Feasibility and Benefits of a Cockpit Traffic Display-Based Separation Procedure for Single Runway Arrivals and Departures

Implications of a Pilot Survey and Laboratory Simulations

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Abstract—This paper reviews the potential benefits of and the need for implementing a procedure for providing Visual-like Separation in Instrument Meteorological Conditions (IMC) through the use of a Cockpit display of traffic information (CDTI), for single runway arrivals and departures. This procedure is referred to as an “IMC CAVS” procedure in this paper. This paper reviews existing research and status of the current “VMC CAVS” procedure (a CDTI Assisted Visual Separation procedure authorized for use in visual meteorological conditions), discusses the potential for benefit in the NAS of an IMC CAVS procedure, highlights issues surrounding such extension of a CAVS procedure into IMC, shows results of an online pilot survey aimed at understanding these issues, provides a description of a CDTI capability aimed at addressing the primary issues, and analyzes results of real-time simulations of conducting such operations. Finally, the paper recommends next steps that should be taken in order to develop an operational IMC CAVS capability.

Keywords—Airport capacity, ADS-B, CDTI, cockpit-based separation, visual operations, cockpit display

I. INTRODUCTION

A significant commitment has been made in the United States, Europe, Australia, Canada and other areas of the world to implement Automatic Dependent Surveillance Broadcast (ADS-B) as a primary source of surveillance for future Air Traffic Management (ATM) systems. The U.S. has issued a notice of proposed rule-making that would require the broadcast (“ADS-B Out”) of certain basic own-ship information by all aircraft operating in certain airspace in the U.S. The rule is expected to provide significant benefits, in the form of radar replacement cost avoidance, more efficient use of the airspace due to improved surveillance accuracy, and, eventually, future ADS-B cockpit-based surveillance applications. The long term goal of the FAA as well as other international ATC providers is to facilitate the provision of significant benefits, to ATC providers as well as to users who must equip with the required avionics.

It is generally accepted that the largest benefits to users will accrue through the users receiving ADS-B information (“ADS-B In”) and using it for airborne applications that will facilitate improvements in system efficiency, capacity and safety. The visions of major initiatives such as NextGen by the Joint Planning and Development Office (JPDO) in the U.S. or Single European Sky Air Traffic Management (ATM) Research (SESAR) in Europe envision such improvements and conceive a central role for ADS-B-based capabilities that include the display of traffic on the flight deck. However, equipage with ADS-B In is hoped to be driven by the benefits enabled by the capability, rather than by a mandate or regulation. In order to realize the potential efficiency improvements of ADS-B, applications of ADS-B In must be developed and demonstrated to provide the expected efficiency.

Definition and development of ADS-B applications, or more accurately Airborne Separation Assistance System (ASAS) applications, has a long history of international research and cooperation. (e.g., [1] through [20]). The formulation of a set of applications that will provide enough benefit to users to justify the cost of acquiring these systems is being progressed. A significant FAA effort, called Application Integrated Work Plan (AIWP) for ADS-B applications is now underway to develop a logical evolution of application packages to foster user benefits. This effort requires functional descriptions of candidate applications, a description of their enabling technologies including the underlying Cockpit Display of Traffic Information (CDTI) capabilities, potential benefits, and an assessment of the risks in their development. This paper starts to formulate the operational concept, potential benefits and the potential CDTI requirements for one set of applications that may be important in developing a benefit case for “ADS-B In;” CDTI assisted “visual-like” separation.
(CAVS) in Instrument Meteorological Conditions (IMC), henceforth called IMC CAVS for brevity. Although not as prevalent in Europe, the U.S. National Airspace System (NAS) employs numerous procedures in which visual separation is used to improve the efficiency of the system. Most of these procedures are applied in terminal airspace. When visual separation is used, operations in the U.S. are considerably more efficient than during operations when visual separation cannot be applied. Perhaps the most notable and well known among these are visual operations during approach to single runways, to closely spaced parallel runways (CSPRs), and for visual separation for departures. This paper describes two ways in which a CDTI could be used to substitute for direct visual separation, and thus help maintain the efficiency of visual operations even when conditions are such that direct visual separation cannot be used: IMC CAVS for single runway approaches (as against parallel or converging runway approaches) and IMC CAVS for departures.

