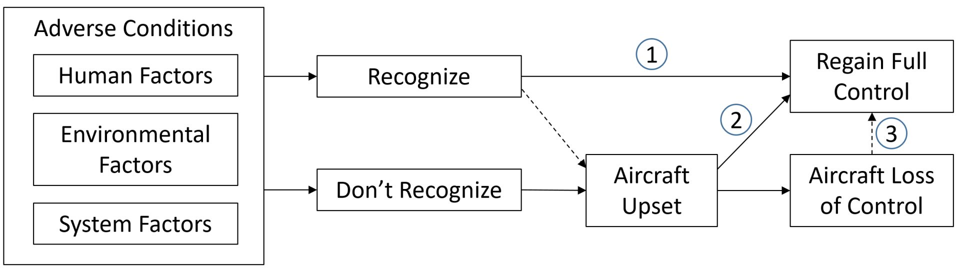


Figure 2.1: Procedure of Upset and Loss of Control Development

Figure 2.1 shows three ways to regain control over the aircraft, numbered 1 through 3:

1. **Upset Prevention** - By timely recognition of adverse conditions, exiting the flight envelope can be avoided by taking preventive control actions. However, if conditions are too extreme or if incorrect action is taken, aircraft upset might still occur.
2. **Upset Recovery** - In case adverse conditions have caused the aircraft to leave its operational flight envelope, recovery is often still possible if the aircraft has enough altitude. This generally requires quick execution of specific steering commands, further discussed in Chapter 3.
3. **LOC-I Recovery** - If no timely or correct action is taken, a pilot will lose complete control over the aircraft. Recovery from this condition is rare as often control surfaces will not be fully functional, and can only be done if conditions line up favorably.

UPRT can be split into two categories: Upset Prevention Training (UPT), covering arrow numbered **1** in figure 2.1, and Upset Recovery Training (URT), covering arrow number **2** in figure in figure 2.1. As stated in section 1.1, this report will mostly deal with UPT, as URT requires an FFS to operate outside the VTE.

2.2 Defining Aircraft Upset Conditions

As upset is a state an aircraft can be in, it is necessary to define when this state is entered and left. Two definitions of upset are discussed: the commonly accepted FAA definition and the Quantitative Loss-of-Control Criteria, of which the latter can be regarded a better quantifiable version of the former.

2.2.1 FAA Definition

The most commonly accepted and referenced definition of aircraft upset can be found in the *Airplane Upset Recovery Training Aid* [15]. This FAA document states: "*While specific values may vary among airplane models, the following unintentional conditions generally describe an airplane upset:*

- *Pitch attitude greater than 25 deg, nose up.*
- *Pitch attitude greater than 10 deg, nose down.*
- *Bank angle greater than 45 deg.*
- *Within the above parameters, but flying at airspeeds inappropriate for the conditions."*

Although upsets and LOC are extensively discussed in this manual, no precise thresholds are specified for these flight conditions occurring. As general statements will not hold for scientific research, a more strict definition of aircraft upset and LOC conditions is necessary.

2.2.2 Quantitative Loss-of-Control Criteria

Recognizing the problem that no metrics for upset/LOC have been defined, James Wilborn from The Boeing Company and John Foster from NASA Langley Research Center have proposed the *Quantitative Loss-of-Control Criteria* (QLC) [16]. The QLC is a set of five plots depicting variables in flight dynamics and control inputs, that together form a tool to determine precisely when an aircraft is operating within the regular flight envelope, under upset conditions or in LOC-I. Some of these variables are normalized to allow comparison across aircraft types.

Each plot shows an envelope of what is considered normal operations, indicated in bold. When the aircraft is flying in normal conditions, none of the five envelopes should be exceeded. Defining upset as starting from a single envelope excursion and LOC from three or more excursions was found to be a suitable standard for analysis of simulator and LOC-incident flight data. The five flight envelopes are summarized below:

The Adverse Aerodynamics (AA) Envelope - α_{Norm} vs β_{Norm}

The Adverse Aerodynamics (AA) envelope can be used to determine excessive angle of attack α, indicating aerodynamic stall, and excessive sideslip angle β. Parameters are normalized as follows:

$$\alpha_{Norm} = \frac{\alpha}{\alpha_{stall}} \qquad \beta_{Norm} = \frac{\beta}{\beta_{MDXW}}$$

Where α_{stall} is the angle of attack for which the aircraft issues a stall warning, and β_{MDXW} the maximum demonstrated sideslip for crosswind landing and takeoff. Figure 2.2 shows the AA Envelope.

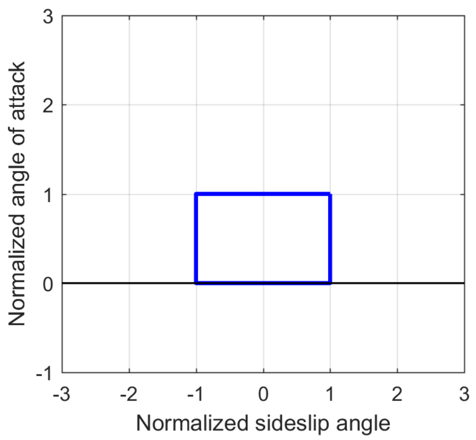


Figure 2.2: The Adverse Aerodynamics Envelope, adapted from [16]

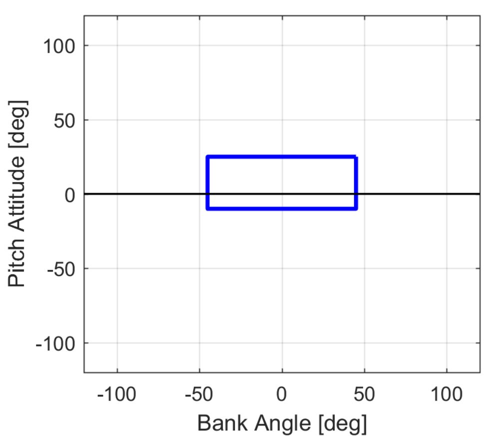


Figure 2.3: The Unusual Attitude Envelope, adapted from [16]

The Unusual Attitude (UA) Envelope - θ vs ϕ

The Unusual Attitude (UA) envelope covers most to the FAA definition of aircraft upset discussed in subsection 2.2.1, and shows the pitch attitude θ and the bank angle ϕ. As these angles determine the angle which the lift vector makes with the projected earth horizontal plane, they play a large role in the effectiveness of the lift in keeping the aircraft airborne. This makes the UA envelope important in both flight safety and upset recovery.

Borders of normal operation correspond to those from the *Airplane Upset Recovery Training Aid*. As the envelope is not dependent on any aircraft specific characteristics, normalization is not needed to compare it between aircraft types. The UA envelope is shown in figure 2.3.

Structural Integrity (SI) Envelope - n vs V_{Norm}

The Structural Integrity (SI) envelope shows the normal load factor n and the normalized airspeed V_{Norm}. This gives insights into an aircraft over/underspeeding or exceeding the structural limitations set by aircraft manufacturers.

When normalizing the airspeed, it is taken to be 0 at stall-warning speed V_{SW}, and 1 at maximum operating speed. As maximum operating speed is dependent on aircraft configuration, either the maximum flaps up speed V_{MO} or maximum flaps extended speed V_{MFE} is used:

$$V_{Norm} = \frac{V_E - V_{SW}}{V_{MO} - V_{SW}} \qquad (or) \qquad V_{Norm} = \frac{V_E - V_{SW}}{V_{MFE} - V_{SW}}$$

Where V_E is the aircraft equivalent airspeed. The SI envelope is shown in figure 2.4. Maximum allowable values for the normal load factor n are set according to FAA Part 25 aircraft design requirements.

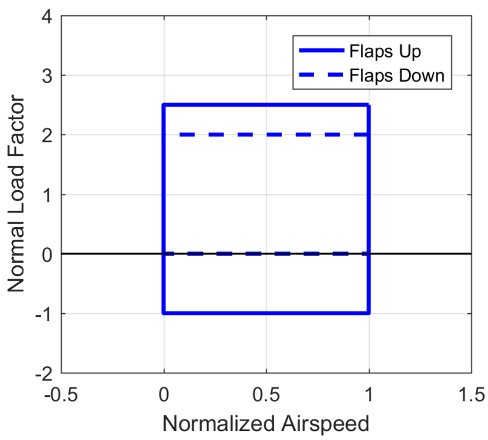


Figure 2.4: The Structural Integrity Envelope, adapted from [16]

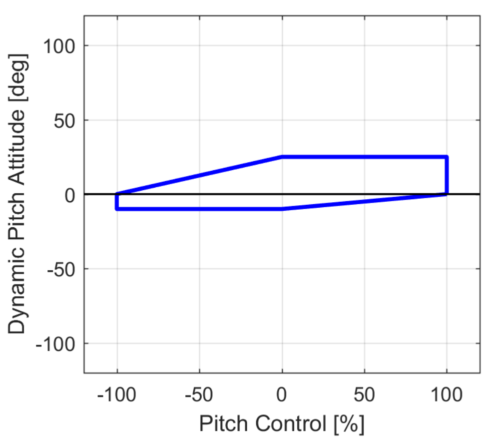


Figure 2.5: The Dynamic Pitch Control Envelope, adapted from [16]

The Dynamic Pitch Control (DPC) Envelope - *Pitch Control* vs θ'

The Dynamic Pitch Control (DPC) envelope is a method to determine whether the pilot is in control over the aircraft pitch by comparing pitch control input to the dynamic pitch attitude. The dynamic pitch attitude θ' is defined as the predicted pitch angle in one second based on the current pitch and its derivative:

$$\theta' = \theta + \dot{\theta} \cdot 1 \; second$$

An alignment of the pitch control input and dynamic pitch attitude indicates that the pilot is under control of the aircraft pitching motion. To quantify when grip over the pitching motion is lost the envelope, shown in figure 2.5, is sloped where signs for pitch control and dynamic pitch attitude θ' are opposite. An excursion in either of these quadrants would indicate events such as PIO, where control inputs are used to oppose a pitch deviation. The limits for θ' are equal to those for θ in the UA envelope.

The Dynamic Roll Control (DRC) Envelope - *Roll Control* vs ϕ'

Much like the dynamic pitch attitude θ', the dynamic roll attitude ϕ' is the predicted roll angle in one second by means of the current roll angle ϕ and its derivative:

$$\phi' = \phi + \dot{\phi} \cdot 1 \; second$$

An alignment of the roll control input and dynamic roll attitude indicates that the pilot is under control of the aircraft rolling motion. In resemblance to the DPC envelope, the DRC envelope is sloped for opposing signs of roll control and dynamic roll attitude ϕ'. Flying through a wake vortex might cause an excursion across these sloped borders, as it requires large control inputs to counter a sudden aircraft rolling motion. The limits for ϕ' are equal to those for ϕ in the UA envelope.

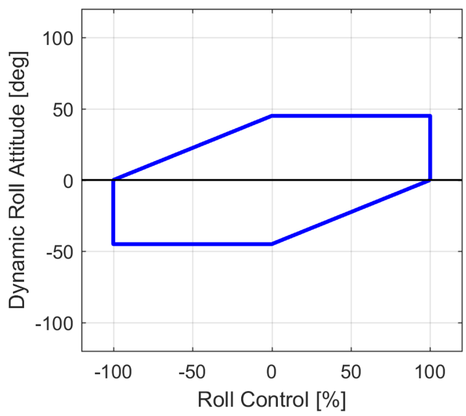


Figure 2.6: The Dynamic Roll Control Envelope, adapted from [16]

As previously mentioned, an aircraft is considered to be in upset conditions from one envelop excursion, whereas three or more excursions indicate LOC conditions. This model will be used throughout the report to analyze flight data.

2.3 Causal Factors in Loss of Control

Causes for aircraft upset can generally be split up into three major contributors: human-induced, environment-induced and systems-induced. Multiple aircraft accident reports are analyzed to determine what the most prominent and dangerous causal factors are, and thus which are most important to address in this research. This analysis is performed across three categories of civil aviation: commercial aviation, business aviation and General Aviation (GA).

2.3.1 Human-induced Factors

Human factors are a common cause for LOC-I, and originate from the pilot mishandling or misjudging a situation. For nearly all aircraft upsets human error could be considered a contributing causal factor, as environmental hazards can frequently be overcome with proper training and malfunctioning systems can be diagnosed on time by an alert pilot.

Table 2.1 compares the parts of LOC incidents that human factors have contributed to. Unfortunately no source is available summarizing all GA LOC-I incidents, thus two separate datasets from subsets of GA will be used as substitute. As incidents might have multiple contributing factors, columns do not necessarily add up to 100%. Data is omitted if the appurtenant source does not mention this statistic.

Table 2.1: Incidents with human-induced factor as contributing cause for loss of control

Publishing Organization	IATA [17]	ISASI [18]	JAAER [19]	ERA Uni [20]
Aviation category	Commercial	Business Jet	GA training	GA APR/LND
Time period	2011-2015	1991-2010	2000-2009	2001-2010
LOC-I incident count	31	246	97	193
Poor energy mgmt	25%	44%	67%	70%
Improper training	21%		44%[1]	32%
Spatial disorientation	13%	10%		13%
Automation mismgmt	8%	14%		
Improper procedure	38%	43%	28%	4%
Bad flight planning			14%	15%
Fatigue	4%	3%	1%	

[1] For GA in training, this entails an inadequate handling/supervision by the instructor rather than the trainee.

Multiple conclusions can be drawn from the data above. Firstly, energy management and improper procedures are the most prevalent cause for LOC-I. It should be noted that the actual contribution of poor energy management to GA is possibly lower than listed in Table 2.1: both the training condition and approach/landing flight phase are those in which stalls are more likely to occur than under conventional conditions [19] [20]. Nonetheless, incidents where pilots did not timely identify they were flying outside of their flight envelope contribute to a significant amount of upset incidents.

Within the category of 'improper procedure', sources report different types of procedures causing problems that might lead to an incident. For commercial aviation these are mostly

Standard Operating Procedures (SOP's) such as checklists and cross-checks. These were either performed insufficiently or took so much attention that pilots got distracted from flying. Most aircraft in general aviation do no have such extensive SOP's, and reported improper procedures as manual flight techniques that are not executed correctly.

Aircraft in general aviation do not have high levels of automation, which is why it is no factor contributing to LOC. Likewise, planning of commercial and business flights is done professionally and aircraft are less susceptible to the results of bad planning, which is why this factor does not contribute to incidents in these categories.

2.3.2 Environmentally-induced Factors

Environmental causes often go hand in hand with human error, when the environment is the source of an adverse condition that is allowed to escalate into an upset due to human-induced factors. Table 2.2 compares incidents in which environmental factors have played a role. As an area of adverse meteorology often induces a combination of potential upset factors, a row "All meteorology" has been added to indicate the total contribution of environmental factors to aircraft upset.

Table 2.2: Incidents with environmentally-induced factor as contributing cause for loss of control

Publishing Organization	IATA [17]	ISASI [18]	JAAER [19]	NTSB [21]
Aviation category	Commercial	Business Jet	GA training	GA
Time period	2011-2015	1991-2010	2000-2009	2001-2013
LOC-I incident count	31	246	97	86
All meteorology	42%	35%	21%	29%
Windshear/Gusts	8%	16%	6%	15%
Lack of visibility	13%		15%	14%
Wake turbulence		18%		8%
Thunderstorm	17%	7%		6%
Icing conditions	17%	2%		9%

It appears that environmentally-induced factors have a larger influence on the accident rate for commercial and business aviation than on general aviation. The explanation for this is found in the nature of general aviation: if meteorological conditions are bad, you can chose not to take off. This is especially true for GA in training: no data on weather-related incidents exists since training generally does not take place when meteorology poses any risks to the flight [19].

In nearly all GA weather related cases that occurred, poor in-flight decision making was related, meaning flight into adverse weather conditions [21]. These pilots either underestimated the weather, or overestimated their own capabilities. Unfortunately no further data is available to distinguish these two sources.

'Lack of visibility' plays a role in half to three-quarters of all GA accidents related to meteorology. The moment most prone to causing incidents is upon entering the low-visibility zone and switching from VFR to IFR, which can go paired with sudden gusts

[21]. While the pilot is adjusting to this lack of visual reference they might not notice a change in airspeed, bank angle or angle of attack, causing it to unexpectedly leave its flight envelope. This sequence of events does not occur in commercial or business aviation, as these do not transition from VFR to IFR.

The occurrence of wake turbulence greatly depends on airports from which flights operate, as both large and small aircraft need to be sharing the same airspace for wake turbulence to cause incidents. This is not often the case for general aviation, and especially training flights are conducted at regional airports without large commercial traffic. Business jets are comparatively light yet fly to large airports, which is why they are at greatest risk for wake turbulence.

Foreign object damage, such as hail or bird strike, was never reported as a cause for aircraft loss of control.

2.3.3 Systems-induced Factors

Since pilots do not frequently encounter aircraft system failures, an offset meter or faulty gauge can catch a pilot off-guard. Especially as continuous automation causes pilots to become increasingly reliant on their systems, a failure can easily cause an incorrect or unwarranted pilot action. Table 2.3 summarizes information from the same sources as Table 2.1 to draw conclusions on the most prominent or dangerous system failures in different types of civil aviation.

Table 2.3: Incidents with systems-induced factor as contributing cause for loss of control

Publishing Organization	IATA [17]	ISASI [18]	JAAER [19]	ERA Thesis [20]
Aviation category	Commercial	Business Jet	GA training	GA APR/LND
Time period	2011-2015	1991-2010	2000-2009	2001-2010
LOC-I incident count	31	246	97	193
All systems	42%	9%[1]	16%	15%
(Partial) loss of power	13%		6%	
Propulsion issues	8%		6%	9%
Bad maintenance	8%			6%
Flight ctrl malfunction	13%	9%[2]	4%	
Ground-systems error	8%			

[1]The ISASI report only lists pure system-induced incidents, omitting those where environment or human factors have contributed. The actual statistic is thus estimated to be larger than 9%.

[2]Multiple databases are consulted in the ISASI Report. Percentages for this statistic range from 4% to 32% depending on the database, 9% results from a merge of all databases used.

Overall, systems-induced factors contribute to less aircraft upsets than human or environmental factors. Percentages vary largely between categories of civil aviation depending on the level of automation and complexity of systems installed on board. Especially aircraft with high levels of automation without proper crew interfaces are at risk. This is illustrated by Adam Air flight 574, which crashed in Indonesia January 1^{st} 2007 when both pilots were focused on troubleshooting the IRS. While they were distracted the autopilot disengaged, the bank angle rapidly shot to 30 degrees (causing spatial disorientation) and the aircraft did not recover [22]. Similar accidents have occurred within Air France and Colgan Air in May and February of 2009 respectively.

Among system-induced factors, a malfunction followed by the autopilot disengaging is a common sequence of events. This scenario might not have to lead to a loss of control if pilots are sufficiently trained, either in upset prevention or upset recovery. As GA has lesser pilot automation dependency, autopilot-induced upsets are less prominent. Similarly, ground-based systems play a smaller role for GA than other categories, as is reflected by the absence of this statistic in table 2.3.

2.3.4 Upsets by Flight Phase

Although it is possible for an LOC accident to occur during any flight phase (or even on ground), certain phases of flight pose higher than others risks in terms of LOC, as is shown in Table 2.4. Note that due to rounding, data might not add up to 100%.

Table 2.4: Loss of Control incidents by flight phase

	IATA [17]	ISASI [18]	FAA [23]
Aviation category	Commercial	Business Jet	GA
Time period	2011-2015	1991-2010	2001-2010
LOC-I incident count	31	71	792
Take-Off	10%	18%	7%
Initial Climb	23%	17%	15%
Cruise	16%	10%	21%
Maneuvering	6%	8%	27%
Approach	23%	34%	20%
Go-Around	10%	3%	
Landing	10%	13%	5%
Emergency Decent			6%

Approach appears as a consistent dangerous flight phases over all civil aviation categories. The incident distribution over other phases of flight depends heavily on the type of aviation.

