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Design and Evaluation of Vertical Situation Display Reflecting Aircraft Configuration Changes

Alexander F. van Geel,* Clark Borst,† Marinus M. (René) van Paassen,‡ and Max Mulder§
Delft University of Technology, 2629 HS Delft, The Netherlands

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Energy management is essential in low-energy flight conditions. Changes in fixed-wing aircraft configuration affect performance and energy boundaries, 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 with enhancements portraying changes in the flight performance envelope. Sixteen pilots were tasked to fly approach and go-around scenarios with both a baseline and an enhanced display, with some of the scenarios including unexpected failures in configuration changes. 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. Failures in configuration changes were more quickly discovered with the new display, although these results could not be substantiated due to a lack of statistical significance. However, pilots did report feeling better able to predict dangerous situations. Overall, pilots preferred the novel display; no significant differences in workload were found.

I. Introduction

ALTHOUGH the past 50 years have seen a spectacular increase in flight safety, flying is still not free of risks. 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) [1–3]. Over three-quarters of LOC-I incidents were the result of flight outside the regular operational flight envelope, a condition better known as aircraft upset [4]. 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 occurring in low-energy flight phases such as takeoff and approach [5]. Managing failures at low-energy flight phases is critical, as shown for instance by the British Airways Flight 38 incident [6]; 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 Instrument Landing System (ILS) antenna.

To prevent pilots from leaving the safe flight envelope that may ultimately result in LOC and upset events that are difficult to escape from, research and industry strive for better pilot training [7–9] with improved simulator motion cueing [10]. In addition, improved pilot information systems that show pilots (elements of) the current flight envelope can be expected to improve their situation awareness and thus prevent pilots from crossing safe flight envelope boundaries. Indeed, many experimental displays, using either visual cues on the primary flight display or navigation display [11–16], or through haptic cues on the control manipulator [17–19], supported improvements in situation awareness. Common in these interfaces is that they present pilots with visual and/or haptic information on about how close the aircraft operates near the safe flight envelope. However, most of the reviewed display solutions do not yet make the impact of aircraft configuration changes on the flight envelope visually salient. Especially in the approach phase of flight, where aircraft are situated in a *low* and *slow* flight state, explicit insight into the location of envelope boundaries relative to the current flight state is expected to help pilots remain within the safe envelope and/or better anticipate (system) failure events that may ultimately lead to upset conditions.

This paper discusses the design and empirical evaluation of an augmented vertical situation display (VSD), called the "Configuration VSD" (CVSD), that portrays the impact of configuration changes (i.e., flaps and gear) on the aircraft vertical flight performance in low-energy approach conditions. This was tested by 16 licensed pilots and compared to a baseline VSD version without these enhancements [20]. The CVSD is the next evolution of the Intentional Vertical Situation Display (IVSD) by Comans et al. [21,22], based on the Experimental VSD (EVSD) by Rijneveld et al. [23], which in turn was based the preliminary ecological VSD designs presented by Suijkerbuijk et al. [24] and Heylen et al. [25]. These VSDs yielded positive results in terms of pilot situation awareness and insight into vertical maneuverability limits under nominal flight conditions in clean aircraft configurations. Similar to previous VSD designs, inspiration was taken from Ecological Interface Design (EID) [26,27] by putting the emphasis on portraying *boundaries* for operator actions instead of explicit action guidance signals (e.g., flight director). Such a constraint-based approach has shown promising results across a wide range of application domains within and outside of aviation [28–30].

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

II. Background

A. Safe Flight Envelopes

According to Upset Prevention and Recovery Training techniques and procedures, awareness of flight envelope limitations and recognizing situations where limits are likely to be crossed are of paramount importance [7,31–33]. Low-energy flight phases, such as takeoff and landing, rank highest in terms of risks in leaving the

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*M.Sc. Student, Section Control & Simulation; alexandervangeel@hotmail.com.

†Associate Professor, Section Control & Simulation; c.borst@tudelft.nl (Corresponding Author).

‡Associate Professor, Section Control & Simulation; m.m.vanpaassen@tudelft.nl. Senior Member AIAA.

§Professor, Section Control & Simulation; m.mulder@tudelft.nl. Associate Fellow AIAA.

safe envelope due to relatively small margins in speed and altitude [34–36]. Additionally, these flight phases often involve changing the aircraft configuration, thus altering its performance characteristics. Here, the altitude envelope (Fig. 1a) and the load-factor envelope (Fig. 1b) both describe aircraft maneuverability limitations in altitude and speed and thereby define operational constraints which pilots must respect.

1. Altitude Envelope

The altitude envelope in Fig. 1a shows the range of true airspeeds which can be achieved at each altitude, with the stall speed V_s as the lower bound. 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 operating Mach number M_{MO} or maximum operation speed V_{MO}. The design Mach number M_{DF} and speed V_{DF} are limits at which the aircraft is designed to remain controllable and to withstand particular loads. Changing configuration from clean will change the envelope limits. Extended flaps or gear decreases velocity limits, thus shifting the whole 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 [7]. The most dangerous region of the altitude envelope is that for low altitude and low airspeed (i.e., lower left side of the envelope in Fig. 1a), as the combination indicates a low total energy state [37]. Unintentionally approaching this region leaves pilots with reduced maneuverability, as there is often a considerable delay for adding total energy through additional thrust.

2. Load Factor Envelope

The load factor envelope in Fig. 1b, or *V-n* diagram, shows the interaction between load factor and equivalent airspeed. Use of equivalent airspeed allows for a single envelope rather than one for each altitude. The roof and floor of the V-n diagram in Fig. 1b correspond to the common structural limits of $+2.5$ g and -1 g, respectively, 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-hand 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 leftmost 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 allows it to gain airspeed again and move away from the envelope border. Note that this does not hold true for inverted flight conditions.

3. Portraying Flight Envelope Limitations

Displays that make envelope limitations visually salient, with the aim to make pilots aware of such limitations, is not new. It has been studied in the context of terrain collision avoidance [15,16], airborne separation assurance [38], in-flight four-dimensional (4D) trajectory management [39], total energy management during complex approaches [37], structural damage [14], and flight envelope protection systems [11–13]. Each context may require a different *coordinate system* to effectively communicate flight constraints. For example, flight phases that involve lateral maneuverability and/or reaching far-away navigation targets are best served with augmentations on a navigation display. Flight phases involving tracking a curved reference trajectory may best be served by augmentations on perspective primary flight displays.

In this paper, the focus is put on an approach path where the aircraft is already lined up with the runway. In this low-energy flight state, configuration changes in terms of extending flaps and gear may significantly impact the longitudinal maneuverability of an aircraft, requiring pilots to more accurately perceive distances between current (and predicted) flight states relative to envelope boundaries. Coplanar projections are often more suited for these purposes than perspective displays due to ambiguities in the perception of spatial relationships [40]. As such, a VSD has been chosen as a promising candidate for this study.