II. POTENTIAL BENEFITS OF AN IMC CAVS PROCEDURE FOR SINGLE RUNWAY ARRIVALS

Fig. 1 shows observed distribution of aircraft separations over the threshold for arriving aircraft during visual and instrument conditions in the U.S. at one major airport: Los Angeles International (LAX). It shows that minimum separation behind small and large aircraft for trailing aircraft of the same or larger weight category is 1.7 nautical miles (nmi) compared to 2.5 nmi when radar separations must be used. It also shows that the mode for visual operations is 0.9 nmi smaller than that for operations in IMC. Fig. 2 shows a similar comparison between the observed separations behind heavy aircraft during visual and radar operations for large or Boeing 757 aircraft following. It shows that the minimum separation achieved in visual conditions is 2.2 nmi less than that during radar operations. It also shows that the mode for visual operations is 1.3 nmi less than when radar separations are used. Thus, observed separations at this major U.S. airport during visual operations are smaller by about a mile or more than those when radar and applicable wake separations are used. Reference [21] documents observed aircraft separation over the threshold during visual operations in the U.S. Those values have been used for the FAA’s airport capacity model for many years. The more recent values reported here are consistent with the values reported in this older study. This difference between the achieved separations in visual conditions and during IMC is one significant cause for the large reductions in arrival capacities when conditions fall below visual approach conditions at U.S. airports. Recouping some of this lost capacity is the goal of the procedures presented in this paper.

Fig. 3 shows the benefit that would accrue for several major U.S. airports if minimum separations of 2 nmi could be achieved behind large and small aircraft in place of the minimum radar separation required at those facilities. (Minima of 2.5 nmi over the threshold, in place of the normal 3 nmi, are authorized for runways that satisfy certain requirements.) The figure also shows the benefits that would accrue at these facilities if, in addition, a future system with associated procedures could be used where the current wake turbulence separations did not have to be used. Based on the differences in achieved spacings noted in Figs. 1 and 2, attaining visual-like separations through an IMC CAVS procedure would provide a benefit somewhere between the two bounds shown in Fig. 3.

Achieving such reduced separations in less than visual conditions is the stated goal of the “IMC CAVS for single runway approaches” procedure. To just what minima such a procedure could be conducted is a matter to be determined with further study and development. It is proposed in this concept that crews will be able to make the same or better spacing judgments in IMC using information from the CDTI as they do during visual conditions with Out-The-Window (OTW) visual contact with the traffic ahead. Whether this can actually be achieved, of course, would depend on the efficacy of the display features, the feasibility of incorporating such a procedure into the ATC system, and the development of appropriate certifications and authorizations.

III. ISSUES IN DEVELOPING AN IMC CAVS PROCEDURE FOR SINGLE RUNWAY ARRIVALS

There already exists a base of experience in using at least some of these display capabilities for similar purposes. A CDTI Assisted Visual Separation (CAVS) procedure has already been developed, approved, and is being used in VMC ([18] and [19]). In this VMC CAVS procedure, the CDTI is used to monitor separation from traffic after initial OTW visual contact has been established and the CDTI target has been cross-checked with an out-of-the-window visual acquisition. After this initial correlation, the visual contact with the traffic to follow (TTF) could be lost, (e.g., in city lights or glare from the sun), but crews can continue to maintain separation based only

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1 The phrase “CDTI Assisted Visual Separation in IMC”, or “IMC CAVS” is used throughout this paper to imply visual-like separation provided with the help of a CDTI. The nomenclature “CAVS” was studied closely during the development of the “VMC CAVS”. In that procedure, initial direct visual contact with traffic was required for providing own separation, but once a cross correlation with the CDTI target was accomplished, visual contact was no more required for providing own separation, and own separation could then be provided for the entire remaining portion of the procedure based on the information provided on the target on the CDTI alone, as long as ownership remained in visual conditions. The intention in the “IMC CAVS” procedure is similar: own separation could be provided by flight crews based on the information provided on the target on the CDTI alone, even when the target cannot be seen visually. However, it is acknowledged that the nomenclature “IMC CAVS” will need to be revisited in the context of its use in IMC, and revised in order to reflect regulatory considerations.

2 Reference 20 describes five potential applications of IMC CAVS in the ATC system. This paper discusses only two of them, because research indicates that these two show significant promise of near term deployment as well as significant benefits for the U.S. NAS.

3 The data used was from the FAA’s Airspace Lab’s recordings of aircraft tracks. The VMC data spans 10 time periods in January 2008 comprising 79 hours. The IMC data spans 7 time periods in January and February 2008 comprising 37 hours.