For commercial aviation, threats are relatively spread out, with peaks for initial climb and approach. These are both phases with many mandatory flight procedures at low altitude, which result in peak mental loads for pilots. Similar conclusions can be drawn for business jets, for which the approach phase poses an increased risk which is consistent with the wake turbulence threat identified in Table 2.2. The common denominator in dangerous conditions is that they occur when the total energy of the aircraft is low, meaning both velocity and altitude states are small in comparison to standard flight conditions. Low speed means any incident is more likely to cause an aerodynamic stall. Low altitude decreases the amount of potential energy that can be converted into kinetic energy for recovery, as well as putting a tighter time constraint on the recovery maneuver.

Commercial aviation generally does not perform many maneuvers, unlike GA. While maneuvering, small aircraft are susceptible to human factors as steering and judgment errors, while autopilot-controlled aircraft are not. Furthermore, the smaller size of GA aircraft makes them more susceptible to weather during maneuvering and cruise phases.

2.3.5 Conclusions on Addressing Loss of Control

Based on the data gathered in this chapter, two large categories of LOC-I can be identified. These are:

1. **Loss of control caused by automation/procedural mismanagement.** This is predominant in commercial and business aviation, and often puts pilots under peak mental loads. Stress leaves pilots vulnerable to mistakes and startle events, which prove increasingly fatal at low altitudes when there is not much time to intervene. This LOC category can be associated with the ironies of automation [24], as without automation it would not exist.

2. **Loss of control caused by manual piloting mistakes.** Poor situational awareness, a wrongly executed maneuver or adverse weather can lead to an aircraft getting upset. In these cases pilots have not been properly trained in preventing or recovering from flight upset, and end up in a loss of control scenario.

When training pilots to prevent loss of control, it can be reasoned that focusing on the second type of LOC-I will be more beneficial. In any situation where an upset is likely to develop, current UPRT standards by ICAO and FAA advise all pilots in commercial aviation to switch off their autopilot, as it might be contributing to the impeding upset [15][25]. Both categories of upset require manual piloting skills to overcome, thus training stick and rudder skills in (near-)upset conditions could prove an effective countermeasure.

Chapter 3

Upset Prevention and Recovery Training

As flight simulation is increasing in its capabilities of replacing on-aircraft training, UPRT practices are adapting to these new possibilities. This chapter aims at giving an overview of the current methodology of UPRT and the recommendations posed by authorities and research. This will solidify the knowledge base which is used to later conduct the display and experiment design.

UPRT can be split into two aspects: UPT and URT. Both have differing training goals and requirements, and certain aspects are better trained on specific devices. The three most common training environments are considered: classroom training in section 3.1, FSTDs in section 3.2 and on-aircraft training in section 3.3. For all environments, relevant recommendations from both aviation safety organizations and research are reviewed.

3.1 Classroom Training

In each UPRT course a series of classroom training sessions will precede any (simulated) flight scenarios. Classroom training is preferable over other training types because of its time- and cost-efficient nature, as classroom training can be effectively conducted with a high student to instructor ratio. Research by Rogers and Boquet [26] even suggests that well-constructed classroom training is more effective than combined classroom and centrifugal-FFS training in teaching pilots to perform on-aircraft upset recovery.

Based on the Airplane Upset Recovery Training Aid [15], created at request of the FAA and NTSB, and the ICAO Manual on Aeroplane Upset Prevention and Recovery Training [25], training material can be categorized as follows:

- Aerodynamic flight principles
- Causal factors for aircraft upset

This section summarizes the most important concepts from each of these categories. Other topics of classroom training are 'monitoring and situational awareness' and 'upset prevention and recovery flight maneuvers', these are discussed in sections 3.2.1 and 3.2.2 respectively.

3.1.1 Aerodynamic Flight Principles

The topics addressed within 'Aerodynamic Flight Principles' have to do with the way in which forces and moments act on the aircraft, and how the pilot can manipulate those to stay within the flight envelope. This knowledge is taught to support the reasoning for certain flight maneuvers treated in later lectures.

Flight Envelope

The constraints within which aircraft are designed to safely operate, the flight envelope, can be visualized in various ways. The most common visualizations are made by plotting V-n and altitude-airspeed diagrams, alternatively known as the load factor envelope and the altitude envelope respectively. These are depicted in figures 3.1 and 3.2.

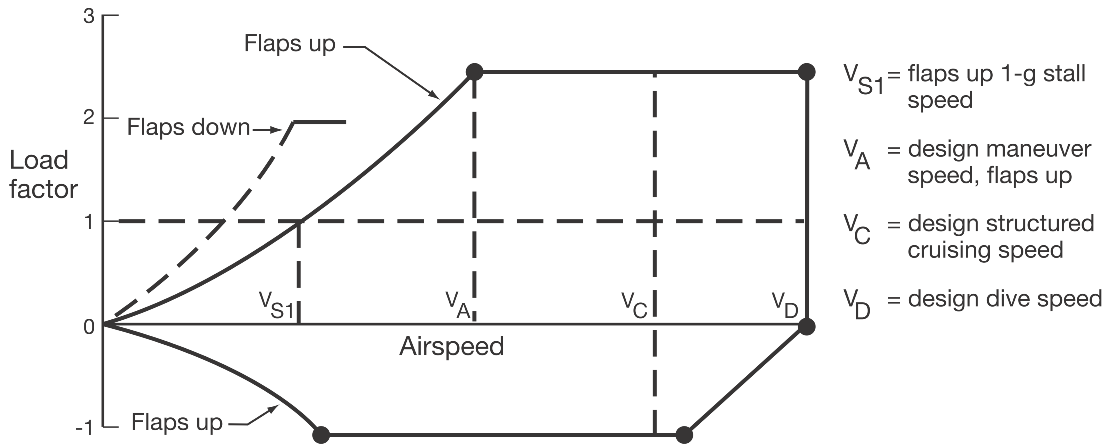


Figure 3.1: The Load Factor Envelope (V-n diagram), as in the *Aircraft Upset Recovery Training Aid* [15]

The roof and floor of the example V-n diagram in figure 3.1 correspond to the common structural limits of +2.5 g and -1 g for general aviation aircraft, or +2 g and -1 g with flaps extended. These limits might differ depending on aircraft type, and pilots should be aware of the maneuvering limits of the aircraft they are flying.

Excursions of the left side of the V-n envelope indicates a deficient airspeed, which will stall the wing. For maneuvering in (near-)upset conditions, an aircraft will most often find itself close to the left-most border for positive load factors, running from (0,0) to (V_A,n_{max}). Stalls for negative load factors are uncommon, as achieving a negative load factor requires the aircraft to make a diving maneuver, which will allow the aircraft to gain airspeed and divert from the envelope border. Note that this does not hold true for inverted flight conditions.

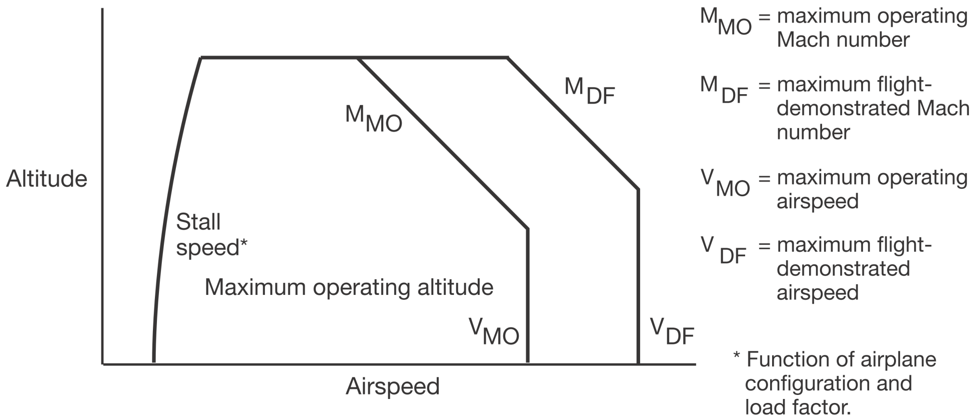


Figure 3.2: The Altitude Envelope (altitude-airspeed diagram), as in the *Aircraft Upset Recovery Training Aid* [15]

Values for the altitude-airspeed diagram in figure 3.2 are heavily aircraft-dependent, and crucial for the pilot to know. Generally M_{MO} and V_{MO} are used as operating limits, as performance may decrease when these limits are exceeded. The maximum operating altitude is determined by the minimum required air density for the engines to generate a thrust that equals the total drag. In case the engine performance is sufficiently high, the stall speed and maximum operating Mach number limits will meet. This limit is often referred to as the coffin corner.

As airspeed and altitude are both measures of energy, the altitude-airspeed diagram alternatively represents a total energy diagram. When flying near the edges of the altitude envelope either the total energy contained by the aircraft must be adjusted or kinetic and potential energy must be exchanged. Exchanging energy is often faster than changing the total energy, making this the preferred option [25].

The most dangerous region of the altitude envelope is that for low altitude and low airspeed, as the combination indicates a low total energy state. Unintentionally approaching this region leaves pilots with reduced maneuverability, as adding total energy through additional thrust has a time delay. This is consistent with section 2.3.4, where initial climb and approach were found to the two flight phases where the largest part of LOC incidents over all civil aviation occur.

Flight Performance Curves

When an airfoil flies at a larger angle of attack (AOA or α), it will increase the lift it generates. This allows the aircraft to climb or to fly at lower airspeeds, up to the AOA at which the airflow separates from the wing and the generated lift plummets. Figure 3.3 shows the relationship between AOA and lift coefficient C_L, which is used in a simulation model of a Diamond DA-42 aircraft by Delft University of Technology. In this figure the critical angle of attack α_{stall} (or α_{crit}), at which flow separation occurs, is indicated.

The angle of attack is measured as the angle between the aerodynamic chord of the wing and the oncoming wind. As α_{stall} is a constant, aerodynamic stall can occur regardless

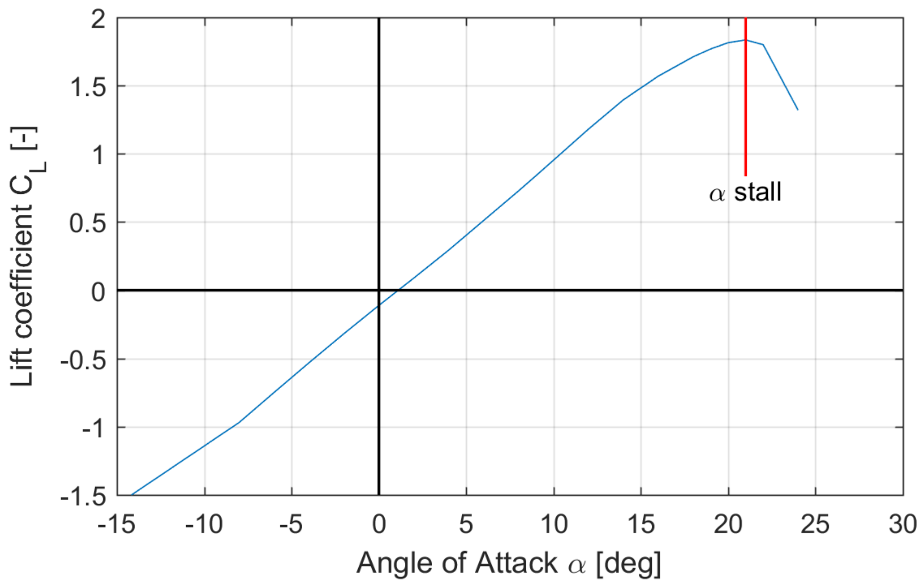


Figure 3.3: Lift curve ($C_L - \alpha$), exported from TU Delft C&S DA42 aircraft model [27]

of altitude or airspeed. However, each aircraft type does have its own characteristic stall speed. At lower airspeeds a wing will generate less lift, which can be compensated by flying at a higher AOA. The stall speed is thus the speed at which flight at α_{stall} is necessary to generate enough lift to prevent altitude loss. If this required lift changes, so will the stall speed.

To attain level flight, the upward lift generated must equal the weight of the aircraft. The effective aircraft weight might change in between or even during a flight, which causes the stall speed to change while α_{stall} remains constant. Pilots should be aware of this phenomenon, as it might cause stall to occur even while flying above the the indicated stall speed. Conditions that cause alteration of the stall speed include:

- Passengers, cargo, tanking or burning fuel will change aircraft weight, thus changing required lift.
- Banking causes the lift vector to tilt, thus decreasing the portion of the lift vector that counteracts the weight. To remain level flight more total lift is required.
- Pitch up/down maneuvers will impose a load factor on the aircraft, which increased the effective weight during pitch up and decreases the weight during pitch down. The stall speed will be adjusted by a factor $\sqrt{n}$ with regards to stall speed under normal conditions [28].
- Deployment of flaps and/or slats will effect the $C_L - \alpha$ curve, allowing higher values of C_L to be attained at lower values of α. This lowers the speed at which the aircraft will stall.

Most modern aircraft have some system in place to warn the pilot when the stall limit is being approached. Pilots should be aware of these signals and take immediate action to ensure the aircraft moves away from this edge of the flight envelope.

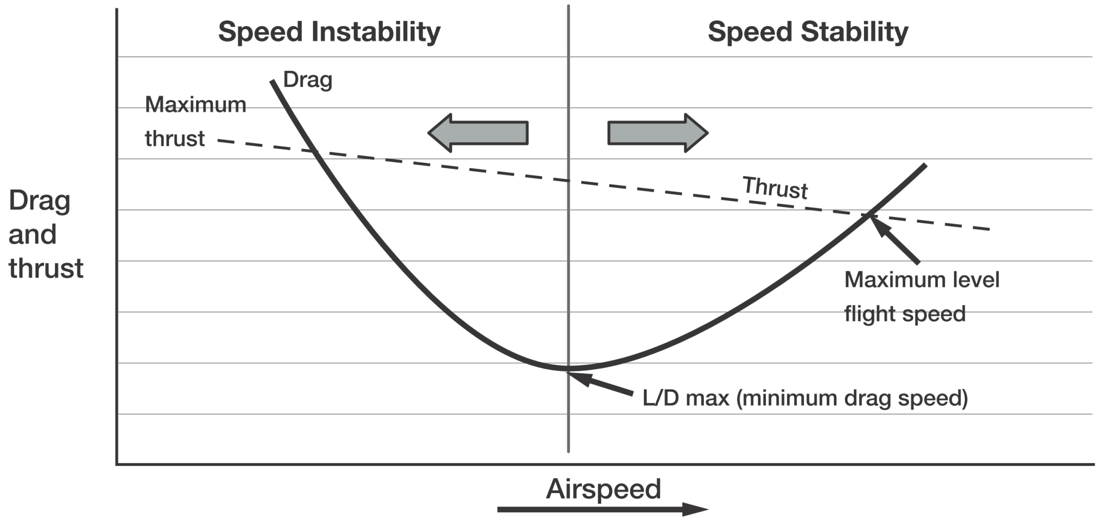


Figure 3.4: The Drag curve, as in the *Aircraft Upset Recovery Training Aid* [15]

The drag experienced by an aircraft is dependent on its airspeed. To fly at low speeds an aircraft must adopt a high AOA, which leads to a high lift-induced drag force. This contribution to drag diminishes at higher airspeeds, where the main contributor is skin friction drag. The corresponding total drag curve is shown in figure 3.4, including the maximum thrust which decreases for high speeds. Once the maximum trust equals the drag, the engines are not capable of further accelerating the aircraft.

In stable, wings-level flight, the point of minimum drag will correspond to the point of maximum lift-to-drag ratio (L/D max). An aircraft flying at minimum drag will require minimum thrust to maintain its airspeed, which makes it desirable to cruise at this speed. An aircraft operating at speeds above L/D max which is perturbed by a gust of wind will show speed-stable behavior: a speed increase will increase the drag, slowing the aircraft down, and a speed decrease will decrease the drag, allowing the aircraft to speed up. The reverse holds true for flight at speeds below L/D max, which is unstable with regards to speed.

Especially during cruise at airspeeds around or below L/D max, it is important for pilots to be familiar with the effects of the drag curve in figure 3.4. As flight below L/D max is inherently unstable, it should be avoided to prevent speed deterioration at any altitude.

Energy Management

Three types of energy are generally contained within an aircraft:

- Potential energy, which is contained in the altitude of the aircraft.
- Kinetic energy, which is contained in the velocity of the aircraft.
- Chemical energy, which is contained in the fuel the aircraft has on board.

Through burning fuel, an aircraft can convert chemical energy to potential and kinetic energy. Potential and kinetic energy can be converted into one-another by control inputs that steer the aircraft to pull up or dive, as was discussed earlier in the section on flight envelopes (specifically figure 3.2). Energy is continuously being lost to drag forces. An aircraft requires minimum amounts of potential and kinetic energy to perform maneuvers, such as climbing and turning. It is a pilots task to ensure sufficient energy is available to maneuver within the flight envelope at all times, a task which is called "energy management".

As was found in table 2.1 in chapter 2.3.1, poor energy management is one of the largest contributing human-induced factors to LOC-I incidents. In most cases the total energy within the system was too low, causing the wings to stall. Stalled wings create large amounts of drag, further reducing the total energy until the stall was recovered or the aircraft crashed. Pilots must be made aware of the way different types of energy are linked, and taught to understand the concept of 'total energy state' when performing energy management [25].

3.1.2 Causal Factors

Classroom training in the potential causal factors of LOC is not as extensive as aerodynamic training, and is taught to make pilots aware of the specific dangers they might face. Table 3.1 shows a summary of LOC causal factors that are discussed during classroom training.

Table 3.1: Summary of causal factors for classroom training

Human-induced	Environmentally-induced	Systems-induced
Improper piloting technique	Turbulence	Flight system malfunction
Poor energy management	*Windshear*	*Control malfunction*
Improper training	*Microburst*	*Propulsion problems*
Automation mismanagement	*Wake turbulence*	*(Partial) loss of power*
Improper procedure	*Thunderstorm*	*Flight instrument malfunction*
Improper monitoring	Aircraft icing	Bad maintenance
Improper SOP adherence	Lack of visibility	Ground-systems error
Pilot impaired	*Fog*	
Spatial disorientation	*Thunderstorm*	
Fatigue		

A more extensive analysis of these causal factors can be found in section 2.3.

3.2 Simulator-Based Training

Simulator training offers benefits in safety and cost, but has limitations in terms of VTE, queuing and stress simulation. Training done in FSTD's is generally non-type specific, as creating simulator layouts, programming advanced flight models and training instructors for a large variety of aircraft types is economically unfeasible. This gives an important role to the instructor, who is tasked not only to guide the pilot in attaining flight skills, but also to elaborate on how these skills relate to the aircraft the pilot will finally fly [29].

Nonetheless, the FAA, ICAO and IATA unanimously recommend specific aspects of UPRT to be trained in FSTD's [30][25][31]. These can be organized into two categories:

- Pilot monitoring skills
- Manual piloting skills and maneuvers

This section will list core aspects of each of these pilot skills, as well as research and recommendations on the element of surprise for FFS pilot training.

3.2.1 Monitoring and Situational Awareness

Especially in commercial aviation a large amount of focus is on training instrument and flight path monitoring skills to the flight crew. This can be related to section 2.3.1, in which it was found that improper procedures (SOP's and checklists) are the largest contributors to LOC incidents in this aviation category.

Both the *Practical Guide for Improving Flight Path Monitoring* by the Flight Safety Foundation and the *Guidance on Development of Pilot Monitoring Skills* by the Civil Aviation Authority list that effective monitoring has multiple aspects, most important of which are an adequate instrument sample rate and effective workload scheduling [32][33]. The latter is mostly important to ensure that the cabin crew is not occupied with non-flying tasks during crucial flight maneuvers such as take-off or approach. By allocating attention, issues are swiftly diagnosed and upsets can be prevented rather than recovered.

For all categories of aviation, the flight path should receive priority in terms of monitoring for flight maneuvers where the aircraft is vulnerable. This does not only include variables such as airspeed and heading of the aircraft, but also specifically the energy state and its derivative. Research by Sarter, Mumaw and Wickens shows that pilots in automated environments tend to monitor basic flight parameters, yet often fail to relate them to more abstract concepts [34]. Statistics by the FSF show that most monitoring errors occur during decent and have the consequence of an altitude deviation, which changes the total energy the aircraft has [32]. This calls for an increased pilot awareness of the aircraft total energy state.