B. Review of Earlier VSD Enhancements

1. Visualizing Flight Envelope

The basis for the CVSD design evaluated here is the flight envelope, which shows maneuverability space in the vertical plane. The envelope encompasses all steady-state velocities that can be achieved with a certain aircraft configuration. The current position within the flight envelope is shown by the (tip of the) aircraft velocity vector. The angle this vector makes with respect to the horizontal corresponds to the flight-path vector, and 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, illustrated in Fig. 2. The steepest possible climb V_X is indicated by a green dot. In some aircraft, such as the Boeing 737 and 787, VSDs are used to display terrain height and issue ground proximity warnings [41]. To integrate the performance envelope with a terrain database, the envelope is expressed in distances by multiplying all velocities with a certain look-ahead time. For example, a look-ahead time of 60 s will result in an envelope of all locations that can be reached in 1 min with a constant steady-state velocity. If any wind is present, the envelope can be shifted as a whole to account for the effects wind has on ground speed.

Note, energy management considerations will vary in turns involving nonnegligible bank angles which change both load factor and drag. This will impact the shape of the vertical flight envelope.

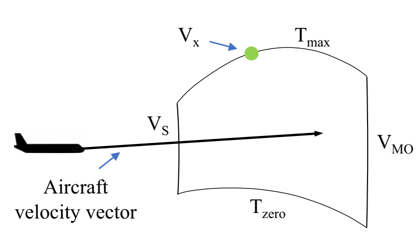

Fig. 2 The vertical speed performance envelope. Reprinted from Ref. [23] (copyright 2010 Delft University of Technology).

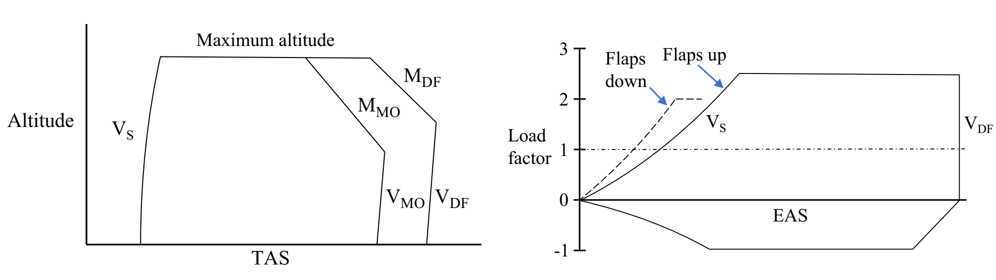

Fig. 1 a) generic altitude and b) load factor envelopes; see the text for descriptions.

Given the scope of this study, however, turns were not taken into account in the visualization of the envelope.

2. Experimental VSD

Rijneveld et al. [23] have added cues to the VSD for purposes of traffic and terrain avoidance in nominal, high-energy flight conditions in clean configurations. 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 Fig. 3. The upper axis shows the horizontal component of the velocity in knots indicated airspeed (KIAS), and 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 axis, and the left vertical axis shows altitude in feet. As an additional cue, the excess kinetic energy ΔV (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 ΔH, 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 [23]. Although performance did not improve, pilots reported 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 felt 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. Intentional VSD

The IVSD by Comans [22] is an adaptation of the EVSD where constraints are split into two types: causal and intentional. Causal constraints are determined by *physical* limitations to operation, such as 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 *intentional* 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. Because 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 eight novices and eight licensed pilots showed no significant effect on safety or performance compared to the EVSD [22]. The IVSD did reduce the variance in altitude and speed tracking performance, suggesting that adding intentional constraint information makes pilots more aware of the aircraft situation relative to the safety boundaries, thus leading to more fine-tuned and consistent control strategies across participants. 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 experiments by Rijneveld et al. [23] and by Comans [22] used scenarios flown exclusively in clean configuration, which means the flight envelope only varied in shape with altitude. Aircraft configuration, however, has a significant 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 paper.

III. Configuration VSD

A. Visualizing Configuration in Performance Envelope

Changing aircraft configuration alters performance characteristics, which can be visualized using the flight envelope discussed in Sec. II.B. The flight envelope, however, is only able to reflect what velocities can be maintained with the current configuration. As an ecological display should show the entire space of possibilities, additional cues are added to give insight into what would happen when the flap and/or gear states are altered. This envelope is shown in Fig. 4, in which dashed lines represent the outlines of the flight envelope in case flap and/or gear is extended, thus providing a preview of the vertical flight envelopes corresponding to specific configurations. Note that the data used to render the flight envelopes in Fig. 4 have been retrieved from measurements (and a mathematical model) of a Cessna Citation II, owned and operated by Delft University of Technology and Netherlands Aerospace Centre. It is expected that aircraft manufacturers and modern flight management systems have similar data and models available for rendering such envelopes.

The most prominent features of the visualization are the current velocity vector and current flight envelope. The velocity arrow must point inside the lines to be flying within the 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 semi-transparent orange area on the left-hand side.

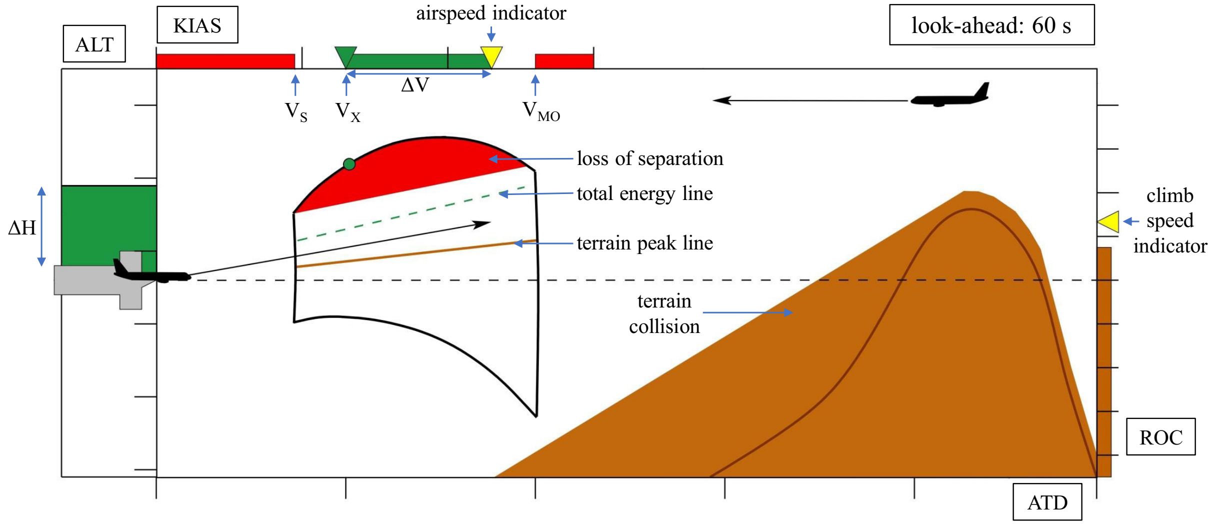

Fig. 3 Layout of the EVSD; see the text for descriptions. Reprinted from Ref. [23] (copyright 2010 Delft University of Technology).