4 Visual separations are most commonly achieved in the U.S. under visual approach conditions, which, ironically, exceed VMC minima (1000 ft ceiling and 3 mi visibility) by a considerable margin. As a result, separations nearing those reported here for IMC are typically also seen in marginal visual conditions. Achieving visual-like separations in marginal visual conditions would thus lead to a considerable improvement in the capacity for many U.S. airports.
on the information available on the CDTI. The systems approved for this application provide pilots with range to target, target groundspeed, relative altitude, and closure rate as essential features, which provide robust and easily interpreted information about the trajectory and speed behavior of TTF. Throughout the VMC CAVS procedure, Ownship is required to remain in VMC. This prohibits using the procedure in conditions such as a descent through thin cloud layers (e.g. the so-called “marine layer”) that occurs at many airports in the U.S.. The proposed IMC CAVS procedure would extend the VMC CAVS authorization to permit visual separation via the CDTI in IMC while following a target that may not be available visually OTW.

During the course of the development of the VMC CAVS procedure, two primary issues were identified regarding the extension of the CAVS procedure into conditions when Ownship would be in IMC: potential collision with terrain, and an inadvertent encounter with wake turbulence while in IMC. When operating on a visual approach clearance, terrain and obstacle avoidance is achieved by direct visual observation. Wakes are avoided by direct visual contact with TTF and adjustments of Ownship trajectory to operate in a manner judged likely to avoid wake.

In the proposed IMC CAVS procedure, terrain avoidance is addressed by requiring that Ownship operate in accordance with a published instrument approach such as an Instrument Landing System (ILS) or an area navigation (RNAV) approach with associated altitude constraints. Wake encounters may be addressed by appropriate pilot-selected distance spacing or by an adjustment of Ownship’s approach path. The approach path adjustment would be assisted by the use of new wake situation awareness tools (described later) that indicate the vertical trajectory actually flown by TTF, information that is not always available by direct observation.

When executing a CAVS clearance, no minimum required separation is specified, just as none is specified for OTW visual separation. Today, when a pilot accepts a visual separation clearance, the separation requirement implied is simply that the following pilot not collide with the lead airplane. Of course, as a practical matter, the lead airplane needs time to clear the arrival runway, and, as described above and cited in [21], around 2 nmi separation is about the minimum observed in actual visual approach/visual separation operations. This could be considered a practical lower limit of separation at the runway threshold.

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5 In the U.S. a heavy aircraft is defined as being capable of a takeoff weight of more than 255,000 pounds. A large aircraft has a certified takeoff weight of more than 41,000 pounds and less than or equal to 255,000 pounds. A small aircraft has a takeoff weight of less than or equal to 41,000 pounds. For wake separation purposes, the Boeing 757 series 100 and 200 have their own separation standard when they are the leading aircraft, and are referred to as B757s in this paper. The Boeing 757 series 300 is considered a heavy aircraft.

6 This does not preclude the specification of tolerance values or other appropriate minima that reflect the navigation and surveillance performance of the ADS-B system. However, such a specification would be different from a separation standard established for ATC operations. In the IMC CAVS concept proposed here, this latter ATC separation standard would not be specified, similar to what is done today in visual operations.
In addition, the pilot is also responsible for his or her own wake separation. As discussed earlier, pilots providing their own separation behind a wake generating aircraft deliver distances that are often less than published wake turbulence separation minima. A concern in the initial CAVS and CEFR development was that pilots may thus space themselves closer than minimum wake turbulence separation minima behind an aircraft, but not have the information needed to execute the strategies they otherwise use for wake avoidance during visual separation. If pilots are unable to use their preferred wake avoidance strategies, the possibility exists that more wakes would be encountered by following aircraft, increasing the possibility of wake upset.

IV. RESULTS OF A PILOT SURVEY REGARDING WAKE CONCERNS AND AVOIDANCE PROCEDURES FOR SINGLE RUNWAY ARRIVALS

The MITRE Corporation’s Center for Advanced Aviation System Development (CAASD) conducted an online survey of 415 commercial pilots. Most (87%) indicated that they currently fly Air Carrier operations. The remaining pilots indicated that they currently fly for Fractional Operators (11%) or a combination of Corporate, On Demand Charter, and Other (2%). The pilot responses were separated into 5 bins (see Table 1) according to the size of the aircraft they indicated they were currently flying. The bins were generated based on an exhaustive list of all reported aircraft types in the survey (i.e., the pilots did not report flying any aircraft not listed in Table 1). The bins were chosen based on expert judgment according to which types would likely have different concerns about wake (loosely based on weight). Table 1 also lists the number of respondents in each aircraft bin and their respective average flight hours.