Current practices to increase pilot awareness firstly include classroom training regarding the total energy state (as discussed previously in this chapter), which is followed by a series of FFS scenarios. These will consist of automatic, hand-flown and combined flight tasks, and include unanticipated tasks and rapid energy changes. Training manual flight is encouraged as it teaches the pilot to disable the autopilot if an upset is approaching, and sets a good standard for instrument sampling frequencies.

The concept of energy state is recommended to be reinforced by reviewing how the total energy state changes throughout the scenario, which is done by the flight instructor during debrief. A combination of proper monitoring and the ability to interpret this information will lead to an increase in pilot situational awareness.

3.2.2 Training Manual Piloting Skills and Maneuvers

Whereas a FSTD has the drawback of a limited VTE, it has the benefits of safety and cost over an actual aircraft. This is why it is generally preferred to train flight maneuvers on a FFS that fall (mostly) inside its VTE, rather than in an aircraft. As current technology only allows limited simulation of stall characteristics, maneuver training covers mostly upset prevention and limited upset recovery [5].

Compiling from the *Airplane Upset Recovery Trianing Aid* and the *Advisory Curricular for Upset Prevention and Recovery Trainig* [15][30],main aspects of what pilots will learn during simulator training are:

- Recognition of (approaching) aircraft upset cause
- Use of full control inputs
- Recovery for excessive nose-high and nose-low attitudes

These are all taught by means of simulating nose-high and nose-low attitude scenarios. The instructor plays a large role in preventing negative training by notifying the pilot when a region outside the VTE was entered during a simulation run.

Recovery from Excessive Nose-High Attitude

A nose-high attitude is generally associated with a low-speed stall. To avoid this stall the pilot must increase the kinetic energy of the aircraft, which can be done in multiple ways. The following procedure is proposed for pilots to recover from nose-high attitude:

1. **Disconnect autopilot and autothrottle** - Autopilot or autothrottle might interfere with the recovery procedure, and inputs they provide can be difficult for a pilot under high workload to process. This is irrelevant for aircraft without these systems installed.
2. **Apply nose down pitch control** - Pitch control must be applied until nose-down pitch rate is achieved and stall warning eliminated. In case this requires sustained full nose-down pitch control, some trim can be added to alleviate the column force.
3. **Optionally: roll to control pitch rate** - In case of an excessively high pitch attitude that cannot be restored using pitch control, the pilot can choose to introduce a bank angle to change the pitching motion into a turning maneuver.
4. **Optionally: reduce thrust for underwing engines** - Engines mounted under the wing produce a nose-up moment. The pilot can consider temporarily reducing thrust to recover pitch attitude, if the aircraft is at sufficient altitude. The reverse is true over aircraft with engines mounted above the wings.
5. **Apply bank control to level wings** - Pointing the lift vector upward increases the lift effectiveness, and reduces altitude loss while recovering.

6. **Apply thrust as necessary** - After control over aircraft attitude has been regained, increase/decrease pitch to return to desired airspeed.

7. **Finish recovery with slight pitch-down** - Pick up enough speed using thrust and/or pitch to prevent another upset before returning to level flight.

Since angle of attack is the main reason for aircraft stall, all actions are taken to reduce it as quickly as possible. Emphasis is placed on preventing stall at the expense of altitude, which employs the principle of converting potential energy to kinetic energy. However, if not enough potential energy is available (at low altitude), additional kinetic energy must be gained from chemical energy through engine power. If the time delay for this is too large, a crash will be inevitable. For this reason, it is crucial to prevent excessive nose-high attitudes at low altitude.

Recovery from Excessive Nose-Low Attitude

The procedure to recover from excessive nose-low attitude is similar to the procedure for nose-high attitude. Altitude loss during recovery is inevitable, and maintaining altitude should not be given priority over recovering attitude and maintaining control.

1. **Disconnect autopilot and autothrottle** - To prevent them from interfering with the recovery procedure.

2. **Recover from stall** - Despite nose-low attitude, an aircraft might still stall if the airspeed is too low (thus effective AoA too high). Recovery from this stall by applying nose down pitch is counter-intuitive yet necessary.

3. **Apply nose up pitch control** - Pitch control must be applied until nose-up pitch rate is achieved. In case this requires sustained full nose-up pitch control, some trim can be added to alleviate the column force.

4. **Apply bank control to level wings** - Pointing the lift vector upward increases the lift effectiveness, and reduces altitude loss while recovering.

5. **Adjust thrust and drag** - Increase/decrease thrust as required. If excessive speeds are imminent, deploy speedbrakes.

6. **Recover to level flight** - One airspeed is within safe bounds, stabilize the aircraft and climb back to desired altitude.

Aggressive pull-up maneuvers are to be avoided if possible, as they might induce high load factors. These can compromise structural integrity and will increase stall speed by a factor $\sqrt{n}$. If an approaching stall condition includes bank angles beyond 45 degrees, it is still recommended to address the stall before rolling back to wings level.

3.2.3 Simulating Surprise and Startle

Although a modern FFS is able to simulate various system failures and flight scenarios, training programs are often still too predictable. Not only does this limit the variability of skills a pilot can learn by recurring simulated flight training, but even pilot performance on commonly simulated abnormal events is degraded when they are unexpectedly introduced [35]. This lack of variety, combined with other aspects such as training specific tasks rather than complete flights, induces what Bürki-Cohen calls a 'simulator mindset' [36]. Evoking an effective emotional response requires fully immersing pilots by adding simulating all communications (ATC, cabin crew, data-link), checklists and never using the freeze or reset function unless absolutely necessary.

This does not mean simulating surprise in a simulator is impossible. Part of the emotional response can still be achieved by introducing events at unexpected moments, as is often done in scientific experiments. Examples of these include experiments done by Schroeder, Borst and Casner [7][9][35], which have consistently shown performance degradation when pilots acted upon unexpected events. Of course this cannot be used in recurring training, as pilots will learn to be aware that an unexpected event will occur, feeding the simulator mindset.

3.3 On-Aircraft Training

As both classroom training and FSTDs are limited in their capabilities, on-aircraft training is a necessary component for pilots to complete any UPRT course. Due to the variety in possible upset conditions there is also a variety of recovery maneuvers, which depend on aircraft states as well as characteristics (turn rates, center of gravity, structural limits, etc.). Rather than practicing all maneuvers, as explained by Hoogervorst [37], UPRT training centers rather focus on teaching a single all-attitude recovery method, which must be performed within structural limitations of the aircraft:

1. **Push** - Unloading the aircraft decreases the downward tendency the nose might have when rolling. Pushing will also decrease the load factor, thus decreasing the stall speed and increasing control surface effectiveness at low speeds. This will feel very unintuitive to pilots in inverted flight.

2. **Roll** - Roll in the shortest direction to wings level, applying rudder as necessary to overcome the yaw it induces. Especially for nose-low upsets quick execution of a roll maneuver is essential to point the lift vector upwards and reduce altitude loss.

3. **Power** - By this stage the aircraft is upright and executing a dive. Recovery from this dive is done using pitch and power. Depending on the speed, power may be increased or decreased to attain maneuvering speed. Even during approach when low speed is desired, increase power to increase maneuverability until upset recovery is complete. If necessary, make a go-around.

4. **Stabilize** - Return aircraft to wings-level flight, well within maneuvering speed limits. After checking aircraft configuration and flight controls, return to original flight level and heading.

Chapter 4

Ecological Interface Design

This report uses the principles of Ecological Interface Design (EID) to design a UPRT display. The foundation of the EID methodology was developed by Vincente and Rasmussen, and aims to support all levels of the Skill-Rule-Knowledge (SRK) taxonomy by focusing on the work domain boundaries rather than on the user. This should allow operators of complex systems to better deal with non-normal events, as they can find new solutions within the boundaries of the problem space [38]. Research in EID has shown performance enhancements of users in facing non-normal events for different tasks within aviation including terrain awareness, airborne separation assistance and air traffic control [9][10][11][12], indicating that EID is a promising tool within this field.

Section 4.1 discusses displays that have been developed using EID, as well as displays used for manual flight maneuver training. These include the Oz and landing display, which were used specifically for training purposes. By analyzing design choices and effects they had on user performance, an ecological display design for UPT is created in section 4.2. An experiment for testing the effectiveness of this interface will be proposed in chapter 5.

4.1 Reference Flight Displays

A total of six displays for enhancing flight maneuver performance are reviewed in this section. The first five adhere to the design principles of EID, and are analyzed to find which EID concepts have been proven to be effective. Afterwards, one command-style display for upset recovery is analyzed to see how aspects of upset recovery are approached from a different perspective. Finally conclusions are drawn on the current state-of-the-art on display design, and what the implications are for an EID upset prevention display.

4.1.1 Energy Display

The energy display was proposed by Amelink et al. [39] to add information on total energy state to the tunnel-in-the-sky display by Mulder [40]. Goals regarding altitude and velocity are set for pilots by means of a virtual tunnel and velocity markers. In doing so, the desired total energy of an aircraft at specific points in time is also defined. This is then shown to the pilot as the Total Energy Reverence Point (TERP), a virtual rail which is, unlike the tunnel, not fixed in space but moves vertically with regards to the aircraft. If the aircraft total energy is too high the TERP will be below the aircraft, a low energy results in flying below the TERP. This can be seen in figure 4.1, where the tunnel and TERP are shown for different energy levels compared to desirable.

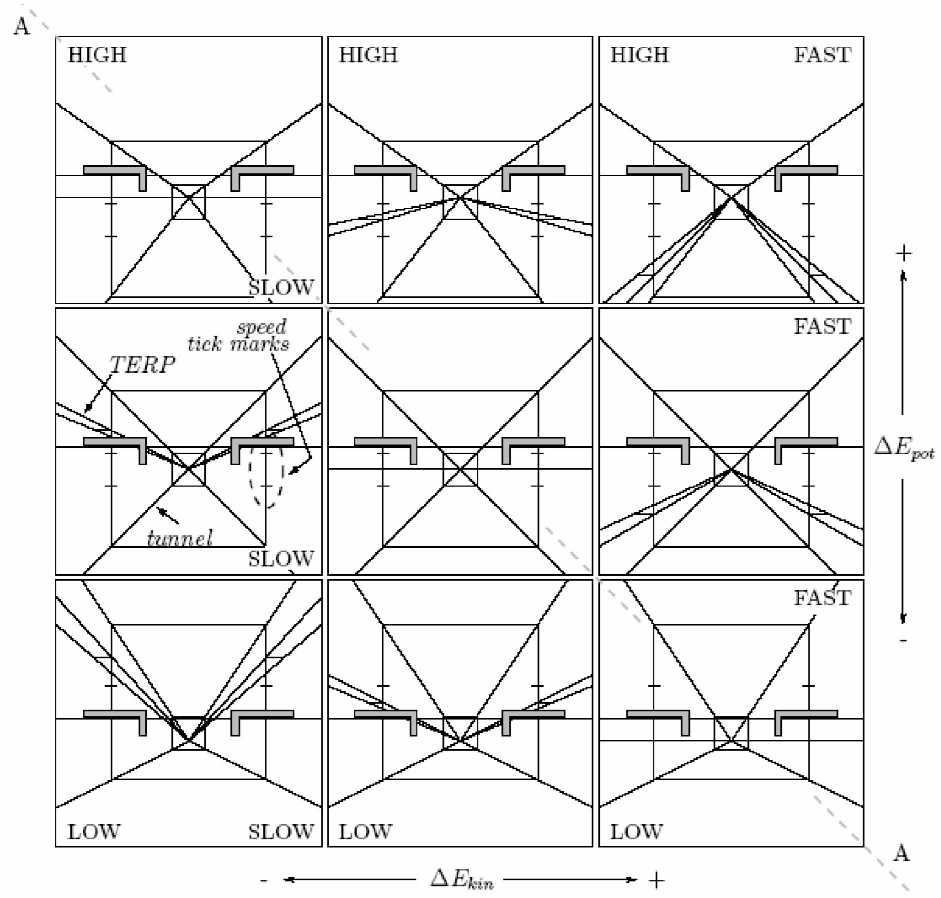
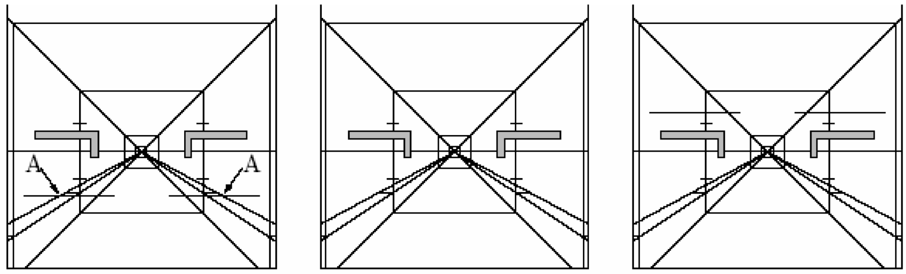


Figure 4.1: Matrix of energy states and corresponding energy display ques in tunnel-in-the-sky display, adapted from Amelink et al. [39]

Apart from the tunnel and TERP, a third que is present in this display: the energy angle. The energy angle, combined with the Flight Path Vector (FPV), can relay information on the rate depending on their position relative to each other and to the artificial horizon. An example is shown in figure 4.2, where the position of the energy angle above or below the FPV indicates whether the energy is increasing or decreasing. The location of the TERP prescribes what energy state is desired, thus which rate is required to attain it.

The TERP and energy angle aim to give the pilot insight in his energy status, thus facilitating him in controlling the kinetic and potential energy. They do not dictate a control strategy, but aid the pilot in analyzing the problem space. In research by Van Den Hoven et al. [41] the energy display was applied to approach scenarios. After using



(a) converging to the TERP (b) parallel to the TERP (c) diverging from the TERP

Figure 4.2: Energy angle que (Point A), indicating whether energy rate is positive or negative by position w.r.t. FPV, adapted from Amelink et al. [39]

the energy display pilots reported increased levels of understanding regarding energy management. In particular the energy angle was appreciated, as it allowed them to see the effects of changes in throttle and configuration instantaneously. However, the display was found to have a higher mental demand, which led to the pilots making mistakes such as following the TERP rather than the tunnel. The energy display still allows for performance improvements, but only if enough mental capacity is available for the pilot.

4.1.2 Oz Display

The Oz functional aviation display, shown in figure 4.3, was designed as a substitute for the basic six configuration in general aviation aircraft by Temme and Still [42]. The display features a single graphical representation of the aircraft and its surroundings, integrating physical properties with higher-order information. Emergent features of colors and patterns are used to convey this information to the pilot, who will have to scan only the Oz display.

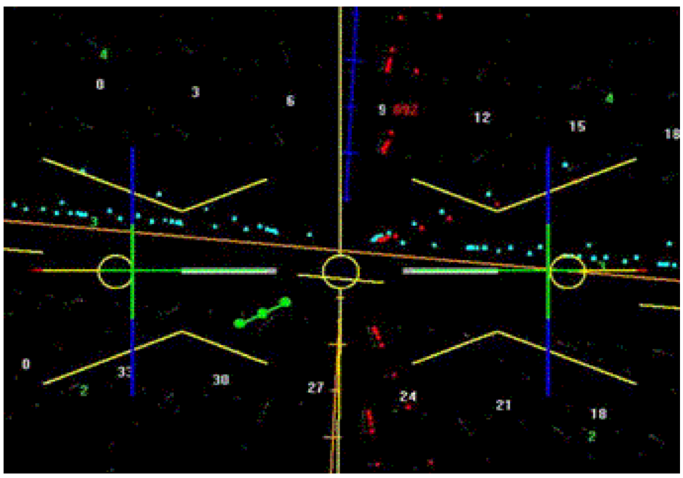


Figure 4.3: Oz functional aviation display, adapted from Temme et al. [42]

The Oz display has multiple features aimed at making the influence of control inputs and external conditions on the aircraft more insightful. An example of this is the depiction of the drag curve, which adapts to the current aircraft configuration and altitude density conditions. Combined with an indicator for the current power setting, this allows pilots to easily select the optimal thrust. The lateral and angular position of the control stick are shown, which the pilot can correlate to the aircraft turn rate and direction.

Several studies have been performed by Smith et al. in which the Oz display is compared to the basic six layout. In one study, experienced pilots performed flight tasks under various workloads by the inclusion of heavy turbulence or a secondary task, which involved operating a GPS instrument. Regardless of workload, pilots achieved significantly higher performance on nearly all dependent variables. However, pilots reported experiencing higher mental workload and temporal effort while operating the Oz display [43]. This has been attributed to the novelty of the display compared to the conventional basic six.

Two training experiments have been conducted by Smith using the Oz display: knowledge development and transfer of training, both for novice pilots. In trianing novice pilots, Smith has concluded that usage of the Oz display contributed significantly to the development and retention of knowledge on flight system dynamics and operation [44]. Novices trained on the Oz display also showed higher performance than those operating a conventional basic six. Performance and knowledge decreased when transferred to a basic six configuration, but subjects still showed significantly higher levels of both compared to novices who had trained exclusively on the conventional display [45]. However, both experiments can be criticized for comparing the Oz display to a basic six, as not only the additional functional information but also the complete visual form are different. Research comparing the Oz display to a conventional PFD is yet to be carried out.

4.1.3 Experimental Vertical Situation Display

The Experimental Vertical Situation Display (EVSD) by Rijneveld et al. [46] combines elements from two earlier VSD concepts: one showing traffic constraints by Heylen [47], the other showing terrain constraints by Suijkerbuijk [48]. A schematic of the display is shown in figure 4.4.

The EVSD shows multiple cues related to energy and performance limits, both in the center of the display and along the edges. The most prominent is the performance envelope, which outlines the possible speed vectors which the aircraft can sustain. It is possible for the speed vector to be above or below this envelope, however this will cause the aircraft to respectively decelerate or accelerate, regardless of its thrust setting. The left and right boundaries indicate stall and maximum speed, as can be seen on the speed tape above the display. The envelope also shows forbidden zones in color, which are areas where a loss of separation with another aircraft or the ground might occur.

A green area on the speed tape indicates the difference between the current and optimum speed, which is the excess kinetic energy. This corresponds to the green area on the altitude tape, which is the height the aircraft can attain when all excess kinetic energy is converted to potential energy. Combined with the total energy line, these cues give the pilot insight in the concept of the aircraft energy state.

Rijneveld tasked pilots to evade terrain and traffic using the EVSD, either with (EVSD) or without (VSD) flight envelope and forbidden zone cues. Results show a trend towards

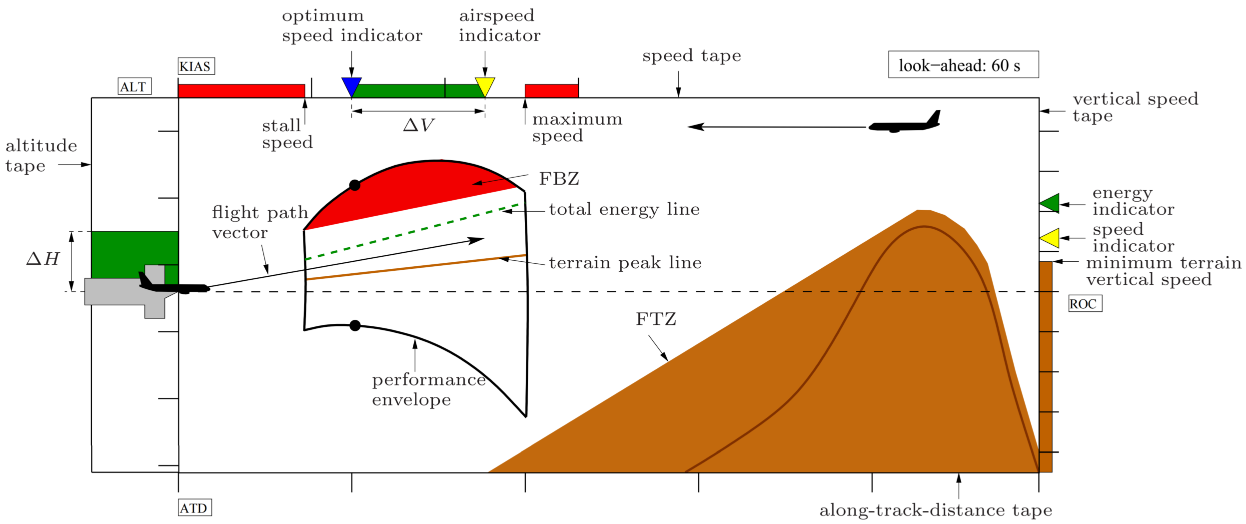


Figure 4.4: Experimental Vertical Situation Display, adapted from Rijneveld et al. [46]

better SA using the EVSD, but no significant improvements in performance were measured. Pilots did report lower levels of workload using the EVSD, although it remains unclear whether peak workload might be higher for the EVSD as pilots receive a lot of information at once. Usage of the EVSD led to more terrain proximity intrusions, as pilots were more aware and confident of the capabilities of their aircraft.