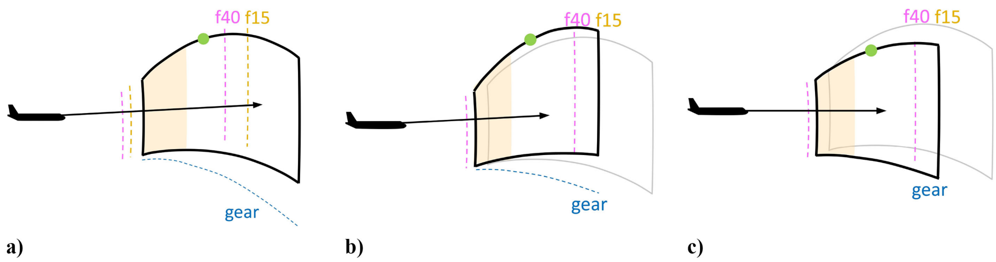

Fig. 4 CVSD performance envelopes with a) clean configuration; b) flaps 15, gear up; and c) flaps 15, gear down.

To keep the velocity arrow inside the envelope, both the aircraft velocity 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 trained and skilled in such basic aircraft handling, no additional cues are dedicated to this type of 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. Lines corresponding to each configuration change are distinguishable by a unique 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 decreases stall and maximum operating speeds. This causes the flight envelope from Fig. 4a to shift left toward lower speeds and slightly up toward higher rates of climb in Fig. 4b. Lowering the gear greatly increases drag, causing the envelope to *drop* in Fig. 4c. Because 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

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

in which the correction factor (CF) depends on aircraft type and environmental conditions. For the Cessna Citation II, the model that will be used in the experiment, the CF ranges from 0 to 20 kt.

B. Integration with VSD Design

As the current display and experiment do not concern terrain avoidance, the EVSD terrain peak line is removed for the CVSD. The total energy cues are also removed because their appearance similar to the newly added configuration cues might be confusing. The CVSD shown in Fig. 5 includes all other features from the EVSD and IVSD. The performance envelope ① is updated as explained in Sec. III.A and responds to flap and gear sensor outputs instead of pilot inputs. This would facilitate the identification of possible failures in configuration changes, for example, when pilots command a certain flap setting, but the flaps do not deploy or are stuck in a certain configuration, resulting in an envelope that does not change according to what should be expected.

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, respectively.

The envelope 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 the speed limits for the current configuration. Finally, a direct readout for the current flap angle and gear status is included ⑧.

IV. Method

A. Goal

The CVSD was evaluated in a pilot-in-the-loop experiment. The goal of the experiment was to test the effectiveness of the CVSD in

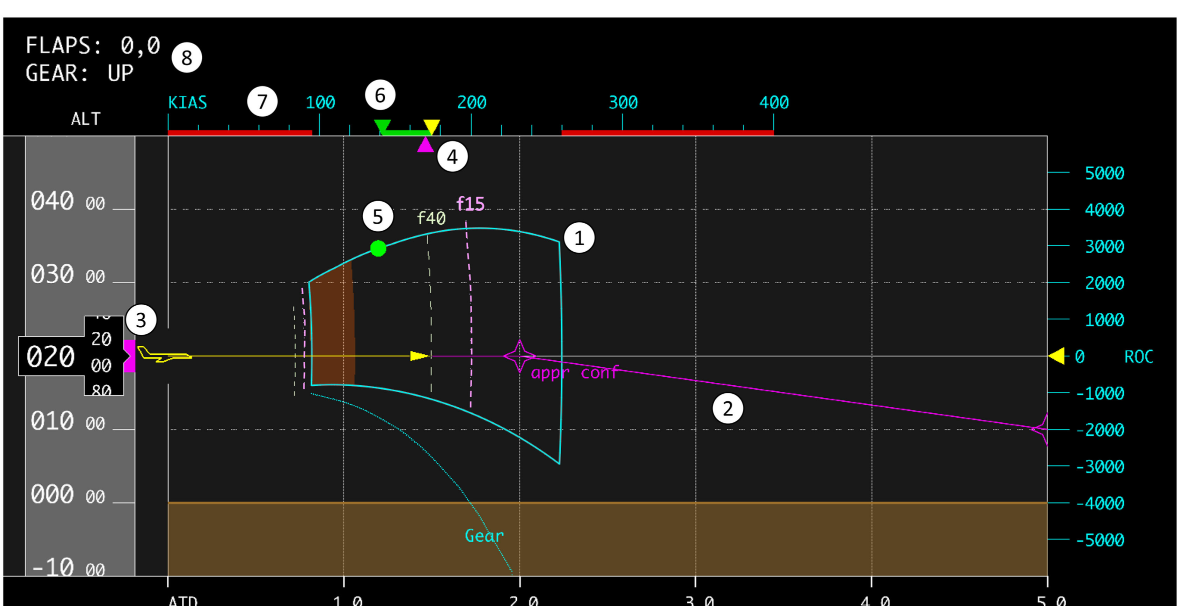

Fig. 5 CVSD elements 1–8; see the text for descriptions.

improving flight-technical performance (i.e., reference tracking), timely detecting configuration failures, and supporting adaptation to unforeseen circumstances when compared to a vaseline VSD (BVSD) that did not portray the velocity envelope.

B. Participants and Tasks

The experiment was approved by the Delft University of Technology Human Research Ethics Committee and involved 16 licensed pilots. Pilots were split in two groups, each composed of four Private Pilot License (PPL) pilots, three Commercial Pilot License (CPL) pilots, and one military pilot. The first group of eight pilots started by using the BVSD (average flight experience 2261 h, $SD = 3198$), and the second group of eight pilots started by using the CVSD (average flight experience 2003 h, $SD = 2588$). All types of licenses require training to perform basic low-energy flight maneuvers, so license type was assumed not to make a difference in performance. Participants had different levels of experience with glass cockpit displays, and therefore they were expected to be able to provide a wide range of feedback after the experiment. All six CPL pilots were familiar with a VSD, but they did not actively use it during line operations.

The participants' task was to fly an approach scenario as best they could in terms of following the spatial approach trajectory and adhering to a predefined flap and speed schedule as indicated on the VSD.

C. Independent Variables

The experiment was set up as a within-participants, repeated-measures design, meaning that all participants completed all scenarios using both the CVSD and BVSD displays. The CVSD is described in Sec. III, and the BVSD is exactly the same, but without the velocity envelope (①) and configuration cues (⑤, ⑥). This version is shown in Fig. 6. The order of the displays was varied between the two pilot groups to balance learning and fatigue effects.

The experiment comprised two subexperiments: one concerning nominal operation and one concerning failure conditions. For both VSD variants, a set of five runs was flown, four of which were nominal runs and one containing a configuration failure. The failure occurred once as the third and once as the fourth run in a set. The configuration failures involved events where either the gear did not retract or the flaps were 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 eight times.

D. Apparatus

The experiment was conducted in a fixed-base flight simulator at Delft University of Technology. A nonlinear six degree of freedom model of a Cessna 550 Citation II was loaded on the simulator [42]. Throttle inputs were controlled by a thrust lever, and control surface inputs were given through a hydraulic side stick with trim buttons. As the approach trajectory did not involve turns, 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 aircraft configuration. International Standard Atmospheric conditions were used with zero wind, but all scenarios did include mild turbulence using a Dryden model [43] to increase the difficulty of the task.

E. 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 (Fig. 7). The PFD shows a pitch ladder and green flight-path vector over a virtual horizon. An altitude tape is shown on the right-hand side, and a velocity tape showing indicated airspeed is shown 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; see Fig. 7. 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-hand 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 (Fig. 5) and the BVSD (Fig. 6). 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, respectively. The current flight configuration can be read from cues such as the numerical readout, red V_S and $V_{\{\mathrm{MO}\}}$ indicator bars and the three green indicator lights on the control panel.

F. Scenario

Before starting the measurement runs, all participants flew multiple training runs. These have been designed to familiarize the pilot with the aircraft model dynamics, flight controls and flight display(s).

Participants were tasked to fly an approach and go-around procedure, as it allows combining multiple low-energy flight maneuvers in a single scenario involving configuration chances. An overview of the flight plan is shown in Fig. 8. The scenario consisted of a standard nonprecision approach using a 3° glideslope with a go-around at an

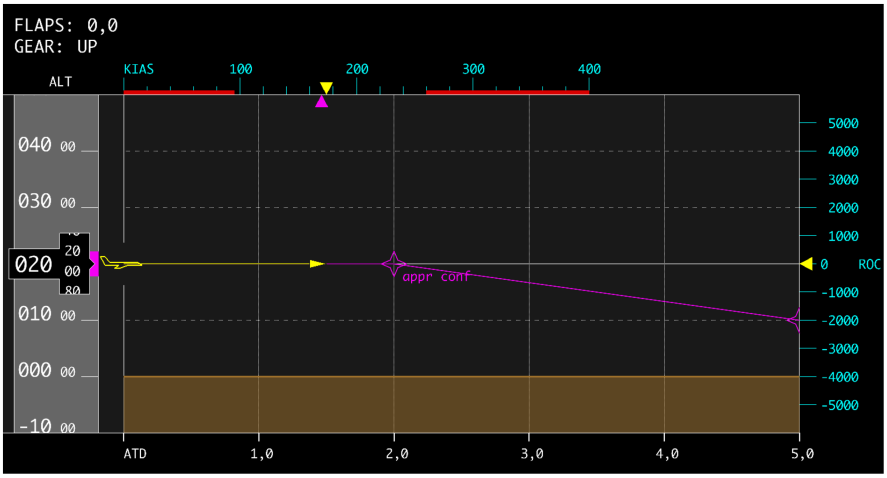

Fig. 6 Baseline VSD as used in the experiment.

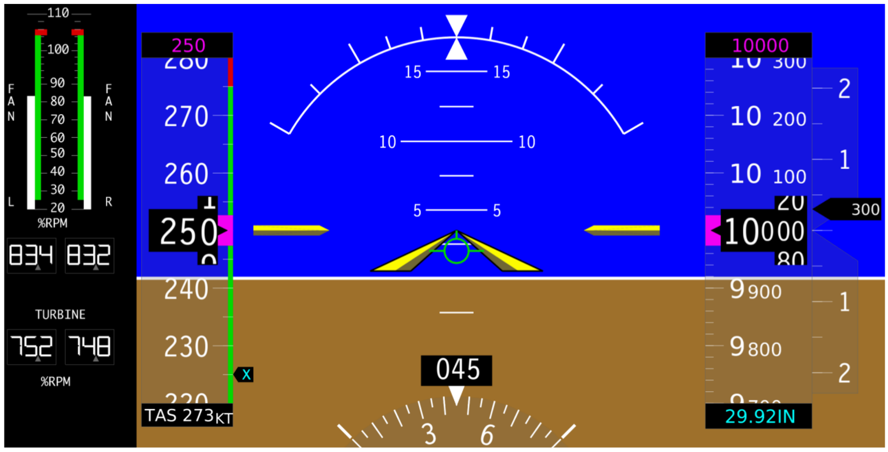

Fig. 7 PFD as used in the experiment.

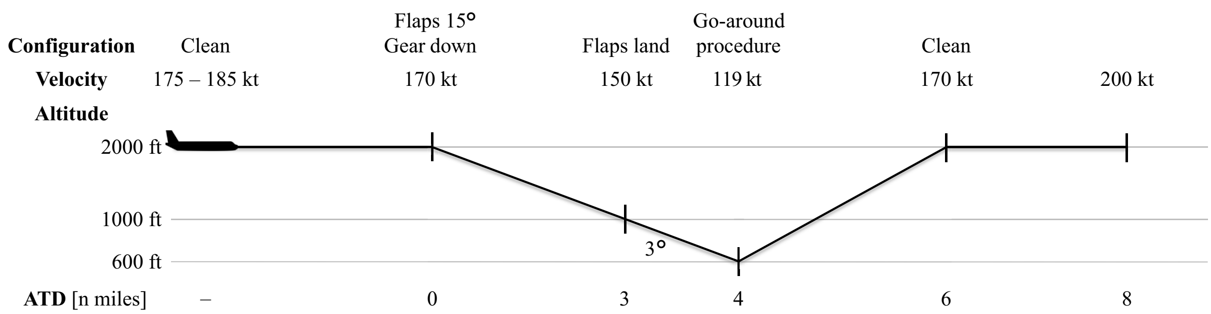

Fig. 8 Schematic representation of the flight profile in each experiment scenario.

altitude of 600 ft. The flight path and corresponding procedures were based on the Citation II Pilot Manual.

Each run started in trimmed condition with an indicated airspeed between 175 and 185 kt at a distance of 1 to 3 n miles from the top of descent. From this point, the participant had to follow the profile as closely as possible with intermittent transitions in target velocity and configuration. All transitions could be conducted within a range of conditions (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 halt the descent.
3) At $V_{\mathrm{REF}} + 5$ 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 the standard procedure if they thought it would be in the interest of safety.