4.1.4 Ecological Synthetic Vision Display

The Ecological Synthetic Vision Display (ESVD) by Borst [9] is designed to aid pilots in executing climbing maneuvers. As the name says it is a synthetic vision display, meaning it is projected as HUD over the environment. A schematic of this projection is shown in figure 4.4.

The angles indicated to the right of figure 4.5 indicate the cues that this display gives. They are, in order of largest to smallest:

- γ_k^{OC} - Optimum climb angle: steepest climb angle flying straight ahead
- $\gamma_{k\phi}^{OC}$ - Optimum climb turning angle: steepest climb angle possible with roll angle
- γ_T - Terrain angle: highest terrain point in current flight direction
- γ_k - Climb angle: Flight path angle indicator
- γ_E - Energy angle: indicator whether total energy is increasing or decreasing

The pilot can use the steepest climb angle combined with the terrain elevation angle to determine whether it is possible to fly over a certain terrain elevation. The energy angle is the same as used in the Energy Display by Amelink et al. discussed in section 4.1.1. The combination of energy angle and flight path vector can be used to see whether the aircraft

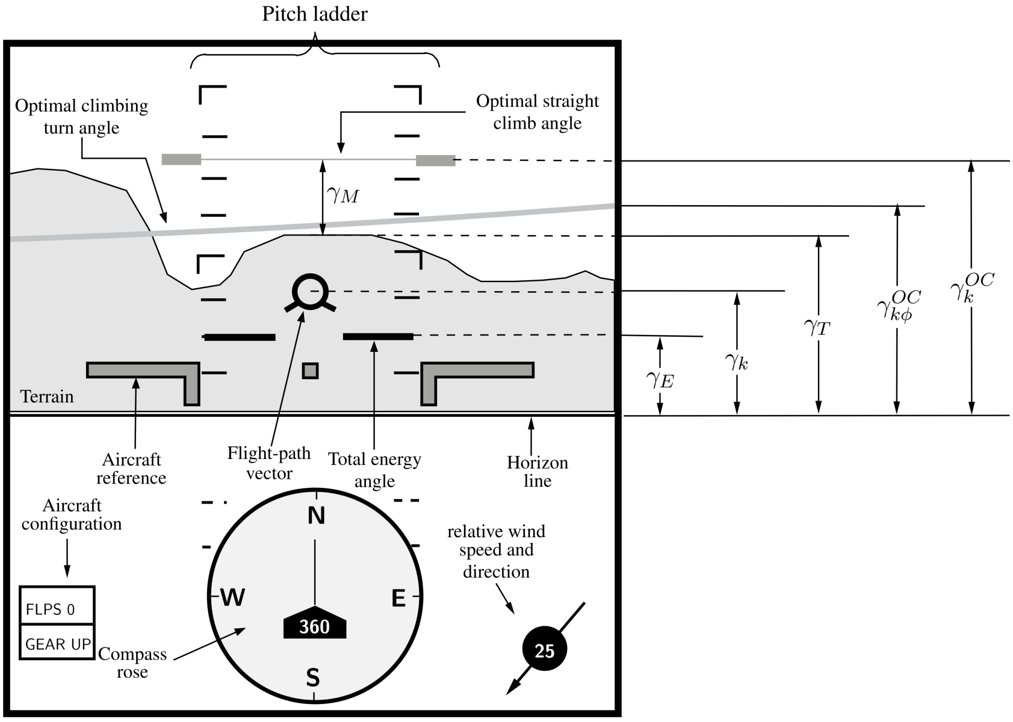


Figure 4.5: Ecological Synthetic Vision Display, adapted from Borst [9]

is accelerating or decelerating. This is especially important for climbing maneuvers, as a rapid deceleration might lead to aerodynamic stall.

The EVSD was tested for anticipated and non-anticipated (such as unexpected engine failure) flight scenarios against a more conventional command display. The EVSD did not significantly effect the performance of pilots for anticipated scenarios, and raised both reaction time and the amount of terrain intrusions. These effects are similar to those when using the IVSD. However, in the unanticipated flight scenarios the EVSD far outperformed the command display. For all flight scenarios the EVSD contributed significantly to pilot SA.

4.1.5 Flight Envelope Protection Display

The Flight Envelope Protection (FEP) display by Ackerman et al. [49] aims to give pilots insight in their maneuverability by showing limitations of both aircraft attitudes and input commands. Aircraft attitude limits are shown on the PFD as yellow lines on the speed, bank, AoA, yaw and altitude strips. Input commands are shown on a separate display, where limits in control inputs are shown in a similar manner. These input limits are a function of the current flight state and configuration, exceeding them would put the aircraft in an upset within one second. Both parts of the display are shown in figure 4.6.

What differentiates the FEP from other displays is that it is able to alter pilot input when this input falls outside of the 'safe input envelope'. This is shown in figure 4.6: the blue dot on the pilot input display shows the pitch command is out of bounds, the green dot

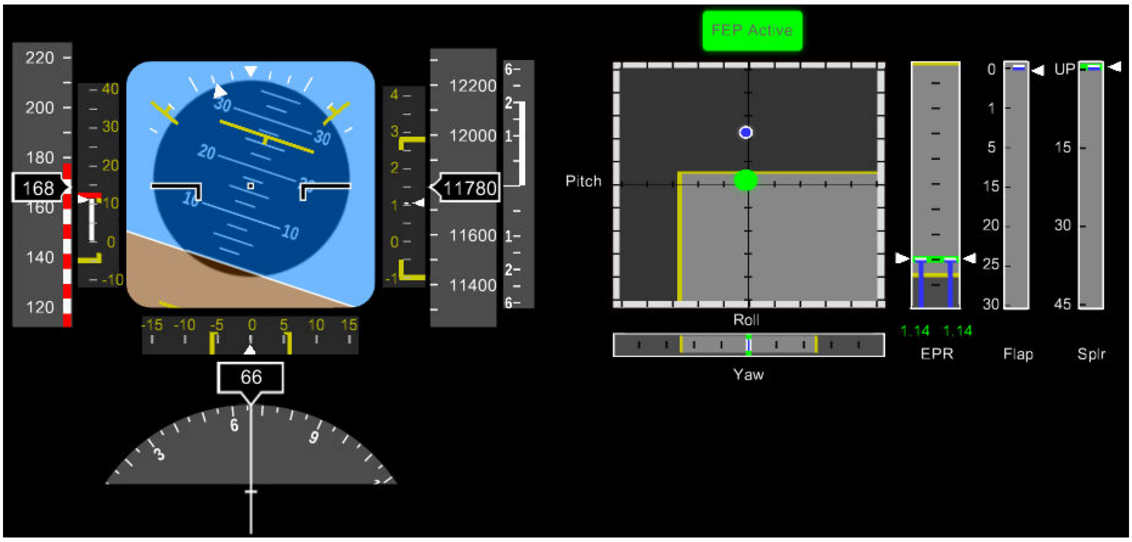


Figure 4.6: Flight Envelope Protection Display, adapted from Ackerman et al. [49]

is the corrected pitch command issued by the FEP system. This input altering mode can be switched on or off.

Unfortunately there are no reports of pilot tests that were conducted using the FEP display. The proposed experiment will have pilots fly scenarios with heavy wind events, which will cause aircraft upset and potential LOC if the pilot does not intervene correctly. Narrowing of the available control input space is hypothesized to make pilots more aware of the dangerous flight condition they are in.

4.1.6 Trajectory Recovery System

The Trajectory Recovery System (TRS) by Kasdaglis et al. [50] is a display alteration to aid pilots in stall upset prevention. Unlike the other analyzed displays it is not based on EID, but rather features a human centered design. This design philosophy prioritizes signals that are easy for humans to observe and interpret. To achieve this, the PFD is 'decluttered' by removing speed and altitude tapes, adding only the TRS circle cue, as shown in figure 4.7. Removal of other information assures that all visual attention is directed at recovering from the current (approaching) upset.

The TRS symbol allows pilots to quickly decide what course of action is required for recovery by its size, color and location. The middle color indicates attitude, and will turn green as the pitch indicator is moved towards it. The size of the outer ring varies with throttle, and will also turn green once appropriate throttle has been selected. The appropriate throttle is shown as a separate ring around the TRS. Quick interpretation of the symbol will allow for very fast pilot reaction times, thus improving the upset recovery procedure performance. The display enhancement will disengage when AoA, airspeed and vertical speed are within normal operating conditions.

Only a validation experiment has been flown with the TRS display, in which pilots were presented with multiple scenarios of extreme wind conditions. Pilots showed better performance and reported lower workload using the TRS, which is likely the effect of the

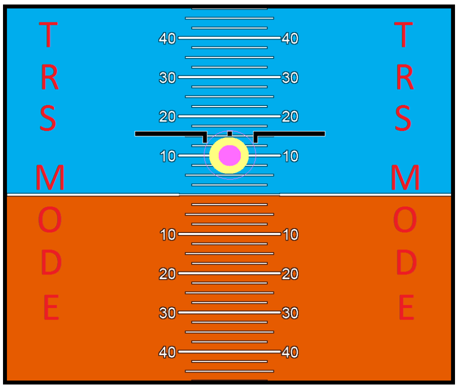


Figure 4.7: Flight Envelope Protection Display, adapted from Kasdaglis et al. [50]

human centered design choices. No conclusions could be drawn on the dependency of pilots on this information if it would be removed.

It can be argued that even though pilots showed performance improvements on semi-random gust events this does not mean the TRS makes aircraft safer in terms of stall prevention and recovery. Especially during low-energy stalls on approach and landing, which are most likely to lead to an accident, speed and altitude tapes are useful for balancing kinetic and potential energy. However, as reaction time is an important factor during approach-to-stall scenarios, a command display might be more effective in preventing LOC-I from developing.

4.1.7 Conclusions on Reference Display Analysis

After analysis of other display enhancements, some conclusions can be drawn which can be used in the development and testing of an ecological interface for upset prevention:

- Ecological interfaces generally cause elongated reaction times as pilots need time to analyze and process all the information they are presented with. This will seem as a drop in performance until an unexpected condition is encountered, in which case the additional information EID offers puts the pilot at an advantage.
- It is preferable for the display to include an aspect that changes directly with input variables, such that pilots can see that their control inputs are registered and can better link control inputs to the effect inputs have on state variables.
- The work domain has many constraints at many different levels. Creating visualizations for them all will likely cause pilots to confuse some of the cues, thus losing the added insight that EID attempts to create. However, too much information decluttering might lead to important information being missing when it might be needed.

4.2 Display Design

In creating the design of the display, recommendations from reference displays are used in combination with a theoretical base framework. The foundation of this framework is the abstraction hierarchy in section 4.2.1, which shows the relations of information layers within the system of piloted flight . This will lead to a specific display design, of which the elements are discussed in section 4.2.2. Finally, section 4.2.3 derives equations and gathers information necessary to draw the ConfVSD.

4.2.1 Abstraction Hierarchy

For creation of the display, an ecological design process is carried out. This design process is based on theoretical foundations [38] and guidelines [51] by Vicente and Rasmussen. As a first step in this framework a work domain analysis is carried out in the form of an Abstraction Hierarchy (AH). This diagram, shown in Figure 4.8, gives insight in the higher orders of information the word domain contains. These are the 'layers' of information the pilot is given more direct access to when operating an EID interface.

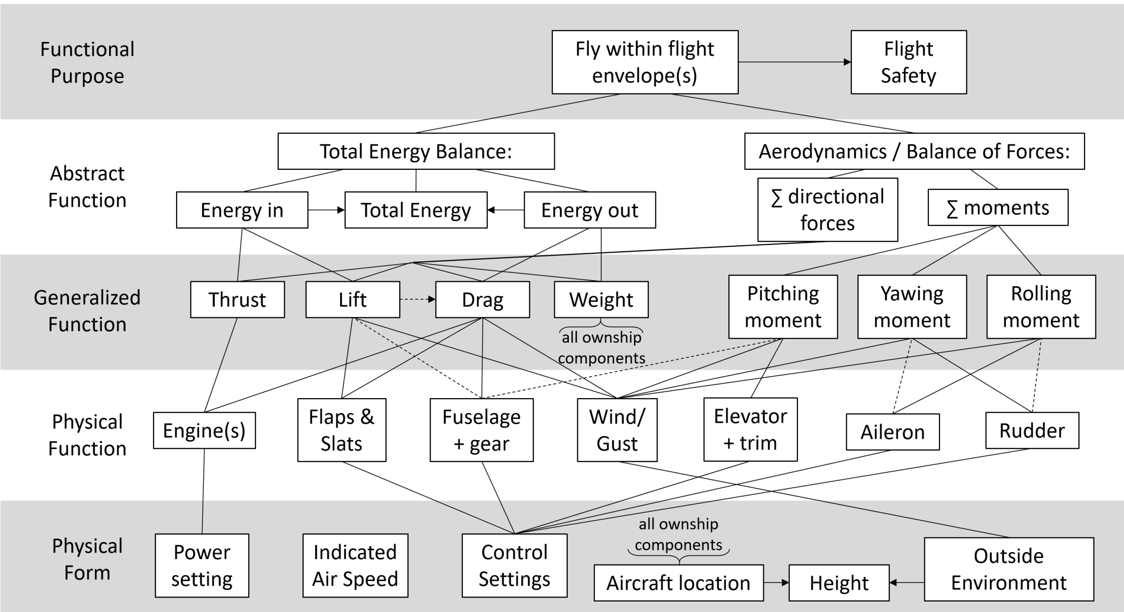


Figure 4.8: Abstraction Hierarchy of manually piloted flight

Generally concepts from the physical form level are most easily accessible by pilots, as they can be easily measured and displayed. Examples of this are the velocity and altitude indicators. Pilots must then use this information to derive information on higher levels of abstraction. EID allows for easier perception of information in higher AH levels, which means knowledge-based behavior can be replaced by rule-based behavior.

4.2.2 The Ecological Approach Vertical Situation Display

Comparing the AH in figure 4.8 to reference displays analyzed in section 4.1 shows that the ESVD, which was used to aid pilots in maneuvering through terrain and incoming traffic, contains many of the elements listed in higher AH levels. This is why it is used as a basis for the Configuration State Vertical Situation Display (ConfVSD), which alters the EVSD design to better match the purpose of energy and flight envelope management in approach and landing.

The ESVD already shows appropriate energy cues, which should allow the pilot more insight in the energy state of the aircraft. Information regarding terrain avoidance is omitted as scenarios will not include terrain, and these cues are replaced with an approach path that the pilot is tasked to follow. This path will include markers indicating at which point flaps and landing gear should be deployed. The excess kinetic energy the aircraft has is displayed on the speed tape, and projected on the altitude tape as potential energy. The total energy line shows the instantaneous energy increase or decrease. The ConfVSD is shown in Figure A.3.

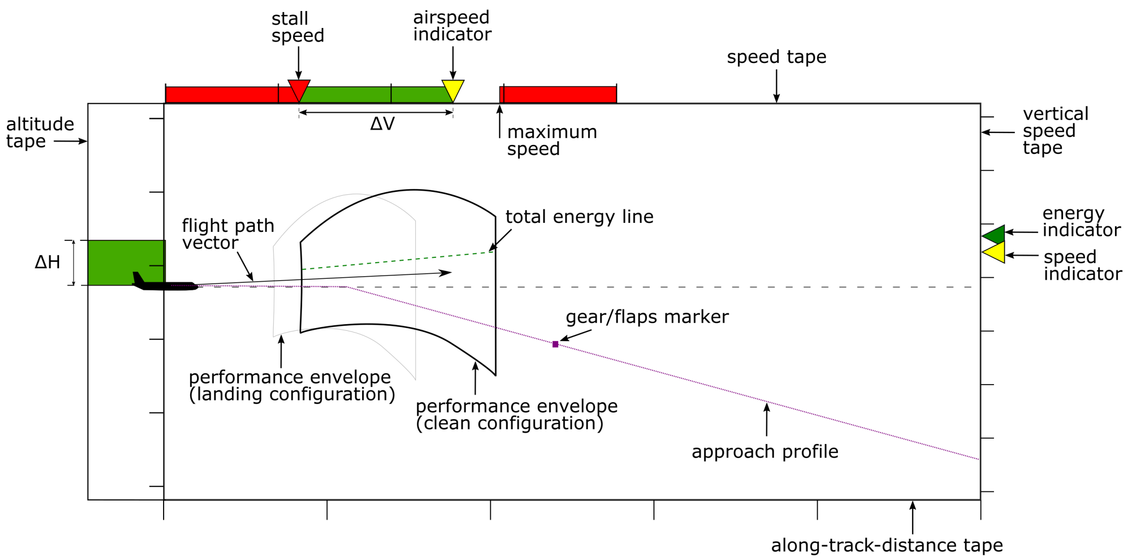


Figure 4.9: Configuration State Vertical Situation Display (ConfVSD), adapted from Rijneveld et. al. [46]

In the experiment bij Rijneveld et al. pilots operating the EVSD were not able to change their aircraft configuration, hence the envelope of possible speed vectors remained constant. As approach and landing involve configuration changes, the flight envelope is made dynamic to reflect these changes. This function of the display is designed to allow pilots to obtain a greater insight in the effect of configuration changes on their maneuverability.

Unlike shown in Figure A.3, only one configuration envelope can be seen at a time. This design choice was made to prevent information cluttering, as envelopes for all combinations of flap and gear settings would have to be shown simultaneously. Proper operation of the display thus involves a training phase in which the pilot learns the effects of changing the aircraft configuration.

4.2.3 Performance Envelope Boundaries

The performance envelope shows the pilot whether he is operating within safe flight conditions, thus gives access to the highest level of the AH. Boundaries for this envelope are determined by aircraft characteristics, most importantly thrust and aerodynamic characteristics. Four boundaries are to be defined: those for minimum and maximum speed (the left and right boundaries in Figure A.3) and those for minimum and maximum thrust (the lower and upper boundaries in Figure A.3).

Speed boundaries are easily defined by the minimum and maximum velocity the aircraft is able to fly in different configurations. The stall speed is taken as minimum boundary, which lowers as high-lift devices are deployed. The maximum speed is defined by the 'never exceed speed' V_{NE}, which is the limit after which structural damage to the aircraft can occur. This speed lowers drastically as flaps and gear are deployed. A list of relevant speeds is compiled from an EASA type-certificate data sheet [52]. These speeds are listed in table 4.1.

Table 4.1: Speed limitations for Citation II configurations [52]

Configuration	V_{stall} [KIAS]	V_{MO} [KIAS]
Clean	95	260 (up to FL 140) 275 (above FL 140)
No gear, flaps 15	90	200
No gear, flaps 40	84	174
Gear, no flaps	95	250
Gear, flaps 15	90	200
Gear, flaps 40	84	174

To draw the envelope boundaries, the maximum flight path angle corresponding to each velocity has to be determined. To derive the necessary equations, a balance of forces is made based on the four basic forces acting on an aircraft in climbing flight. These forces are shown in figure 4.10.

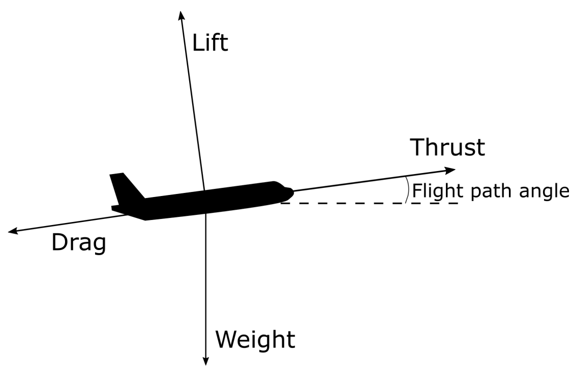


Figure 4.10: Balance of four basic forces acting on an aircraft

Summing forces over the axial direction of the aircraft:

$$T = D + W \cdot \sin(\gamma)$$

where γ is the flight path angle. Rearranging this equation results in:

$$\sin(\gamma) = \frac{T - D}{W}$$

As lift and weight are the largest forces in vertical direction, these two can be assumed equal for small values of γ. Replacing W with L in the equation gives:

$$\sin(\gamma) = \frac{T}{W} - \frac{D}{L}$$

which is the same as

$$\sin(\gamma) = \frac{T}{W} - \frac{C_D}{C_L} \tag{4.1}$$

As the weight is assumed constant throughout the flight, only Thrust, C_D and C_L are required to compute the corresponding value for γ. For the upper envelope boundary thrust is taken to be maximum (as a function of altitude and true airspeed), for the lower boundary thrust is zero.