G. 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 a fixed set of five 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 and flew the second set of runs with the other display to control for display order effects. This briefing and training runs were slightly shortened because the participant was already familiar with the flight controls, dynamics, and procedures. The experiment was concluded by a questionnaire and debriefing. The complete experiment procedure is shown in Table 1.

Table 1 Experiment procedure

Duration	Phase	
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 debriefing	

H. Dependent Measures

1. *Altitude and Speed Tracking Performance*

As the task was to follow the approach and go-around flight path as closely as possible, performance was measured in terms of accuracy with which altitude and velocity goals were met. This was measured as the root mean squared deviation (RSMD) of both altitude and velocity with regards to the reference flight path of Fig. 8.

Failure scenarios were analyzed separately from the nominal scenarios, as the different configuration failures could influence flight performance in various ways and also pilot responses to the failures may differ considerably.

2. *Adherence to Altitude and Speed Constraints*

Adherence to altitude and speed constraints was assessed by measuring the minimum in terms of both altitude and velocity obtained during a run. Additionally, the total time spent below the final approach speed $V_{\{FAS\}}$ was computed.

In scenarios where a failure occurs, measures included both whether it was detected and, in case of detection, how long it took to diagnose the failure. To obtain this information, pilots were requested to *think aloud* during the experiment, and timestamps could be deduced from the audio recordings.

3. Control Activity and Experienced Workload

Control activity was taken as an objective measure of workload. The variability of control rates rather than deflections were analyzed, as large stick deflections can be expected in a go-around scenario.

After each run, pilots were requested to submit a workload score on the Rating Scale Mental Effort (RSME) [44,45]. This, as well as data gathered from the postexperiment questionnaire, was used as a subjective measure for workload.

4. Questionnaire

A postexperiment questionnaire was used to collect further data on safety and workload that participants experienced as well as general comments on their preferences and suggestions.

I. Hypotheses

First, it was hypothesized that using the CVSD would increase altitude and speed tracking performance at reduced variance compared to the BVSD (H. 1, Hypothesis 1), as the V_{FAS} constraint assisted pilots in velocity tracking when workload would be largest, and the steepest climb indicator showed the quickest method to recover altitude at the start of the go-around. The CVSD showed more detailed information regarding aircraft maneuvering limitations and capabilities, giving pilots more explicit aiming targets for specific velocity and altitude goals.

Second, it was hypothesized that with the CVSD occurrences and time spent flying below the altitude profile, Indicated Airspeed (IAS) profile, and V_{FAS} were decreased compared to the BVSD as limits were shown explicitly (H. 2, Hypothesis 2). In other words, no envelope excursions were expected to occur with the CVSD.

Third, control activity and experienced workload were hypothesized to be lower using the CVSD (H. 3, Hypothesis 3), due to the mapping of higher-level information on the display that would support faster skill- and rule-based behavior. Fourth, as the CVSD included more information on (the effects of) aircraft configuration changes, it was hypothesized that detection and diagnosis of configuration failures would be faster than using the BVSD (H. 4, Hypothesis 4).

J. Data Analysis

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

Runs which did not include a failure were effectively the same scenario with a random starting velocity and distance offset. These runs were aligned by disregarding all data until 0.5 nmi (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.

Throughout the experiment, some small issues arose which might have affected the results. When using the simulator for multiple experimental trials on a single day, the hydraulic side stick could overheat, which caused the simulator to stop operating. This required a restart of a handful of scenarios, and on two occasions, it even forced to take a second, small recess during the experiment. The effect of the extra experience, rest, and/or fatigue which some participants experienced due to hardware issues is unclear. However, the effects are 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.

V. Results

A. Altitude and Speed Tracking Performance

Generally, altitude RMSD scores were similar between displays, and velocity RSMD scores showed better tracking performance using the BVSD. Visualization of the data through box plots in

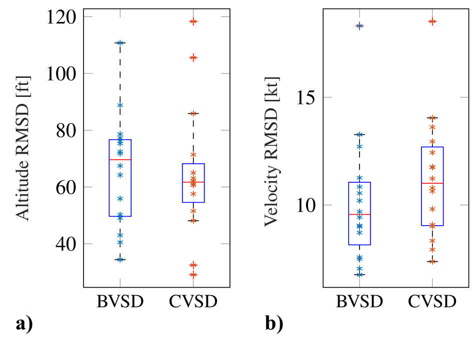

Fig. 9 RMSD for a) altitude and b) velocity.

Fig. 9 shows a smaller variance in altitude error using the CVSD. The total range in variability is, however, still similar.

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

This improved velocity tracking performance using the BVSD is contrary to the hypothesis, which stated that this improvement would be found for the CVSD (H. 1). 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 Fig. 10, showing similar trends at all velocity targets except when approaching the 4 nmi point, the start of the go-around maneuver, and thereafter. At this point, the velocity target is equal to V_{FAS} (see the magenta x in Fig. 10), which is explicitly shown by the intentional constraint on the CVSD. For completeness, a similar running 95% confidence interval plot is made of the altitude profile in Fig. 11, confirming no notable differences between the two displays.

Considering Fig. 10, it appears that participants using the CVSD prevented their velocity from violating this intentional constraint, often keeping some margin to account for turbulence effects. The variations in velocity during go-around also decreased, but this effect is not reflected in the velocity tracking performance, as no velocity targets are present in this part of the scenario.

To further analyze participants' strategies, the altitude and velocity tracking performances are compared. Pearson's correlation coefficient shows that for both displays a significant relationship between the two measures exists ($r = -0.637$, $p < 0.01$ and $r = -0.715$, $p < 0.01$ for BVSD and CVSD, respectively). This is illustrated through plotting both measures against one another in Fig. 12.

Trend lines for the BVSD and CVSD are of comparable slope and show that pilots trade off optimizing for altitude or for velocity tracking performance. Figure 12 confirms that pilot license seems to

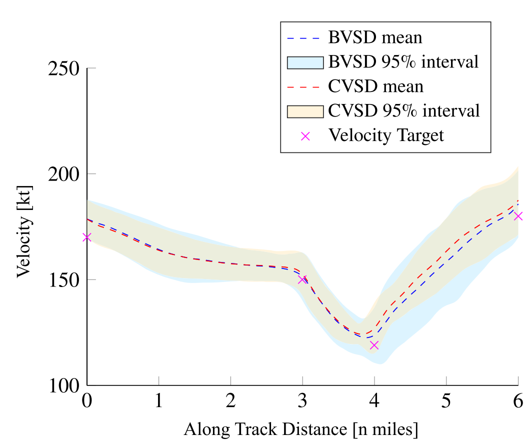

Fig. 10 Mean and running 95% confidence interval for velocity profile.