C_D and C_L are approximated by assuming a steady state flight with both an angle of attack $\alpha = 0$ and flight path angle $\gamma = 0$, where lift is equal to the weight:

$$W = L = \frac{1}{2} C_L \rho V^2 S$$

This can be rewritten to approximate which value for C_L is required to fly a given airspeed V:

$$C_L = \frac{2W}{\rho V^2 S} \tag{4.2}$$

This is then taken to be the lift coefficient belonging to a specific airspeed for all γ. Of course as the flight path angle increases, the lift vector tilts and more lift is needed to counteract the weight. This amount of additional required lift scales with $cos(\gamma)$. Preliminary simulations show that the largest values of γ that can be expected are around 10 degrees, which means the estimate for C_L is off by at most 2%. This indicates that the lift coefficient estimated using equation 4.2 can be used for all values of γ in the envelope.

After C_L has been estimated, C_D can be computed by adding together the zero-lift drag $C_{D,0}$ and lift-induced drag C_D components:

$$C_D = C_{D,0} + C_{D,i} = C_{D,0} + \frac{C_L^2}{\pi A e} \tag{4.3}$$

Increased lift from high-lift devices will also increase the drag, and deploying the gear increases the value of $C_{D,0}$. Both also change the minimum and maximum airspeeds which the aircraft is able to attain.

Performance Envelope Simulations

Using data of the standard atmosphere and the Cessna Citation 500 model by Delft University of Technology, faculty of Control & Simulation [53], velocity envelopes can be drawn for the Cessna Citation II. These envelopes are shown in knots true airspeed, so later they can be multiplied by a lookahead time and mapped over a surface. The lookahead time will be determined based on the scale of the map. Figure 4.11 shows the envelopes for the Citation II flying at low, cruise and maximum altitudes. A higher altitude causes both the pressure to drop, thus true airspeed to increase and thrust to drop.

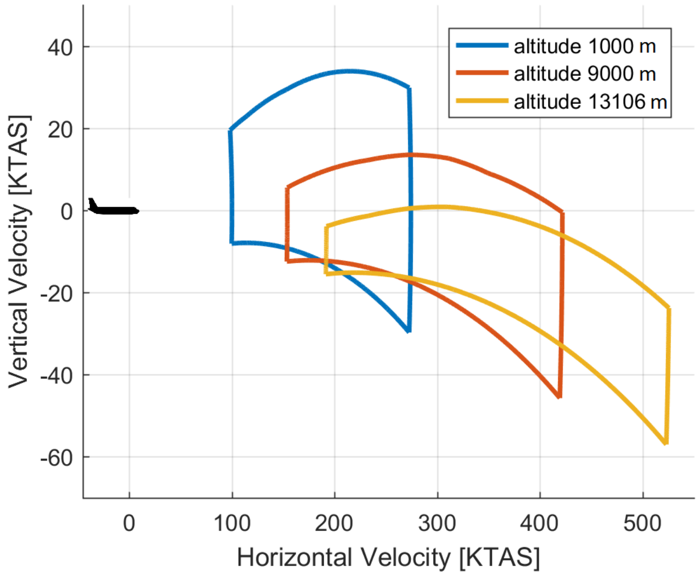


Figure 4.11: Velocity Envelopes for varying altitude

It can be seen that at the roof of 13106 ft, the maximum sustainable vertical velocity (around 300 KTAS) is nearly 0. This can be used to verify the envelope, as it indeed indicates that the aircraft cannot rise any further at this altitude.

Deploying the gear will increase the zero-lift drag coefficient. This effect is especially large at higher velocities, as can be seen in figure 4.12. To counter the effect of the increased drag, a pilot can deploy flaps on the aircraft. Flaps shift the $C_L - \alpha$ curve by a fixed amount, increasing both the maximum C_L as well as the value for C_L at each angle of attack. However, flaps do heavily limit the maximum operating speed of the aircraft. Both these effects can be seen in figures 4.13 and 4.14 for respectively gear not deployed and gear deployed.

An effect that cannot be seen is that using flaps allows the aircraft to fly at lower angles of attack for lower speeds. This is especially useful for landing, as it gives the pilot a better visual and allows for putting the aircraft on the ground more easily. A small amount of flaps is also used for initial climb, as it allows the pilot to attain a large amount of lift without coming too close to stall.

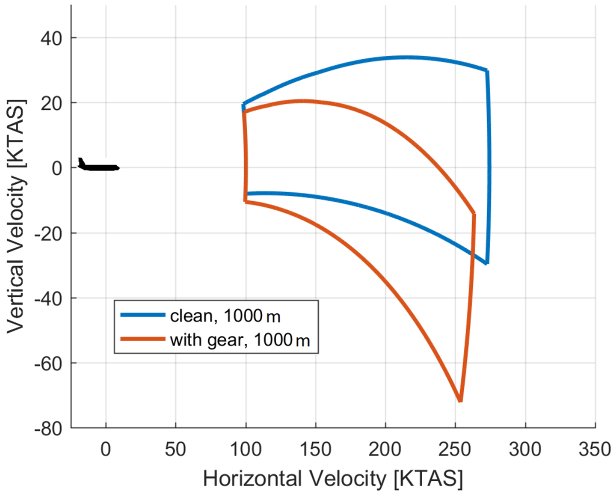


Figure 4.12: Velocity Envelopes for clean and gear deployed configuration

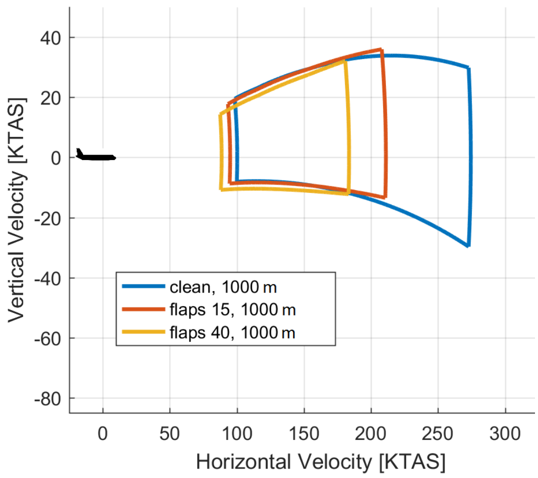


Figure 4.13: Velocity Envelopes for varying flaps

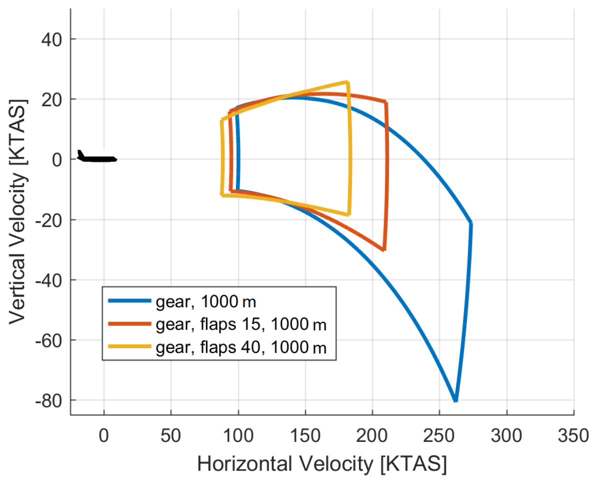


Figure 4.14: Velocity Envelopes for gear deployed configuration with varying flaps

Chapter 5

Experimental Design Proposal

Now a clear display design has been proposed, the literature research is used as foundation to propose an experimental design. This design will be targeted towards the most dangerous flight phases and external conditions, inducing a approach-to-upset scenarios.

Before concrete experimental design is proposed, first in section 5.1 the research question from section 1.2 is refined. The research setup in terms of equipment and participants is described in section 5.2, after which the different experimental runs, control and dependent variables are explained in section 5.3.

5.1 Updated Research Question

Chapter 1.2 first listed a research question and set of sub-questions which were used as guidelines for a literature study. At present some of these have been answered and others reframed, which gives need for a new research question and set of sub-questions to be defined. These questions will be leading in the experiment described in the remainder of this chapter:

How can addition of visual cues contribute to an increase in performance for preventing aircraft upset conditions in low-energy maneuvers?

The following sub-questions can be defined:

- What is the effect of display enhancement on pilot reaction time to abnormal events?
- What is the effect of display enhancement on flight safety, e.g. distance to the leading/trailing edge of the flight envelope?
- What is the effect of display enhancement on pilot subjective workload rating?

The experimental results will be used to answer these questions, thus answering the main experiment research question.

5.2 Research Setup

Three aspects of the experimental setup are elaborated upon: the simulation hardware, simulation software and participants for the experiment. After these three components are clearly defined, section 5.3 will further explain how exactly they will be employed to answer the research question.

5.2.1 Simulation Hardware

The ConfVSD will be simulated in one of the flight simulators at the Delft University of Technology. The flight simulator that will be used for this experiment is the SImulation, MOtion and NAvigation (SIMONA) flight research simulator, which is stationed at the faculty for Aerospace Engineering, department of Control and Simulation. This simulator is a level D certified, 6 degree of freedom motion base FFS, capable of simulating any aircraft for which software is available. The SIMONA research simulator is shown in figure 5.1.

Figure 5.1: SIMONA research simulator [54]

After simulation runs have been completed, data analysis will be done on an external computer using Matlab and SPSS.

5.2.2 Simulation Software

The aircraft model which will be loaded on the simulator is the Cessna Citation 550, which was made by the faculty Control & Simulation of the Aerospace faculty at Delft University of Technology. This model includes a stall functionality and the ability to add turbulence and exert external forces on the aircraft. These external forces can be used to simulate winds or other environmental conditions acting on the aircraft.

5.2.3 Experiment Participants

As the experiment requires participants to be able to perform an approach and go-around maneuver under environmentally unfavorable conditions, only people with an active piloting license in general aviation are asked to perform in the experiment. As GA pilots are generally not accustomed to additional flight interfaces, the training phase will be extensive enough for them both to understand the display as well as getting used to gathering information from it. Participants will be assigned randomly to either the ConfVSD or VSD groups. Grouping participants based on flight hours is considered if there is a large variety in flight experience between participants.

5.3 Experiment Execution

This section explains the ideas and practices of the experiment that is to be performed. First the general idea of the experiment is explained in section 5.3.1, after which concrete examples for all three types of variables are listed in section 5.3.2. This will lead to a Latin square experiment design, proposed in section 5.3.3.

5.3.1 General Experimental Run

Before the experiment, potential participants are contacted by email and asked to indicate whether they would be available and at what times. Based on their availability and willingness to come, a timetable is made and participants are invited.

Experiment Briefing

Upon arrival, a participant is brought to the SIMONA to sign a form and receive a briefing. This briefing consists of two parts. First, an introduction about the experiment is given, and the task of an approach and go-around is explained. Pilots are specifically instructed that the task is to fly a go-around, but this being a realistic scenario they are free to land if they feel it might be unsafe to continue. As flying approach and go-around scenarios is not very conventional, participants receive additional information about appurtenant procedures. A small reference sheet is given to the participant with relevant procedures and configuration schedule for take-off and landing.

Pilots will fly their task either with the complete ConfVSD or without the velocity envelope, which will be named the Vertical Situation Display (VSD) condition. Those flying with only the VSD will receive additional information about best practices when flying in turbulence or approaching an upset condition, as well as the working of the VSD. Pilots flying with the ConfVSD will receive aforementioned information in a condensed version, and extra information on the functionality of the ConfVSD such that both briefings are roughly the same length. Briefings are based on the theory taught in UPRT classroom training, which has been discussed in chapter 3.1.

Training

The participant is given training scenarios to familiarize with the simulator, flight controls and VSD/ConfVSD. These include a take-off, approach & go-around and free flight in turbulence. The time spent on familiarization will be determined by pre-experimental tests, most likely it will last from 1 to 2 hours to ensure a performance constant is reached.

Experimental Runs

After familiarization a break is offered to the participant, after which experimental runs will begin. Participants are notified in case the scenario they will fly contains turbulence and/or heavy winds. The schedule for these experimental runs can be found in section 5.3.3.

During experimental runs data is recorded, and feedback given on their performance is standardized as far as possible. The final experimental run will always be an engine failure scenario in which the participant must act against instructions and land in stead of making a go-around. After each experimental run has finished, participants are asked to rate their workload on a Rating Scale for Mental Effort (RSME) [55].

5.3.2 Experiment Variables

The independent and dependent variables are chosen to find a clear answer to the research question. All other factors will be kept as constant as possible.

Independent Variables

Independent variables are changed in a controlled manner throughout the experiment to create different experimental conditions. The names of these variables as well as the values they can attain are listed in table 5.1.

Table 5.1: Independent variables and appurtenant values

Between subjects	Display	VSD
		ConfVSD
Within subjects	Turbulence	Mild
		Heavy
	Event	None
		Microburst
		Upwind
	Special Event	Engine Failure

The display variable being a 'between subjects' variable causes the experiment to require a larger number of participants. However, this is deemed necessary as it is the only way to remove the confounded carry-over effects, as participants might learn by operating the ConfVSD and later visualize how the performance envelope might look when operating the regular VSD. All experimental conditions are subject to change based on limitations in capabilities of the simulator and simulation software.

The experiment will task pilots to fly approach and landing maneuvers under various environmental conditions. Since the experiment is aimed at upset prevention, scenarios should induce dangerous conditions through external factors. These external factors will have the following effects:

- **Turbulence** - Unpredictable shifting of the flight path vector.
- **Microburst** - Sudden large loss of potential energy.
- **Upward gust of wind** - Sudden large upward wind, increasing potential energy and decreasing kinetic energy.
- **Engine Failure** - Loss of an energy source, forcing pilots to manage their current energy as efficiently as possible

Other varieties in training might include alterations in the approach path steepness. Finally, the most important independent variable is in the display condition: with or without the performance envelope in the ConfVSD.

Dependent Variables

Dependent variables are measured throughout the experiment to draw conclusions about the different experimental conditions. The names of the variables that will be measured are listed in table 5.2 by category. More variables may be added as experimental design progresses.

Table 5.2: Dependent variables and appurtenant values

Control Inputs	Control stick input
	Flap setting input
	Gear setting input
	Thrust setting input
Aircraft states	p, q, r, $\dot{p}$, $\dot{q}$, $\dot{r}$
	α, β, ϕ, θ, ψ
	V_{TAS}
	altitude, x_{earth}, y_{earth}
	Thrust
Pilot workload	RSME

As with independent variables, the list of dependent variables might be expanded if other data is deemed necessary to draw conclusions on the research questions stated in 5.1.

5.3.3 Balanced Latin Square Experiment Design

In conducting the experiment, a balanced Latin square experimental design is used. In designing this experiment, the two turbulence conditions (mild/heavy) and three event conditions (none/microburst/upwind) are combined into six total combined conditions. These are arranged according to the pattern in table E.3.

Table 5.3: Balanced Latin square layout

Participant Number	1	2	3	4	5	6
Experimental	A	B	F	C	E	D
conditions	B	C	A	D	F	E
	C	D	B	E	A	F
	D	E	C	F	B	A
	E	F	D	A	C	B
	F	A	E	B	D	C
	S	S	S	S	S	S

The balanced Latin square is designed to minimize the effect that the order of runs might have on the experimental outcome. The final scenario in each run sequence is labeled 'S', which stands for 'special'. This scenario is the engine failure event listed in table 5.1, which is combined with mild turbulence. By performing this scenario last, the surprising effect it might have is maximized and pilot resilience is optimally tested.

Chapter 6

Conclusion

This section briefly glosses over the remainder of the MSc thesis which is to be completed. First the imminent next steps are listed, after which the considerations that might be relevant when executing these steps are discussed. This will conclude the preliminary thesis report.

Next Steps

The most imminent next step is to start programming the ConfVSD in the DUECA framework. This requires setting up the framework on a host computer with Linux openSUSE. To test whether the ConfVSD is fully dynamic and correct, data must be drawn from the simulation and compared to MATLAB simulated flight envelopes.

Once the display has been programmed, the next step will be to program scenarios. These will have to be finely tuned to both match realism and induce an appropriate amount of threat to the pilot.

Once scenarios are in place, a pilot testing phase will show whether these scenarios have indeed been constructed correctly. This includes a try-out of the experiment briefing and training phase. All three of the briefing, training and scenarios are refined after this testing phase.

Finally, an experiment is conducted which places pilots in the SIMONA research simulator. A research paper will be written about the results of this experiment.

Considerations

Different phases of the plan stated above still have multiple considerations. The following alterations or variations might be considered throughout execution of the steps previously listed:

- The ConfVSD is currently still under review, as a more clear visualization of the means-ends relationships is still possible in the display. The current design choice of only showing one envelope might be revised to allow more insight into these relations. Possible solutions for this problem include showing full or partial envelopes that can be attained by changing the flight configuration, which are respectively shown in figure 6.1 and 6.2.
- The best suitable coloring of the ConfVSD will be further investigated as the simulation is programmed. Potentially flight envelopes will not be shown as (dotted) lines, but rather opaque colored areas.
- As the entire thesis project is quite large, shortcuts might be taken to have it fit better within the time of an MSc thesis. Such shortcuts might include simplified experimental conditions, or a pilot verification rather than full-blown experiment.
- It is possible that after the testing phase, also elements of the display are redesigned to better fit pilot perception. If this does occur, it might influence other decisions on grounds of time-management.