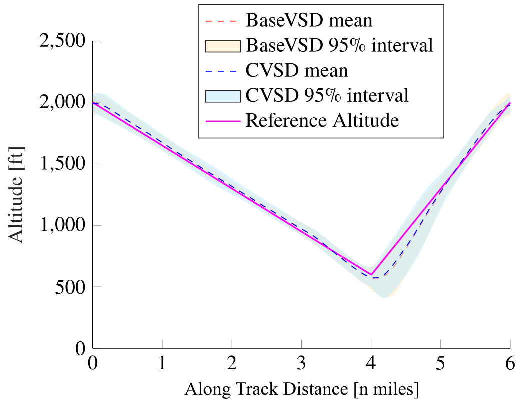

Fig. 11 Mean and running 95% confidence interval for altitude profile.

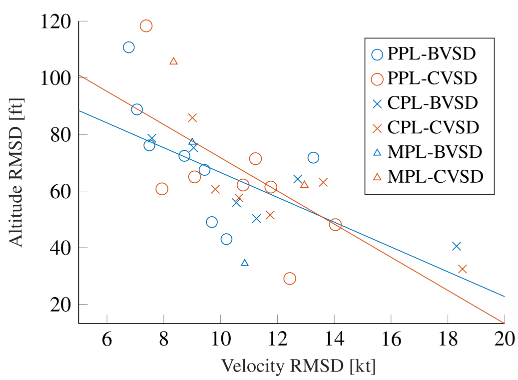

Fig. 12 Velocity versus altitude RMSD's for both displays, including regression lines. Participants are visually distinguishable by pilot license type (PPL, CPL, and MPL (Military Pilot License)).

have had no effect on performance, as no type of pilot is consistently above or below the trend line. This is confirmed by multivariate ANOVA (Analysis of Variance) 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 that display order had no significant effect on tracking performance.

B. Adherence to Altitude and Speed Constraints

Given that no significant differences were found between the two displays regarding the altitude tracking performance (see Fig. 11) and that no large altitude deviations below the approach path (i.e., close to the ground) were recorded, only speed constraint adherence is analyzed.

One of the goals of the CVSD is to make pilots more aware of physical (equal to casual) and intentional velocity limits. No envelope excursions (physical constraints) occurred, so only intrusions of the intentional constraint are analyzed. Intrusion depth and total intrusion time are investigated, which translate to the minimum obtained velocity and the total time spent below V_{FAS}, respectively. These metrics are represented by box plots in Figs. 13a and 13b, respectively.

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 Sec. V.A, Fig. 10. Because 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 the better velocity tracking performance as achieved with the BVSD for better adherence to intentional speed limits. Note that violating the intentional V_{FAS} speed constraint does not necessarily imply that pilot performance was unsafe. There will always be a natural variability around V_{FAS} due to variances in pilot control inputs and environmental factors and operational

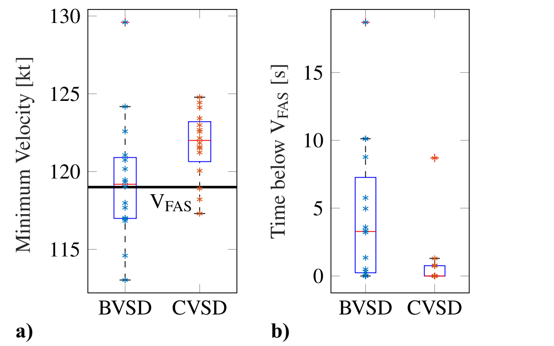

Fig. 13 Distribution box plots for a) minimum velocity and b) time spent below $V_{\{\mathrm{FAS}\}}$.

procedures. When using the CVSD, it appears that variability is reduced and pilots assumed more margin in tracking V_{FAS}, but that cannot be interpreted as either safe or unsafe behavior.

Because minimum velocities for the CVSD generally did not drop below V_{FAS}, it is no surprise that most participants averaged 0 s below V_{FAS} in this condition, as can be seen in Fig. 13b. Eleven out of 16 participants never exceeded V_{FAS} in any of their four nominal runs, bringing the median and bottom quartile both to zero.

The single CVSD outlier with a mean time of 8.7 s often pitched up too quickly during go-around in order to follow the reference height, thus neglecting the velocity for a brief moment.

As data for time below V_{FAS} did not pass the Shapiro–Wilk test for normality, a Wilcoxon-Signed-Rank test was used to compute significance ($Z = -2.29$, $p < 0.05$). Both speed measures are indeed in favor of the CVSD, and the hypothesis that pilots would better adhere to (intentional) speed constraints using the CVSD (H. 2) is considered confirmed.

C. Control Activity and Experienced Workload

Control activity was analyzed through control input variation and workload was reported subjectively through self-reported RSME ratings. Side stick deflection and thrust setting were used for control activity measurements. Using the control input *rates* rather than deflections eliminates the effect a different trim position might have, thus allowing comparison of results of participants using varying trim settings. At least one large peak in both control inputs is expected each run, namely, at the start of the go-around. Because this input is present for all runs, it can be expected to introduce the same bias in all data and thus does not prove a problem for this analysis. Box plots with standard deviations of control input rates are shown in Fig. 14.

A small decrease in rate variability is visible with the CSVD, especially for elevator inputs in Fig. 14a. This might be explained by participants being able to see that their aircraft is not flying close to any limits, thus relaxing the need to correct for smaller, higher-frequency velocity and altitude errors introduced by the turbulence.

Wilcoxon-Signed-Rank tests found no difference for standard deviation in elevator input rates ($Z = -0.958$, $p > 0.05$) or throttle

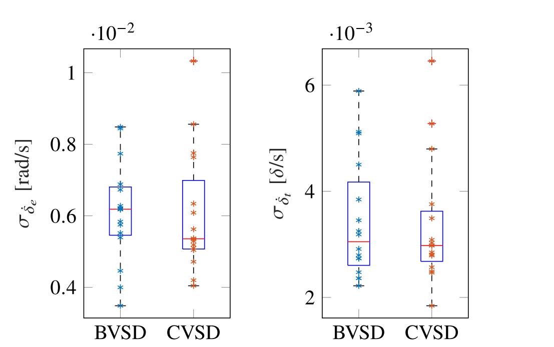

Fig. 14 Standard deviation of a) elevator input rate and b) throttle deflection rate.

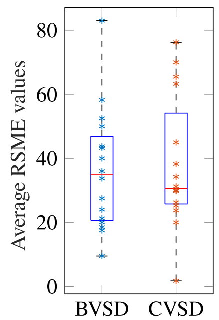

Fig. 15 Mean self-reported workload ratings.

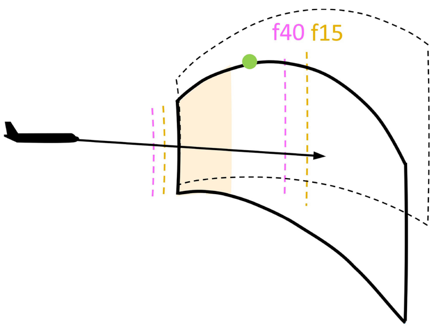

Fig. 17 Performance envelopes with zero flaps and gear deployed.

deflection rates ($Z = -0.675$, $p > 0.05$). These results are corroborated by the self-reported RSME workload ratings in Fig. 15, which show no significant changes either ($t(15) = -0.798$, $p > 0.05$). These metrics provide sufficient evidence to conclude that no differences in control activity and workload exist between displays, rejecting hypothesis H. 3.

D. Failure Run Analysis

It was expected beforehand that all tested configuration failures would be discovered; however, this did not end up being the case. Failures were diagnosed in only half of the BVSD failure runs and three-quarters of the CVSD failure runs; see Table 2. Possible reasons for missed detection are discussed in Sec. VI.

Although the 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 failure with the BVSD, while all of them identified it with the CVSD. Only one participant identified the failure with the BVSD and not with the CVSD.

For all failures successfully diagnosed, the time it took for pilots to do so is shown in Fig. 16. Times are measured from the moment a rejected input is given until the start of an audible diagnosis by the pilot. No box plots are drawn because of the limited amount of data.

Diagnosis times for the CVSD are generally shorter than for the BVSD. This was hypothesized (H. 4), as the CVSD flight envelope visualization offers additional cues 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 appear grouped at certain time intervals. This grouping correlates with particular moments in the go-around occurring, which facilitates 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.

Table 2 Number of diagnosed failures

Event	BVSD	CVSD
Gear failures diagnosed	4 / 8	6 / 8
Flap failures diagnosed	4 / 8	6 / 8
Total failures diagnosed	8 / 16	12 / 16

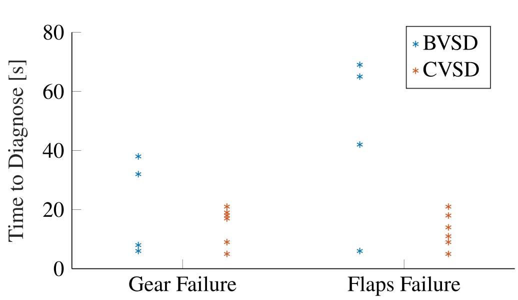

Fig. 16 Time to diagnose flight control failure.

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 (Fig. 17).

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 at the end of the go-around, after the speed goal changed to 200 kt. This corresponds to V_{MO} for the Citation II with flaps 15 deg, and pilots noticed something was wrong as their velocity indicator on the VSD horizontal speed tape approached the red area.

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° adds both drag and lift, but more noticeably reduces V_{MO} to 200 kt. Participants originally gave more throttle but later reduced to keep their velocity around 190 kt, again sacrificing tracking performance for better adherence to limits. These adjustments were similar for both displays after the failure was diagnosed. The CVSD did not appear to lead to different control strategies, such as changes in configuration schedule.

In summary, despite some quicker failure diagnosis with the CVSD, H. 4 cannot be statistically confirmed with the limited number of data.

E. Pilot Feedback

Two forms of feedback were collected at the end of the experiment. First, a questionnaire asked pilots to compare both displays and explain their answers. Second, pilots were asked for feedback on the displays, simulator, or any other aspect of the research in an open format.

1. Questionnaire

Each of the 10 questions in the questionnaire presented pilots with a scale showing the BVSD on the left, CVSD on the right, and a small mark in the middle for neutral/equal. Pilots 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 Fig. 18.

Pilots indicated that the CVSD allowed them to better handle failures, to better predict dangerous situations, and to improve their perception of flight safety. 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 configuration failures. Two out of 16 pilots did not like the CVSD and noted that the flight envelope visualization sometimes caused cluttering of the display.

Generally, pilots indicated the CVSD cues were useful additions to the VSD. Although they stated to have experienced lower workload (question 2), this claim is not supported by the control activity and workload metrics analyzed in Sec. V.C. Additionally, multiple pilots said the CVSD was more difficult to work with (question 1), yet still rated their workload in favor of the CVSD. When asked about this inconsistency, one participant explained,

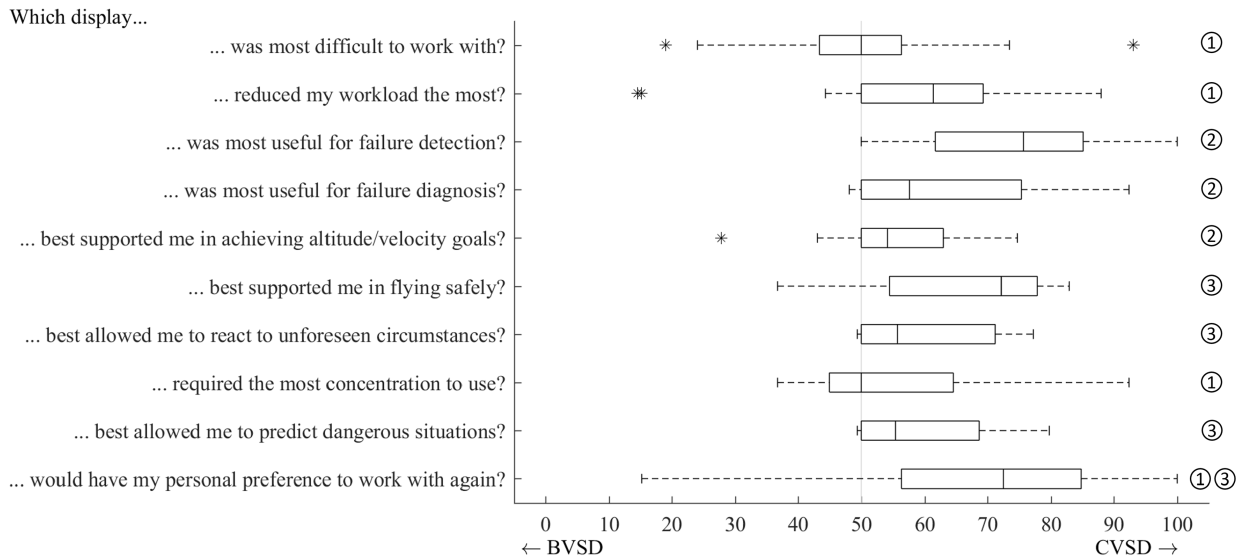

Fig. 18 Box plots of questionnaire results. The numbers on right indicate principal component categories: ① workload, ② performance, and ③ safety awareness.

“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 generally confirmed by the answers to question 8 on “most concentration to use,” although the median lies exactly halfway.