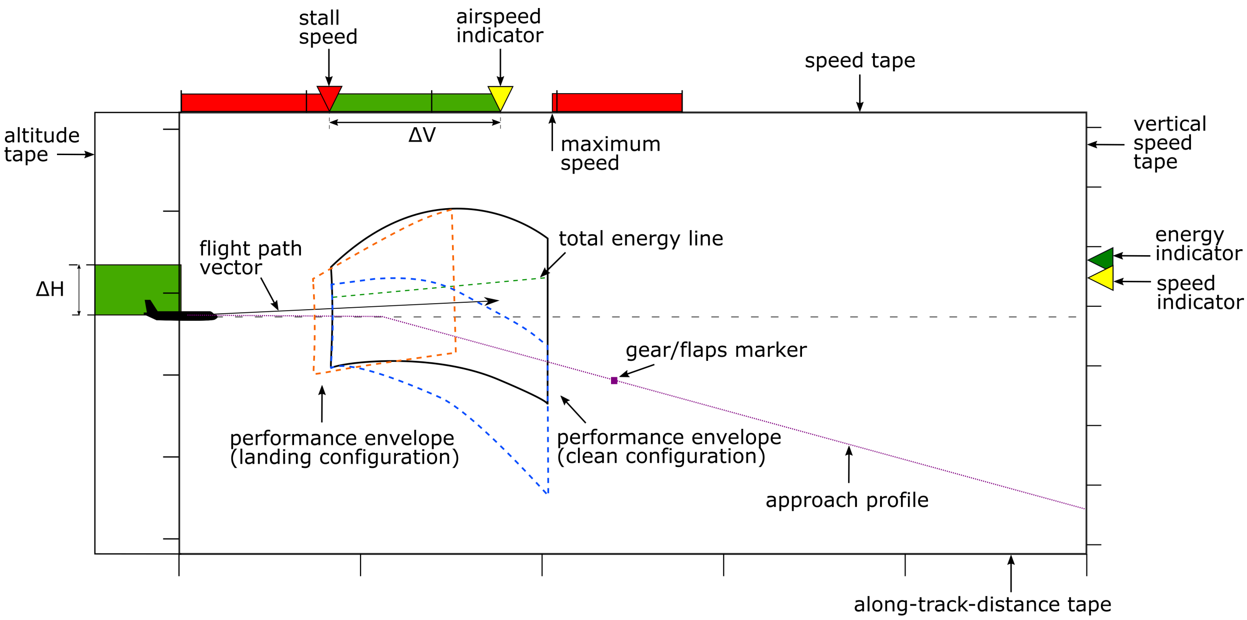


Figure 6.1: Ecological Vertical Situation Display with full alternative envelopes, adapted from Rijneveld et al. [46]

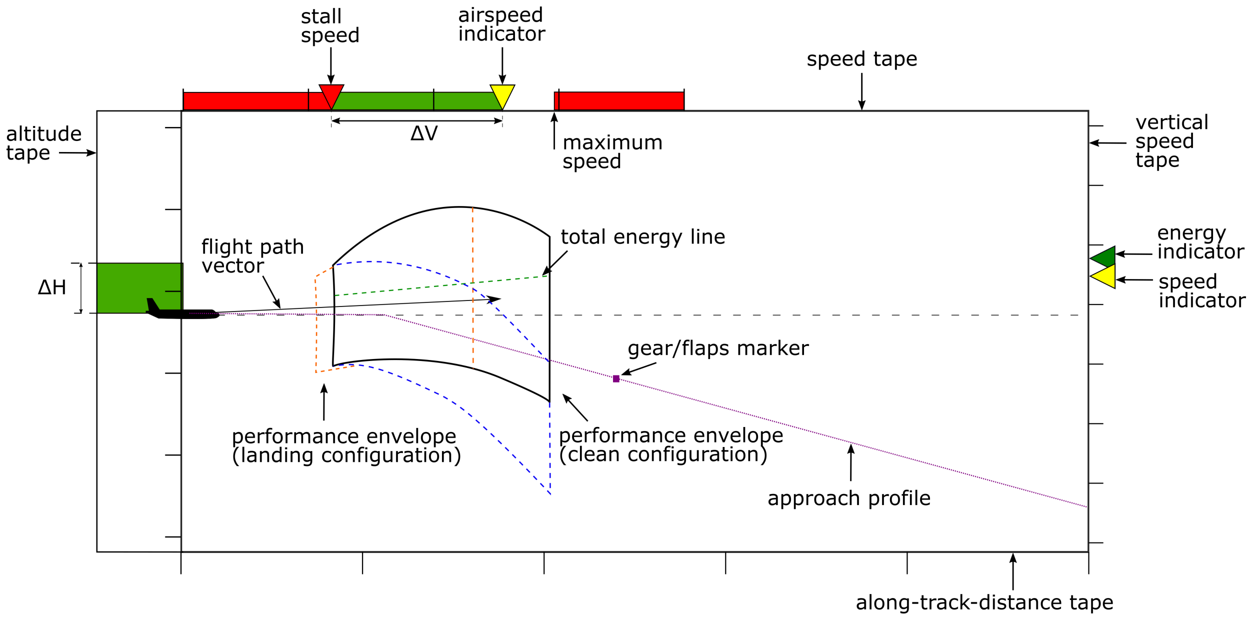


Figure 6.2: Ecological Vertical Situation Display with partial alternative envelopes, adapted from Rijneveld et al. [46]

References

[1] E. F. Weener. General Aviation LOC and the NTSB Most Wanted List. *National Transportation Safety Board*, 2016.

[2] C. M. Belcastro and J. V. Foster. Aircraft Loss-of-Control Accident Analysis. In *AIAA Guidance, Navigation, and Control Conference*, Toronto, Ontario, 2010.

[3] S. R. Jacobson. Aircraft Loss of Control Causal Factors and Mitigation Challenges. In *AIAA Guidance, Navigation, and Control Conference*, pages 1–59, 2010.

[4] J. Croft. Reconsidering Upset Recovery Training. *Aviation Week & Space Technology*.

[5] S. K. Advani, J. A. Schroeder, and B. Burks. What Really Can Be Done in Simulation to Improve Upset Training? In *AIAA Modeling and Simulation Technologies Conference*, Toronto, Ontario, 2010.

[6] J. Bürki-Cohen and A. Sparko. Airplane Upset Prevention Research Needs. In *AIAA Modeling and Simulation Technologies Conference*, pages 1–15, 2008.

[7] J. A. Schroeder, J. Bürki-Cohen, and D. A. Shikany. An Evaluation of Several Stall Models for Commercial Transport Training. In *AIAA Modeling and Simulation Technology Conference*, Atlanta, Georgia, 2014.

[8] J. Flach, M. Mulder, and M. M. van Paassen. The concept of the situation in psychology. In *A cognitive approach to situation awareness: Theory and application*, number January, pages 42–60. Ashgate Publishing, Aldershot, UK, 2004.

[9] C. Borst. *Ecological Approach to Pilot Terrain Awareness*. PhD thesis, Delft University of Technology, 2009.

[10] J. Ellerbroek, M. Visser, S. B. J. Van Dam, M. Mulder, and M. M. Van Paassen. Design of an airborne three-dimensional separation assistance display. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans*, 41(5):863–875, 2011.

[11] M. Visser. *Ecological Interface Design: Training Air Traffic Control Novices in Conflict Detection and Resolution.* PhD thesis, Delft University of Technology, 2016.

[12] P. Hermes, M. Mulder, M. M. Van Paassen, J. H. L. Boering, and H. Huisman. Solution-Space-Based Complexity Analysis of the Difficulty of Aircraft Merging Tasks. *Journal of Aircraft*, 46(6):1995–2015, 2009.

[13] K. Christofferson, C. N. Hunter, and K. Vicente. A Longitudinal Study of the Effects of Ecological Interface Design on Skill Acquisition. *Human Factors*, 28(3):523–541, 1996.

[14] K. Christoffersen, C.N. Hunter, and K. J. Vicente. A Longitudinal Study of the Effects of Ecological Interface Design on Deep Knowledge. *International Journal of Human-Computer Studies*, 48:729–762, 1998.

[15] D. Carbaugh, L. Rockliff, and B. Vandel. *Airplane Upset Recovery Training Aid.* Number 2. Washington DC, 2nd edition, 2008.

[16] J. E. Wilborn and J. V. Foster. Defining Commercial Transport Loss-of-Control: A Quantitative Approach. In *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, pages 1–11, Providence, Rhode Island, 2004.

[17] International Air Transport Association. Safety Report 2015 Edition. Technical report, International Air Transport Association, Montreal, Quebec.

[18] P.R. Veillette. Investigating and Preventing the Loss of Control Accident, Part II. Technical Report December, ISASI, 2012.

[19] S. J. Houston, R. O. Walton, and B. A. Conway. Analysis of General Aviation Instructional Loss of Control Accidents. *Journal of Aviation/Aerospace Education & Research*, 22(1), 2012.

[20] B. N. Branham. *Analysis of Fatal General Aviation Accidents Occurring from Loss of Control on Approach and Landing.* PhD thesis, Embry-Riddle Aeronautical University, 2013.

[21] D. Eick. Turbulence Related Accidents & Incidents, NTSB Weather Upset Statistics Presentatio, 2014.

[22] National Transportation Safety Committee. Aircraft Accident Investigation Report - Adam Air 574. Technical Report January 2007, Republic of Indonesia NTSC, Sulawesi, 2008.

[23] Federal Aviation Administration. General Aviation Fatal Accidents 2001-2010 by CICTT Occurrence Category. Technical report, FAA, Washington DC, 2010.

[24] L. Bainbridge. Ironies of automation. *Automatica*, 19(6):775–779, 1983.

[25] Federal Aviation Administration. *Manual on Aeroplane Upset Prevention and Recovery Training.* FAA, Montreal, Quebec, first edition, 2014.

[26] R. O. Rogers and A. Boquet. The Benefits and limitations of ground-based upset-recovery training for general aviation pilots. *The Aeronautical Journal*, 116(3754):1015–1039, 2012.

[27] W. Falkena. SAFAR Diamond DA42 Model, 2009.

[28] L. J. Clancy. *Aerodynamics.* Pitman Publishing Limited, London, 1975.

[29] T. ten Velde, C. Norden, and B. Bennetts. Loss of Control In-Flight Accident Analysis Report 2010-2014. Technical report, International Air Transport Association, Montreal, Quebec, 2015.

[30] J. Barbagallo. Advisory Circular: Upset Prevention and Recovery Training. Technical report, Federal Aviation Administration, Washington DC, 2015.

[31] International Air Transport Association. Guidance Material and Best Practices for the Implementation of Upset Prevention and Recovery Training. Technical Report June, International Air Transport Association, Montreal, Quebec, 2015.

[32] Active Pilot Monitoring Working Group. A Practical Guide for Improving Flight Path Monitoring. Technical Report Nov, 2014.

[33] Loss of Control Action Group. Monitoring Matters: Guidance on the Development of Pilot Monitoring Skills. Technical report, Civil Aviation Authority, 2013.

[34] N. B. Sarter, R. J. Mumaw, and C. D. Wickens. Pilots' monitoring strategies and performance on automated flight decks: an empirical study combining behavioral and eye-tracking data. *Human Factors*, 49(3):347–357, 2007.

[35] S. M. Casner, R. W. Geven, and K. T. Williams. The effectiveness of airline pilot training for abnormal events. *Human Factors*, 55(3):477–485, 2013.

[36] J. Bürki-Cohen. Technical Challenges of Upset Recovery Training: Simulating the Element of Surprise. *AIAA Guidance, Navigation, and Control Conference*, pages 1–5, 2010.

[37] H. Hoogervorst (Chief Flight Instructor at Aviation Performance Solutions). Interview, 10-05-2016, APS Training Center Breda.

[38] K. J. Vicente and J. Rasmussen. Ecological interface design: theoretical foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(4):589–606, 1992.

[39] M. H. J. Amelink, M. Mulder, M. M. Van Paassen, and J. Flach. Theoretical Foundations for a Total Energy-Based Perspective Flight-Path Display. *The International Journal of Aviation Psychology*, 15(3):251–231, 2005.

[40] M. Mulder. *Cybernetics of tunnel-in-the-sky displays.* PhD thesis, Delft University of Technology, 1999.

[41] M. Van Den Hoven, P. De Jong, C. Borst, M. Mulder, and M. M. Van Paassen. Investigation of Energy Management during Approach: Evaluating the total energy-based perspective flight-path display. In *Guidance, Navigation and Control, AIAA Conference*, Toronto, Ontario, 2010. AIAA.

[42] L. A. Temme, D. L. Still, and M. Acromite. OZ: A Human-Centered Computing Cockpit Display. *Annual Conference of the International Military Testing Association*, (November 2003):70–90, 2003.

[43] C. F. Smith and S. Fadden. Use of a functional aviation display under varying workload conditions. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, pages 59–63, 2005.

[44] C. F. Smith. Using Displays to Improve Training: Functional Aviation Displays Improve Novice Piloting Knowledge. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 51(25):1583–1587, 2007.

[45] C. F. Smith. *The effect of functional display information on the acquisition and transfer of novice piloting knowledge.* PhD thesis, George Mason University, 2008.

[46] P. Rijneveld, C. Borst, M. Mulder, and M. M. Van Paassen. Towards Integrating Traffic and Terrain Constraints. In *AIAA Guidance, Navigation, and Control Conference*, Toronto, Ontario, 2010.

[47] F. M. Heylen, S. B. J. van Dam, M. Mulder, and M. M. van Paassen. Design and Evaluation of a Co-planar Separation Assistance Display. *AIAA Guidance, Navigation and Control Conference and Exhibit*, pages 1–6, 2013.

[48] H. C. H. Suijkerbuijk, C. Borst, M. Mulder, and M. M. Van Paassen. Development and Experimental Evaluation of a Performance Based Vertical Situation Display. *AIAA Guidance, Navigation and Control Conference and Exhibit*, pages 1–23, 2005.

[49] K. A. Ackerman, B. D. Seefeldt, E. Xargay, D. A. Talleur, R. S. Carbonari, A. Kirlik, N. Hovakimyan, A. C. Trujillo, C. M. Belcastro, and I. M. Gregory. Flight Envelope Information-Augmented Display for Enhanced Pilot Situation Awareness. *AIAA SciTech*, (January):1–16, 2015.

[50] N. Kasdaglis, T. Bernard, L. Stephane, and G. A. Boy. Affordant Guidance for In-Flight Loss of Control : The Trajectory Recovery System (TRS). In *Human Computer Interaction International Conference Proceedings*, number September, Toronto, Ontario, 2016.

[51] K. J. Vicente. *Cognitive Work Analysis - Toward Safe, Productive, and Healthy Computer-Based Work.* Lawrence Erlbaum Associates, Mahwah, New Jersey, 1 edition, 1999.

[52] European Aviation Safety Agency. Type-Certificate Data Sheet. Technical report, EASA, 2009.

[53] Faculty Control and Simulation. CitAST Citation 500 model, 2004.

[54] Faculty Control and Simulation. SIMONAimage. http://cs.lr.tudelft.nl, accessed 16-03-2017.

[55] F. R. H. Zijlstra and L. Van Doorn. *The Construction of a scale to measure perceived effort.* Delft University of Technology, Delft, 1985.

Part III

Appendices

(Not graded yet)

Appendix A

Experiment Briefing

A.1 Background

This experiment, conducted as part of a MSc thesis, researches the field of display design. The goal of this experiment is to evaluate and compare two variations of a flight display with each other. This comparison is done by asking licensed pilots to fly flight maneuvers with both displays in a fixed-base flight simulator.

A.2 Simulator Setup

The experiment will be conducted in the Human Machine Interface (HMI)-lab, where a fixed-base flight simulator is loaded with a model of the Cessna Citation II. The simulation is controlled by a hydraulic side stick with trim switch, a thrust throttle, a flaps switch and a gear handle. The simulation is fixed in the vertical plane, which means that rolling and yawing inputs are disabled during the simulation.

Two displays are shown during the simulation: a Primary Flight Display (PFD) and a Vertical Situation Display (VSD). The PFD, which is modeled as the top half of a Garmin G1000, is simply to support the pilot flying and is not modified during the course of the experiment. Two versions of the VSD are used, appropriately named the VSD-1 and the VSD-2. Both versions will be used by each pilot.

A.2.1 Primary Flight Display

The center of the PFD shows the current aircraft attitude ① and flight path vector ② with regards to an artificial horizon. On the left the speed tape shows the current calibrated airspeed ③. The target airspeed for the next checkpoint in the flight plan is shown at the top of the speed tape ④, as well as marked with a magenta indicator on the strip itself ⑤. An indicator shows the velocity for steepest climb ⑥.

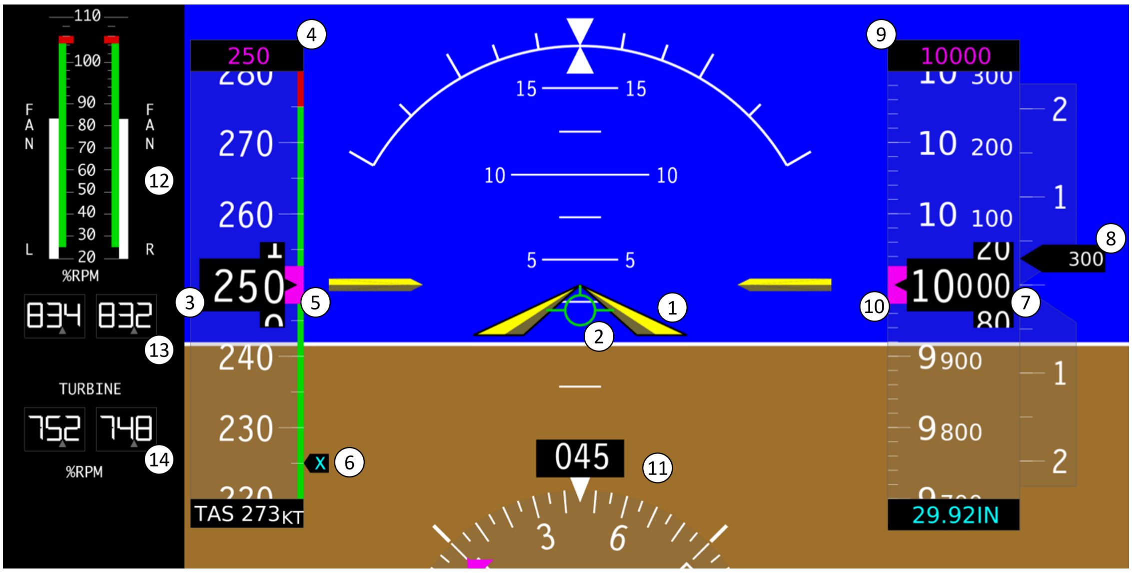


Figure A.1: Primary Flight Display

To the right of the attitude indicator the altitude tape shows the current altitude in feet ⑦ as well as the climb/descent rate ⑧. As on the speed strip, the next target altitude is shown at the top ⑨, as well as indicated with a magenta mark ⑩.

To the bottom of the PFD shows a compass rose ⑪. As the simulation takes place in a vertical plane, the rose will always be correctly aligned. Finally, the left of the screen shows the engine status. Fan RPM is shown in both bar ⑫ and number ⑬ formats, below which the turbine RPM is shown ⑭.

A.2.2 Vertical Situation Display

The VSD, as the name suggests, shows the vertical plane in which the aircraft is flying. Two versions of this display are used in the experiment: VSD-1 and VSD-2. First the elements of the VSD-1 are explained, after which the additional elements of the VSD-2 are elaborated upon. During the experiment, these displays might be presented to you in reverse order.

VSD - Version 1

The controlled aircraft is shown in yellow on the left side of the VSD ①. From the aircraft a velocity vector ② indicates the speed and direction which the aircraft is travelling in. The vertical component of the speed can be read as the ROC on the right axis ③, the horizontal component is read as the velocity on the upper axis ④.

The current ROC and velocity are indicated by yellow arrows. The velocity axis also contains red strips ⑤, which indicate the minimum and maximum design velocities of the aircraft. These limits shift according to the configuration of flaps and gear.

The left of the VSD shows the altitude of the aircraft on an altitude strip ⑥. The altitude of the next waypoint is, as on the PFD, shown with a magenta mark ⑦. The altitude

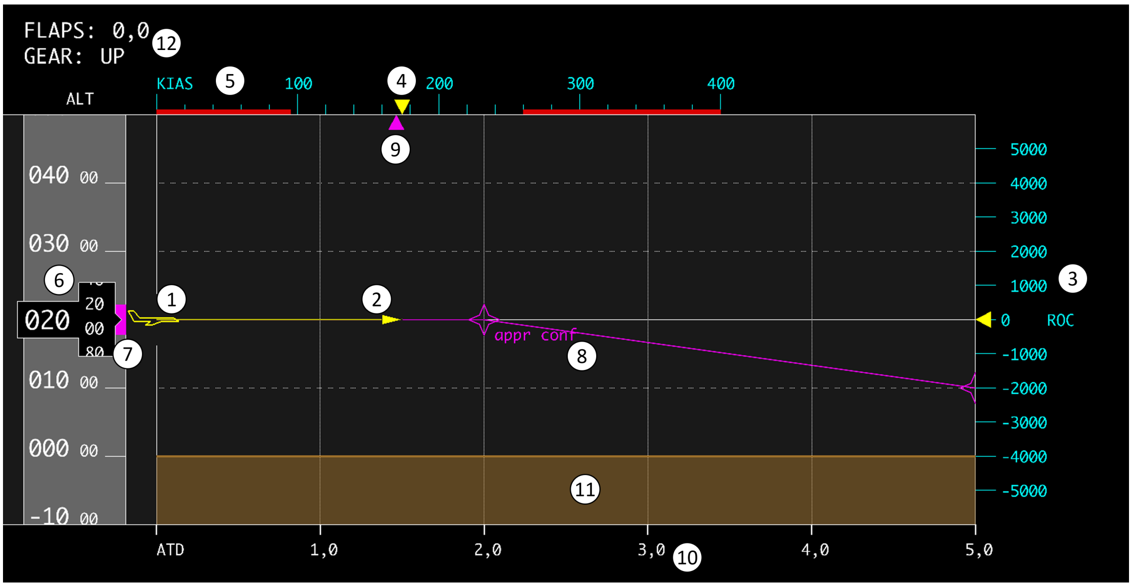


Figure A.2: Vertical Situation Display - version 1

corresponds to the altitude at which the next waypoint is projected in the flight plan ⑧. The velocity for the next waypoint is shown by a magenta indicator on the upper speed tape ⑨.

The bottom of the display shows the along-track distance ⑩, indicating how far away certain obstacles and waypoints are. The VSD contains a height profile of the terrain ⑪, which in this case is a flat plain. At the top of the display the current flap deflection and gear status are indicated ⑫.

VSD - Version 2

The second version of the VSD, the VSD-2, contains multiple additional elements compared to the VSD-1. The main inclusion is that of the flight envelope, shown in cyan ①. This envelope shows what the steady limits of the flight path vector are. It will shift according to changes in configuration, leaving behind a grey copy of the clean-configured envelope.

When the flap angle is adjusted, the shift which the envelope makes can be predicted by the dotted lines. The maximum speeds ② and stall speeds ③ are shown for flaps 15° and flaps 40° in purple and white respectively. Below the envelope a cyan dotted line marks where the envelope will drop to when the gear is deployed ④.

Within the envelope, a section at low velocities is colored orange to represent the Final Approach Speed ⑤, which can vary depending on the amount of turbulence present. A green dot on the cyan flight envelope corresponds to the maximum climb angle, for which the required velocity is shown on the airspeed strip as a green arrow ⑥.

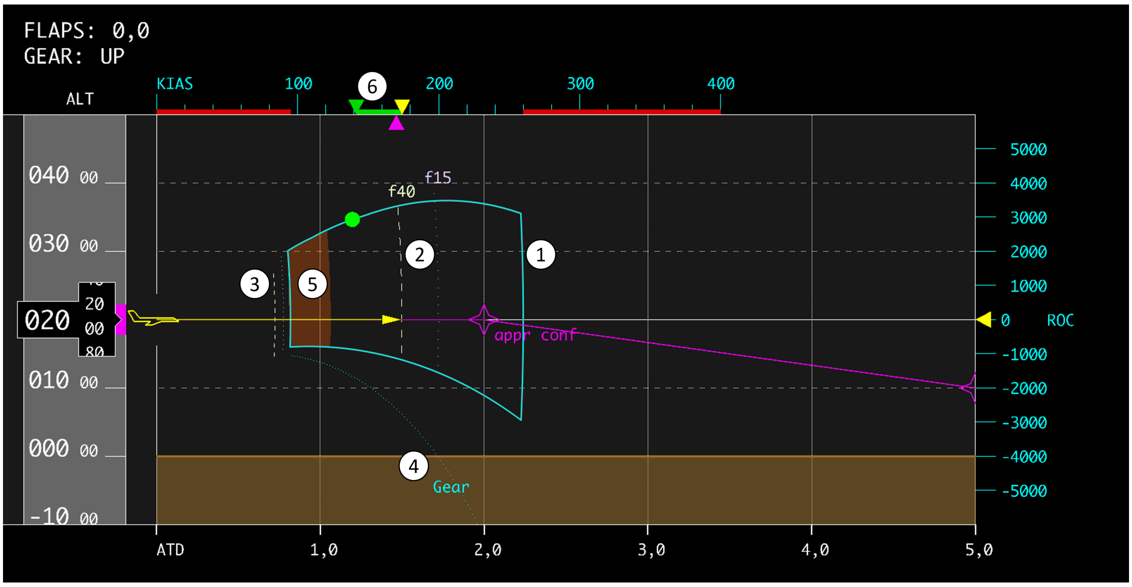


Figure A.3: Vertical Situation Display - version 2

A.3 Experiment

To test the effect of the additional cues on the VSD-2, an experiment is done in which pilots fly approach and go-around scenarios under various levels of turbulence intensity. After a briefing and training runs, two set of five measurement runs are done, one with each variation on the VSD.

Throughout the experiment pilots are asked to provide feedback regarding their workload and perceived safety. When the experiment comes to an end, pilots will be asked to provide feedback through a questionnaire.

A.3.1 Pilot Goals

As pilots are flying an approach and go-around, they have a set of objectives. In decreasing order of importance, these are:

1. Fly an approach & go-around that feels safe
2. Track the altitude and speed goals as indicated on the VSD/PFD
3. Follow the magenta flight profile in between the waypoints
4. Think out loud as you are controlling the aircraft

A.3.2 Approach and Go-around

The approach and go-around maneuver has a standard procedure, which will be explained in the briefing and practiced in the training runs. Deviations from the standard procedure are allowed when the pilot feels that a safer option is available under his/her circumstances.

A.3.3 Procedure

The experiment will start with a briefing phase in which the main outline of the experiment is stated, as well as an explanation of the first of the two displays which will be used. After training and measurement runs, a break is offered to the pilot.

After the break, a second briefing is held. As the experiment outline has not changed, this briefing is only to inform the pilot about the second display. Fewer training runs will be held since the pilot is familiar with the mechanics of the aircraft. After the second set of measurements is done, the pilot will be asked to comment on the experience flying with both displays.

10 min	Briefing	
30 min	Training	Display 1
20 min	Measurements	
20 min	Break	
5 min	Briefing	
20 min	Training	Display 2
30 min	Measurements	
15 min	Questionnaire and debriefing	

Appendix B

Experiment Execution Procedure

This document was created to ensure uniformity in the way the experiment is executed. The experiment procedure is standardized in an attempt to minimize the possibility of confounds entering the experiment, to ensure a professional and smooth experience for participating pilots and to reduce researcher workload. Slight deviations from the execution procedure have occurred (such as a small brake due to the hydraulic sidestick failing), but no mayor changes have taken place.

Week Before the Experiment

- Send briefing document to pilot
- Reserve HMI-Lab, staring 1 hour before pilot arrival
- Reserve Meeting Room 3, starting 1 hour before pilot arrival

Hour Before the Experiment

- Run experiment multiple times to warm up sidestick
- Set up presentation in Meeting Room 3
- Prepare participation form for pilot
- Ensure documents as 'Experiment Schedule, 'Questionnaire and this document are hidden
- Ensure briefing powerpoint slides are in correct order corresponding to participant display order

Pilot Arrival

- Bring to meeting room

- Offer a drink (water, tea or coffee)
- Take note of: flight experience (hours), aircraft type
- Go through briefing

Training Runs

- “Due to calibration, please dont touch sidestick until Are you ready? question.”
- “Sidestick pump might malfunction; we must restart software and redo current run.”
- Load first training scenario
- Procedures every run:
  - Stand next to pilot, explain scenario and new controls
  - Notify pilot of possible change in turbulence
  - “Flight controls matched?”
  - “Are you ready? → Answer → 3 2 1 go”
  - After last checkpoint → Hold & “Pause”
  - “How did it go?”
  - Short, verbal feedback on performance
  - Set up new run (Select and load new scenario, change turbulence level as training scenario requires)

Experiment Runs

- “I will now also record the audio in this room”
- Place workload rating scale
- “After run, I will ask you to verbally tell what your Workload and Subjective Risk scores are.”
- “Oh yes, sometimes the aircraft can show signs of failure. In these cases, the task of a safe approach & go-around will remain the same.”
- Set correct subject no. and press ‘Start
- Procedures every run:
  - Check turbulence
  - Check failures on/off
  - “Flight controls matched?”
  - “Ready?” → Answer → 3 2 1 go”
  - After last checkpoint → Hold & “Pause”
  - “Workload and Risk rating?”
  - If necessary: short, verbal feedback on performance
  - Press ‘success
  - Press ‘next

- When a failure occurs:
  - If pilot asks nothing → dont react
  - If pilot asks/reacts → "Yes, it is part of the experiment"

After first set

- Pause recording
- Take workload rating scale
- Check pilot physical and mental health
- Offer break (not mandatory, but recommended)
- After break do quick second part of briefing on second display
- Execute second set similar to first set, except exclusion of one or two of the earlier training scenarios

Debrief & Questionnaire

- Instruct to put one mark on each axis
- "After you have finished questionnaire, we will discuss questions and open-format feedback."
- Make sure to ask:
  - What was general impression?
  - What was most useful feature?
  - How can display be improved?
- Share goal of research, and what part of the data will be analyzed
- Give participation gift

Appendix C

Experiment Consent Form

Informed consent for participation

I volunteer to participate in a research project conducted by Alexander van Geel from Delft University of Technology. I understand that the project is designed to gather information about academic work of the faculty of Aerospace Engineering. I will be one of the 16 participants in this research.

1. My participation is voluntary. I may withdraw and discontinue participation at any time without penalty and without having to offer any reason.
2. Participation involves being subject of a fixed-base flight simulator experiment. The experiment is divided into two parts for two different displays, each lasting up to one and a half hours. A thirty-minute break is included in between the two parts, and additional fifteen-minute breaks can be included as requested within smaller sections of the experiment.
3. No details that can identify me as an individual will be used during the remainder of the research project.
4. Audio will be recorded as part of the data collected. This audio will be saved anonymously and will strictly be used for purposes of this research.
5. I have read and understand the explanation provided, had all my questions answered to my satisfaction and voluntarily agree to participate in this study.
6. I have been given a copy of this consent form.

Participant name ____________________ Participant Signature ____________________

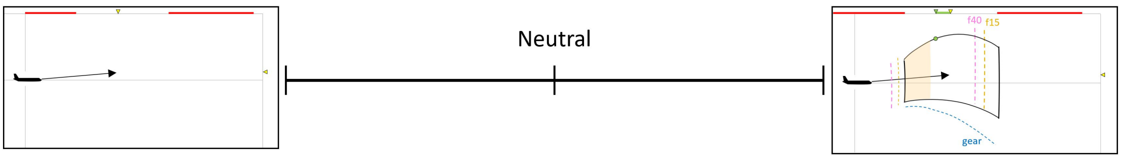
Date ____________________ Researcher Signature ____________________

Researcher: A. F. van Geel (A.F.vanGeel@student.tudelft.nl)
Supervisor: Dr. ir. C. Borst (C.Borst@tudelft.nl)

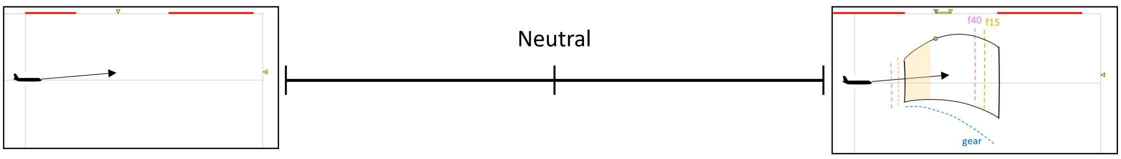
Appendix D

Experiment Questionnaire

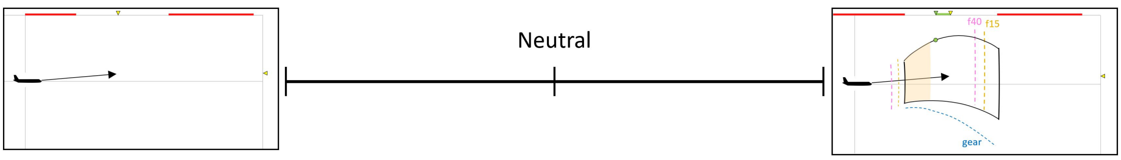
Which display was most difficult to work with?



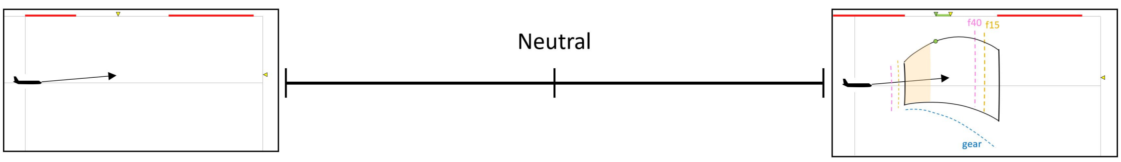
Which display reduced my workload the most?



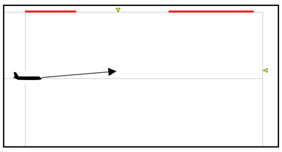
Which display was most useful for failure detection?



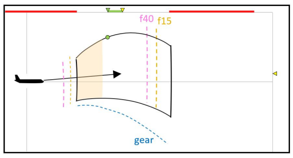
Which display was most useful for failure diagnosis?



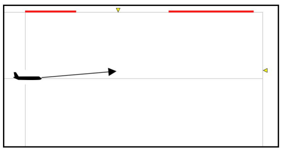
Which display best supported me in achieving altitude/velocity goals?



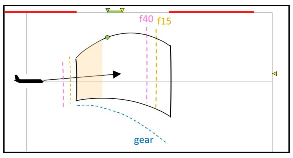
Neutral



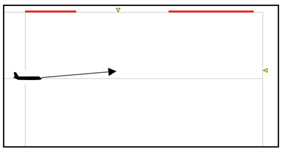
Which display best supported me in flying safely?



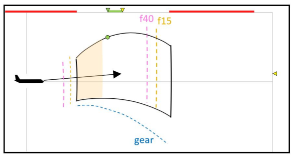
Neutral



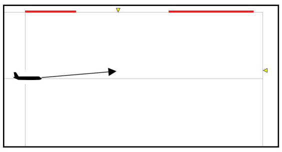
Which display best allowed me to react to unforeseen circumstances?



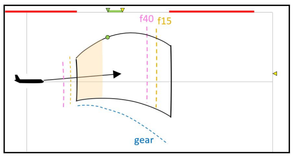
Neutral



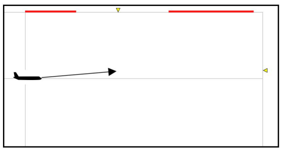
Which display required the most attention to use?



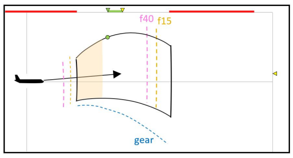
Neutral



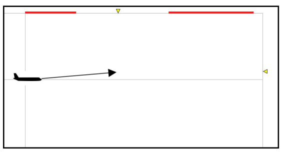
Which display best allowed me to predict dangerous situations?



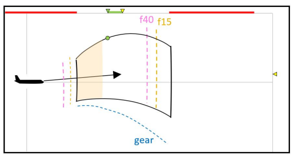
Neutral



Which display would have my personal preference to work with again?



Neutral



Appendix E

Experiment Design Overview

This section aims to give an overview of the experiment design, providing tables that list (in)dependent variables and the latin square matrix. These tables simply sum up information stated in the paper, no extra information has been added.

E.1 Overview Independent Variables

Table E.1 lists Independent Variables (IVs) and the values they could take on. Only two independent variables were chosen for this research as the group of participants was rather small, and a greater number of variables leads to less available data per variable.

Table E.1: Overview of Independent Variables

IV name	IV type	IV values
VSD Variant	Within subjects	Baseline VSD & Configuration VSD
Failure Order	Between subjects	Gear stuck first & Flaps stuck first

To balance the experiment the order of the displays was changed between participants. This also allowed for both types of failures to be tested on both displays, each combination of display and failure occurring 4 times across 16 participants.

E.2 Overview Dependent Measures

The experiment was done to compare the BVSD and CVSD on multiple measures, where each measure consists of multiple components. Table E.2 lists all dependent measures as discussed in the paper and the specific components that were used to draw a conclusion on each metric.

Table E.2: Overview of Dependent Measures

Performance

Height	Root Mean Squared Deviation	
Velocity	Root Mean Squared Deviation	

Safety

Envelope Excursions	Amount	
Velocity	Minimum	Time below V_{FAS}

Workload

Control activity	St Dev of input rate	
Subjective rating	Rating Scale Mental Effort	

Failure Scenarios

Detection	Amount detected	Detection time
Performance	Height & Velocity RMSD	
Safety	Excursions, minimum velocity & time below V_{FAS}	
Control strategy	Qualitative Analysis	

Subjective Feedback

Questionnaire	Question Boxplots	Principle Component Analysis
Pilot feedback	Qualitative Analysis	

E.3 Latin Square

Finally in this section, the latin square matrix created for the experiment design is shown in Table E.3. Two displays and two failures were used, combined with two display orders results in $2x2x2 = 8$ participants needed to fill the Latin square. As a total of 16 pilots participated, the entire square was run twice. In Table E.3, 'N' denotes a nominal Scenario, FF stands for for 'Failure → Flaps' and FG for 'Failure → Gear'. All letters include a subscript, which is the set of initial conditions (starting velocity and distance to runway) that were used. Initial conditions only varied slightly, and were placed at such a distance that pilots were easily able to prepare for approach where data collection started.

Table E.3: Latin Square Design for the Pilot-in-the-loop Experiment.

	Participant nr.	1	2	3	4	5	6	7	8
Set 1	Display	BVSD	CVSD	BVSD	CVSD	BVSD	CVSD	BVSD	CVSD
	Conditions	N_1	N_1	N_2	N_2	N_6	N_6	N_5	N_5
		N_5	N_5	N_6	N_6	N_3	N_3	N_3	N_3
		FG_6	FG_6	N_4	N_4	FF_5	FF_5	N_6	N_6
		N_3	N_3	FG_1	FG_1	N_4	N_4	FF_2	FF_2
		N_4	N_4	N_3	N_3	N_2	N_2	N_1	N_1
Break									
Set 2	Display	CVSD	BVSD	CVSD	BVSD	CVSD	BVSD	CVSD	BVSD
	Conditions	N_6	N_6	N_6	N_6	N_2	N_2	N_1	N_1
		N_2	N_2	N_2	N_2	N_5	N_5	N_6	N_6
		N_5	N_5	FF_5	FF_5	N_4	N_4	FG_4	FG_4
		FF_3	FF_3	N_1	N_1	FG_3	FG_3	N_3	N_3
		N_1	N_1	N_4	N_4	N_1	N_1	N_5	N_5

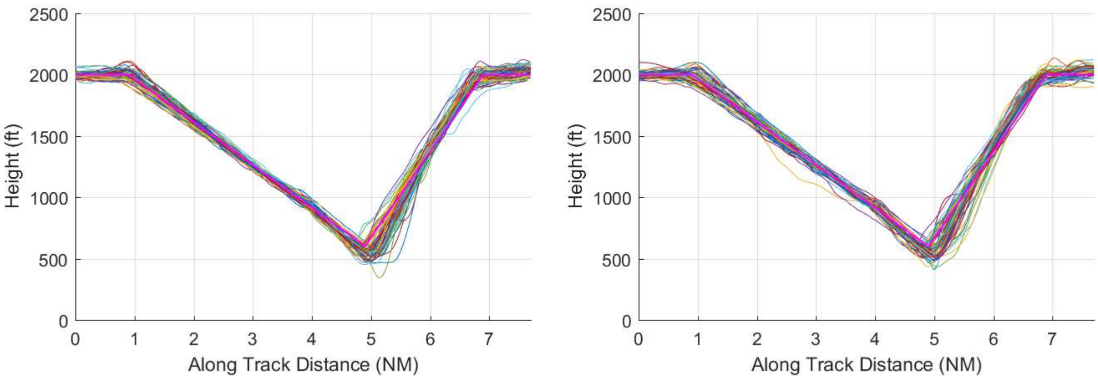
Appendix F

Detailed Experiment Data

This chapter provides additional visualizations of data gathered during the experiment, showing both raw data and more detailed metrics.

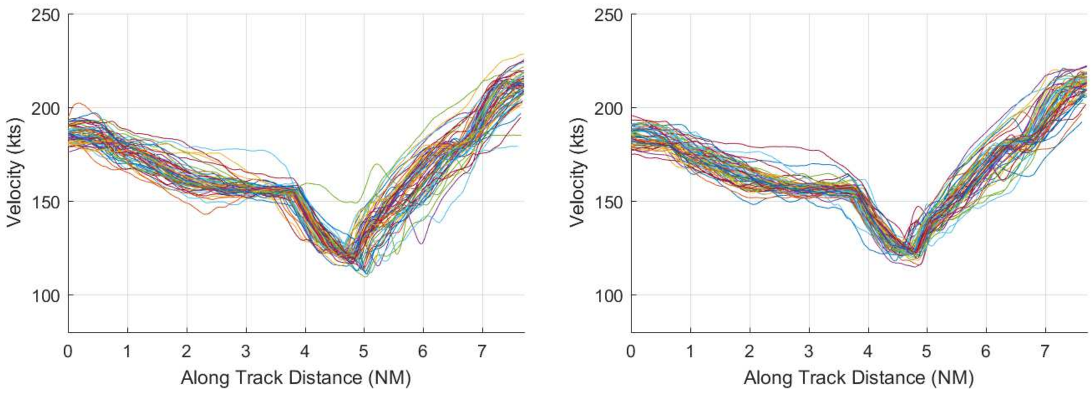
F.1 Raw Flight Data

The following figures contain time traces for altitude and velocity of all flights. This data can be used to confirm that no participants went far off track or out of bounds throughout their flight.