A principal component analysis (PCA) was performed on the questionnaire data and resulted in three significant categories (with eigenvalues greater than 1) which together captured 80% of the variance in the answers given. The categories are marked with numbers 1, 2, and 3 in Fig. 18. The numbers appear to capture 1) the experienced workload and effort (when working with the display), 2) task performance perception as specified by the tasks set for the experiment (i.e., reference tracking and failure diagnosis), and 3) a general sense of flight safety and being able to anticipate dangerous aircraft states.

Intuitively, failure detection and diagnosis may seem to belong to *safety awareness*, but the PCA found notable correlations with questions on achieving altitude/velocity targets. This can be explained by the nature of the display in conjunction with the scenarios and tasks set for this particular experiment: two configuration failures 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, pilot preference correlates with both workload and a sense of flight safety, although correlations are less strong than commonly found within one category. Here, correlation weights of 0.71 were found for workload and 0.63 for flight safety. The relatively higher correlation weight for workload suggests that the preference for working with one display over the other is more determined by workload rather than the sense of safety the display may offer.

2. *Further Pilot Comments*

Because 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 made 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, such an acceleration indicator 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. Because most cues are centered around the left-hand side of the VSD, the ROC tape on the right is difficult to include in a natural-feeling cross-check. 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 (out of 16) participants disliked the CVSD in general, as they said it makes the situation unnecessarily complex.

VI. Discussion

This research investigated the effects of an ecological VSD enhancement on the ability of pilots to perform an approach and go-around maneuver, with potential configuration failures, while adhering to speed and altitude targets. An analysis of flight paths and control inputs shows that pilots were better able to abide by intentional speed constraints when using the CVSD than when using the more basic BVSD, confirming hypothesis H. 2. However, this did come at the price of reduced velocity tracking performance, indicating that the CVSD caused pilots to place more emphasis on maintaining speed margins than on optimizing their tracking performance, rejecting hypothesis H. 1. The desirability of this effect can be questioned when it would become too large, as the gain of larger buffers might not always outweigh decreases in performance, especially in the approach phase of flight. Additionally, no conclusions about safety can be drawn, as violating intentional speed constraints are not necessarily unsafe.

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 speed tracking performance. Previous research on ecological flight deck interfaces by Comans has shown EID to cause a reduced variance in flight-path traces [22], an effect which can also be seen in the velocity traces for the CVSD (Fig. 10). Reducing the turbulence might cause pilots to reduce the velocity buffer size they maintain. This would result in flight consistently closer to, but rarely under, V_{FAS}, thus optimizing both intentional speed constraint adherence and tracking performance.

Reduced reference tracking with the CVSD can also be explained by the lack of cues that helped pilots to decide on *when* to (best) switch to a certain speed and configuration to smoothly intercept the reference flight profile. We expect that including such cues (e.g., by taking deceleration/acceleration, wind, etc. into account), reference tracking with the CVSD may improve. Currently, timing of control actions was left to the pilot's judgement, and results indicate that the baseline VSD had slightly better reference tracking, albeit not significantly. We believe that, with the CVSD, the pilots' attention was captured by the conspicuous envelope and boundary markers, presumably shifting the focus of the control task from *reference tracking* to *boundary adherence*. Pilots were not explicitly briefed on this, and thus they seemed to naturally converge to a slightly different strategy. Note that this is not uncommon because ecological interfaces generally tend to sacrifice optimality in favor of increased robustness and flexibility [30].

Neither the control activity measures nor the subjective postrun workload scores indicated any significant difference between displays. However, comparing the two displays in the postexperiment 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, Hypothesis 3, stating that the CVSD leads to a workload reduction, cannot be accepted; the results are inconclusive.

The CVSD increased configuration failure detection rates (from 50 to 75%) and reduced diagnosis times, relative to the baseline. Multiple failures went undetected, however, and the low amount of data rendered producing a reliable statistic impossible. Note that the failures were all unexpected, and *not* trained for. With the CVSD, pilots could at some points directly *see* the effects of failures. Showing the effects of the aircraft configuration settings on performance allowed pilots to better see (and adhere to) the causal and intentional safety constraints, confirming earlier findings [14,21,22]. Visual inspection of the data seem to support Hypothesis 4, but more data will be necessary for a statistical confirmation.

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 showed that pilots could not detect all failures with either VSD. Reasons for unnoticed failures are suspected to lie in their noncritical consequences and the limited amount of cues they can be detected from. Pilots were only presented with visual cues during the experiment, whereas something as an extended gear would usually also lead to audible and haptic cues. Including these in the simulation is expected to reduce detection times, 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 increased simulation fidelity for better failure simulation.

Although pilot license type did not affect performance metrics, recent experience with flight simulation training devices (FSTD) might have affected metrics for failure diagnosis. Three pilots 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 s regardless of flight display and achieved all diagnosis times below 10 s for the BVSD. This would indicate that recent FSTD training outweighs the effect of our display enhancements when handling unforeseen circumstances. Whereas the CVSD might not play a significant role for well-trained pilots, its use as a diagnosis aid for pilots who have not had recent simulator training is strengthened when these findings are accounted for.

For future research, it is recommended to look into redesigning (parts of) the CVSD, as well as testing its use in other scenarios, for example, approach trajectories involving turns. Various small, yet valuable, suggestions were made by participating pilots, 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, and future work could aim to study effects of a windshear, a microburst or engine failures [46,47]. Previous versions of the VSD were used as tools for traffic and terrain awareness [22,23], and incorporating these in scenario design could lead to a more varied experiment and potentially to a more versatile display. It is also recommended to investigate the effects of turbulence on pilot strategies. If introducing random variance to a controlled system with an ecological display, showing causal and intentional constraints of aircraft performance, causes pilots to change their control strategy, this may have unexpected consequences. Understanding these consequences is paramount to adapting these displays for use in the real, turbulent outside world. These investigations also need to include discussions on what pilot control behavior is desirable according to company standards and/or is considered to be safe or unsafe. Finally, the efficacy of the display should also be tested in approach conditions with autoflight engaged so as to investigate if the display offers support in *supervisory control* conditions.

VII. Conclusions

Two versions of a vertical situation display were evaluated by 16 pilots, to test the effects of showing aircraft flight envelope boundaries and configuration changes on their tracking performance and adherence to envelope boundaries in an approach and go-around maneuver. Some scenarios included a gear or flap failure, which pilots had to detect and diagnose. The new CVSD showed pilots their flight envelope, which was variable with configuration and included an approach speed indication. Compared to the baseline VSD, the CVSD increased safety margins at the cost of velocity tracking performance, as pilots avoided violating intentional constraints by maintaining an additional velocity buffer. Configuration failures were more often detected and diagnosed more quickly with the CVSD. Not all failures were detected, however. Although pilots reported the CVSD to reduce workload, this statement is not backed by objective metrics. In addition, pilots stated that the CVSD required more attention and that more training is required for the display to be optimally used.

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N. Neogi
Associate Editor