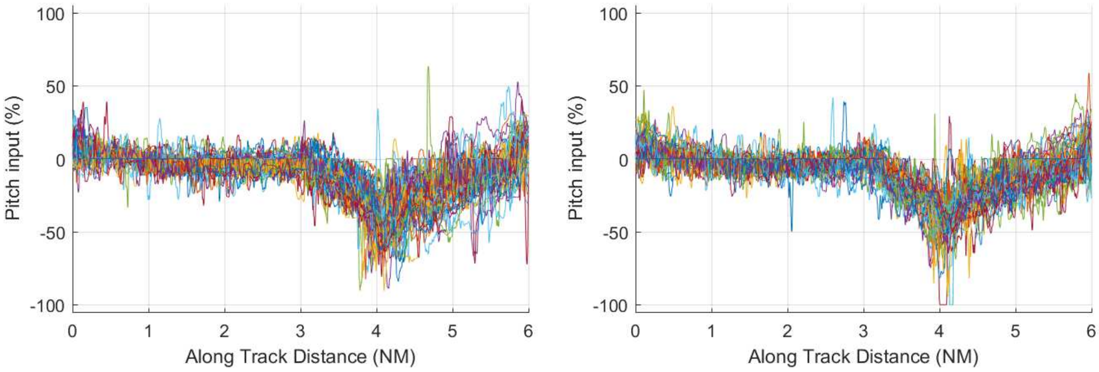
(a) (b)

Figure F.1: All Height Traces for Participants Using the BVSD (a) and CVSD (b)



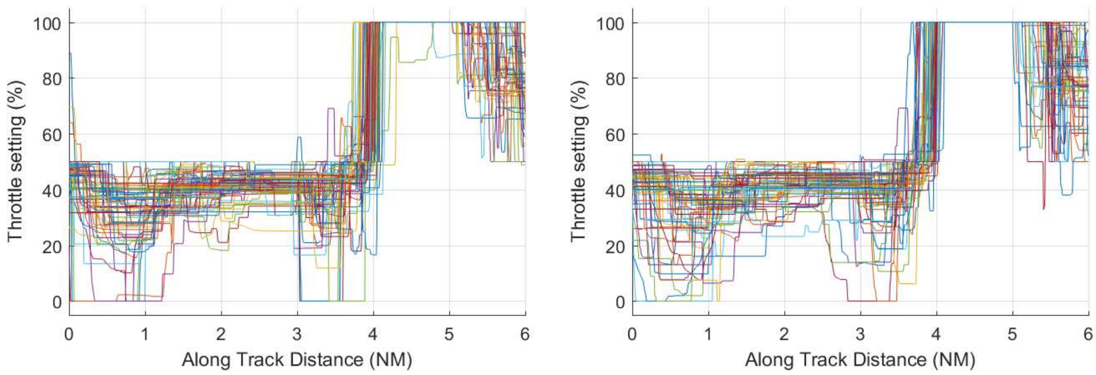
(a) (b)

Figure F.2: All Velocity Traces for Participants Using the BVSD (a) and CVSD (b)



(a) (b)

Figure F.3: All Pitch Input Traces for Participants Using the BVSD (a) and CVSD (b)



(a) (b)

Figure F.4: All Throttle Input Traces for Participants Using the BVSD (a) and CVSD (b)

F.2 Raw Performance, Safety and Workload Metrics

Performance metrics in the research paper are compiled of multiple individual scores obtained by pilots. The following figures show the scores pilots achieved with individual runs on each display, including the final average per pilot per display. Since the averages shown in figures in the main report are only for nominal runs, the following figures only include nominal run statistics. As mentioned in the report, failure runs follow the same trend as nominal runs.

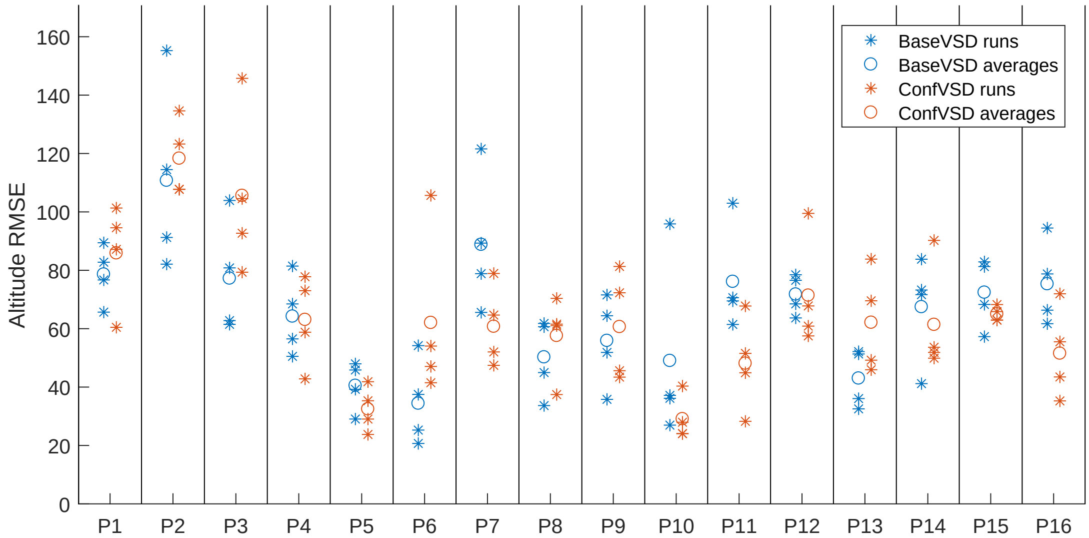


Figure F.5: Altitude RSME Scores Per Participant, Split by Display.

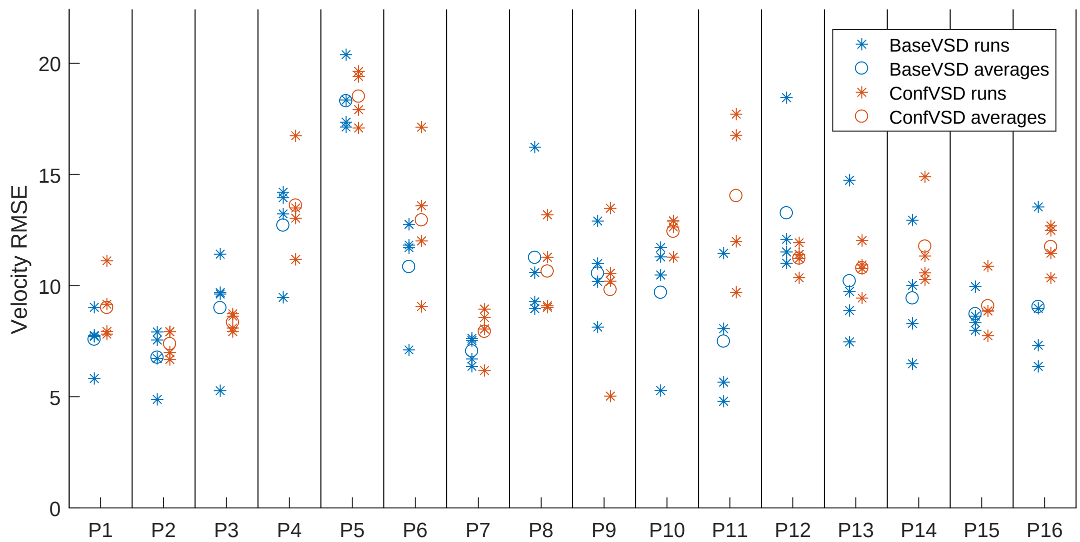


Figure F.6: Velocity RSME Scores Per Participant, Split by Display.

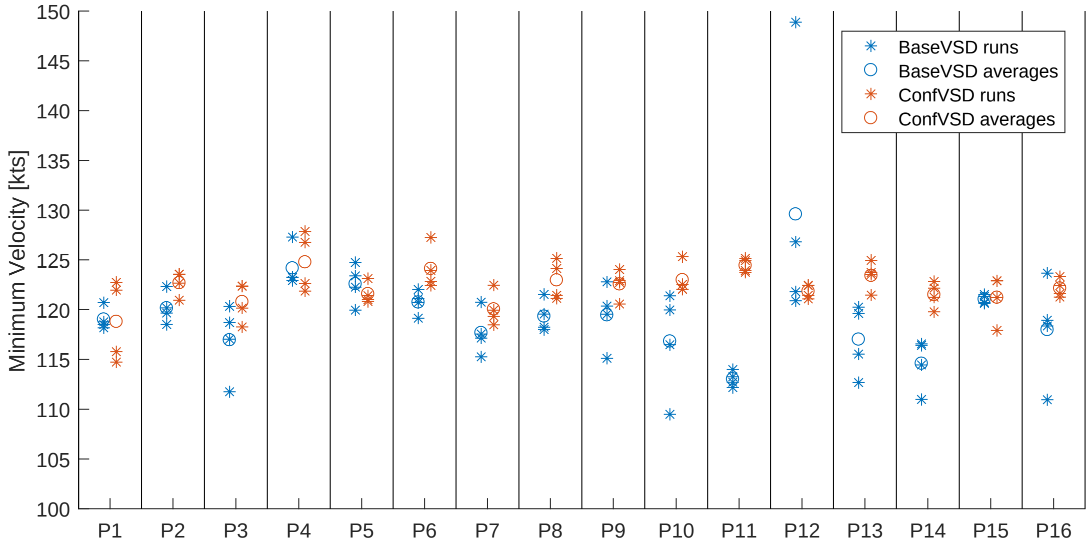


Figure F.7: Minimum Velocities Per Participant, Split by Display.

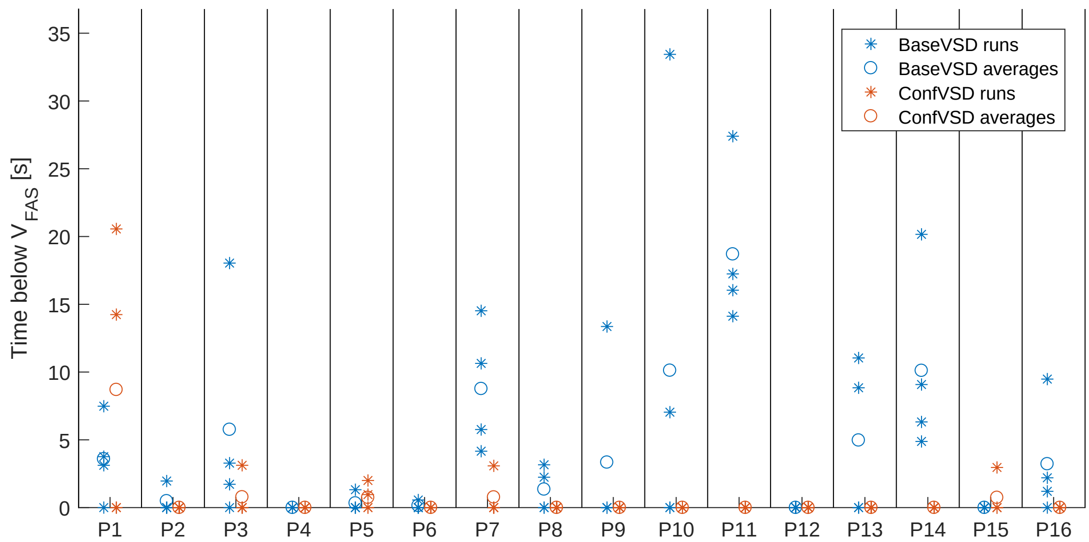


Figure F.8: Times Below FAS Per Participant, Split by Display.

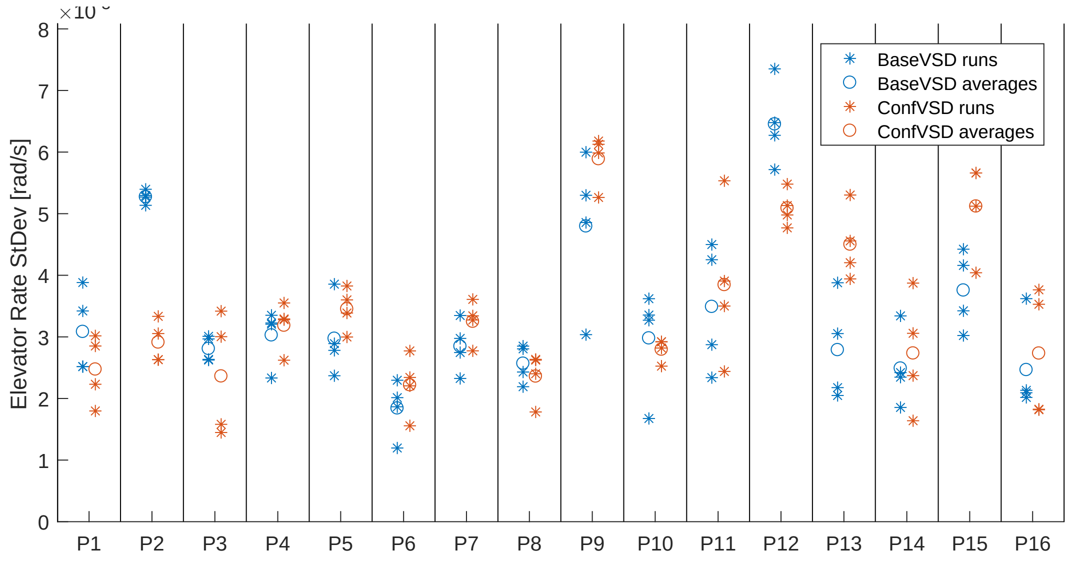


Figure F.9: Elevator Deflection Rate Standard Deviations Per Participant, Split by Display.

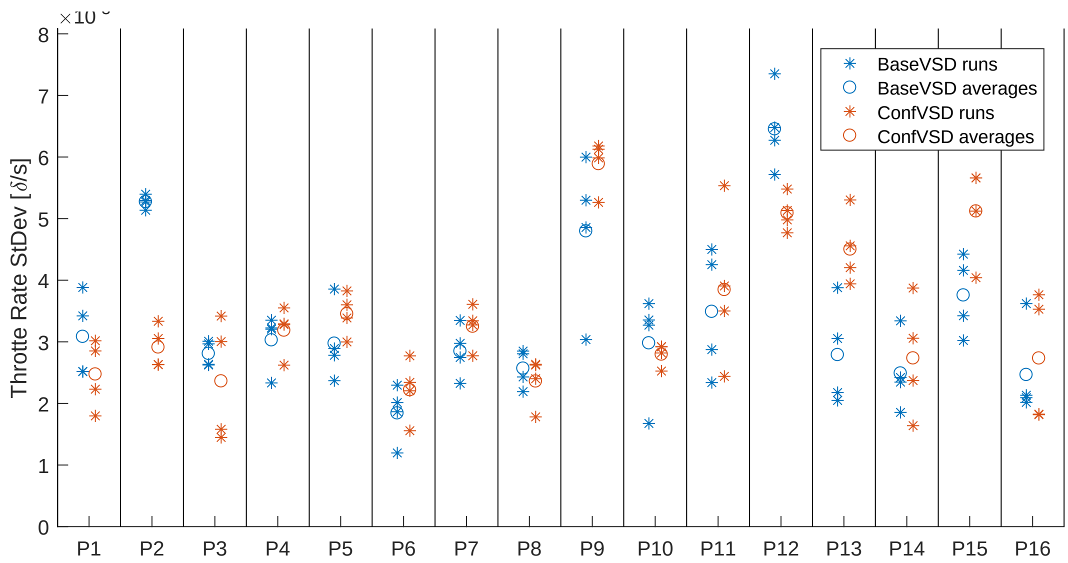


Figure F.10: Throttle Rate Standard Deviations Per Participant, Split by Display.

Appendix G

DUECA Simulation Structure

Shown below is the structure of the simulation software. The code is programmed in C++ with DUECA (Delft University Environment for Communication and Activation) as middleware layer. The code used was adopted from Jan Comans' DUECA project to simulate a Cessna Citation II with the IVSD. This can still be seen in some subcomponents named IVSD rather than ConfVSD (or CVSD), as it was found too error-prone to replace this name within over one hundred scripts.

The bold boxes in figure G.1 represent main modules of the simulation. Blue arrows are either files being read or continuous streams of data. Names of the most important data channels are written in blue by their arrow, arrows of which the purpose might be unclear are described in a few key words. Multiple less significant dependencies and data channels are not shown, as adding all dependencies would make the image too cluttered for practical use.

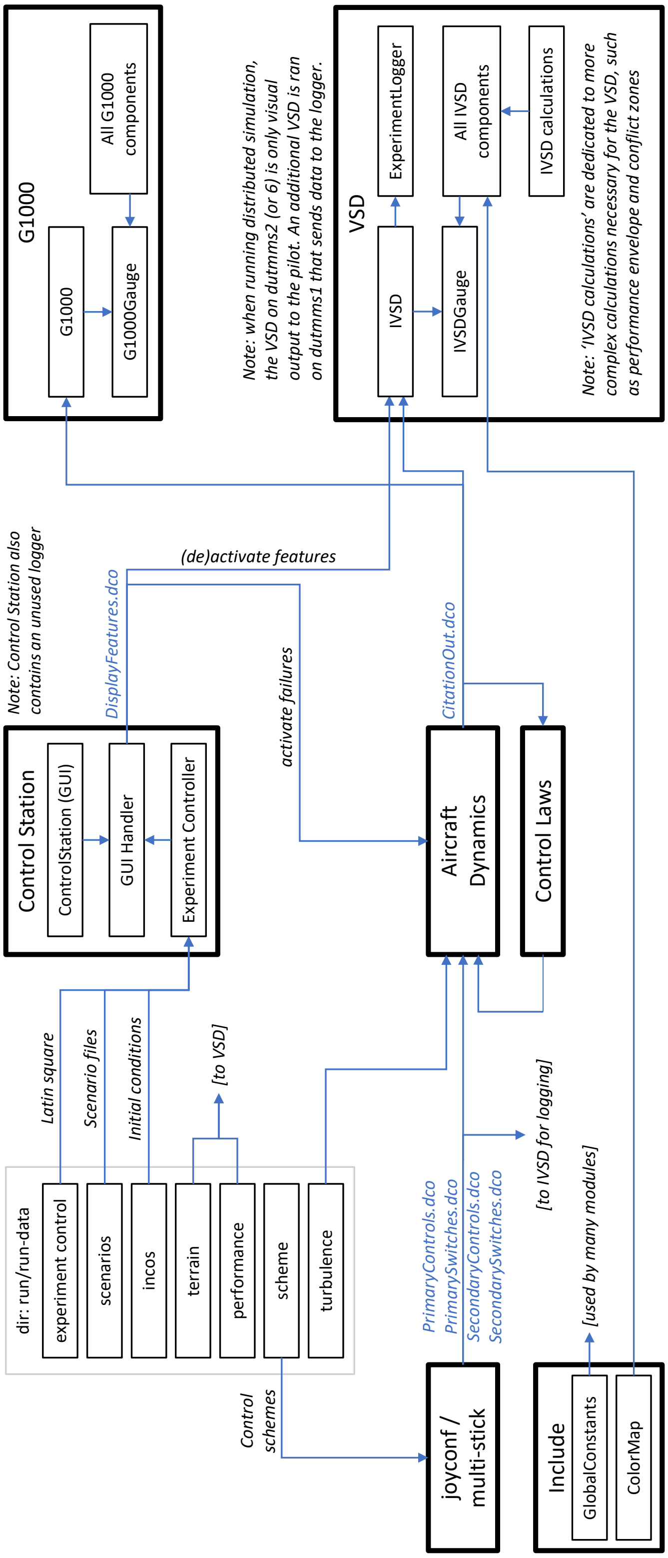


Figure G.1: Structure of the DUECA C++ Project for Simulation of the Cessna Citation II with VSD