Table 1. Bins Used to Separate Pilot Responses for Analysis (Includes Number of Pilots in Each Bin and Average Total Flight Hours Across Pilots within each Bin)

<table>
<thead>
<tr>
<th>Aircraft Types</th>
<th>80</th>
<th>25</th>
<th>116</th>
<th>142</th>
<th>54</th>
<th>415</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy</td>
<td>13,069</td>
<td>13,943</td>
<td>13,710</td>
<td>6,957</td>
<td>8,446</td>
<td></td>
</tr>
<tr>
<td>B757</td>
<td>A300</td>
<td>B757-200</td>
<td>A320</td>
<td>A318</td>
<td>B700</td>
<td></td>
</tr>
<tr>
<td>Large A</td>
<td>50</td>
<td>38</td>
<td>82</td>
<td>1,122</td>
<td>1,145</td>
<td></td>
</tr>
<tr>
<td>Large B</td>
<td>757</td>
<td>757-300</td>
<td>757-200</td>
<td>500</td>
<td>300</td>
<td>757</td>
</tr>
<tr>
<td>Small</td>
<td>10</td>
<td>20</td>
<td>120</td>
<td>140</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>25</td>
<td>116</td>
<td>142</td>
<td>54</td>
<td>415</td>
</tr>
</tbody>
</table>

The pilots were asked “When you are maintaining visual separation behind an aircraft you are following to the same runway: Is wake ever a concern to you?” Nearly all of the pilot respondents (98%) indicated that they were concerned about wake encounters when maintaining visual separation to single runways. Fig. 4 depicts the factors that pilots indicated caused them to be concerned about wake, separated into their respective Ownship aircraft size bins. It shows that when combined, the various wind categories were cited most often with the second and third most frequent concerns cited being position of the lead (with regard to both separation and altitude with respect to glidepath) and lead size respectively. Interestingly, even though the questionnaire specifically asked about wake concerns while on approach, some of the pilots indicated that the lead position (separation and horizontal/vertical trajectory) and close spacing caused them concerns while departing. Not surprisingly given the phrasing of the question, the overall numbers were low, but it does appear that pilots have some concern about wake encounters on departure. It is also interesting to note that the pilots generally indicated the same categories regardless of which aircraft they were currently flying.

Pilots were also asked “When wake is a concern, do you adjust your flight path or speed to avoid wake?” The vast majority of pilots (97%) indicated that they did make some kind of flightpath adjustment on single runways to avoid wake encounters when conditions led them to be concerned. The pilots were then asked to describe the adjustment methods that they used to avoid wake when maintaining visual separation from an aircraft on the same runway. Fig. 5 shows the methods listed by pilots in mitigating their concern regarding wake during single runway arrivals separated into their respective Ownship aircraft size bins. The bar colors represent the category of Ownship being reported, and the percentage of pilots who reported using the listed technique.

When aggregated across the pilot respondent’s Ownship aircraft type (not shown in the figure, but computed separately), 51% of the pilots reported “flying high” as the technique used for wake avoidance on single runways. 28% reported slowing down, timing the turn and making S-turns etc. to increase the spacing from the lead as their wake avoidance technique, and 16% reported flying upwind as their wake avoidance technique. Some also reported flying faster in order to increase the flight control effectiveness in case of a wake encounter. Although the numbers just listed are aggregates over the entire set of pilots that responded, Fig. 5 shows the remarkable consistency between the methods of choice for avoiding wakes regardless of the weight classification of Ownship. Another notable item in Figs. 4 and 5 is that even crews of heavy aircraft reported both concern for wakes and that they adjusted their flight paths to avoid them when they were concerned.

Table 2 lists the lead aircraft types for which each group expressed concern regarding wake. It is no surprise that most crews expressed concern about following heavies and Boeing

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8 The data collected was “free text” in nature and was binned into categories of concern. Since each pilot could respond with several categories of concern, the total responses are greater than the number of pilot participants within each ownship aircraft bin. Therefore, each bar within the graph depicts the percentage of the total responses from that ownship aircraft bin for that category. This was done in order to compare across the various ownship aircraft type bins.
9 An example of adjusting the flight path would be flying slightly above the glide-slope. However, no such specific methods were suggested in the wording used in the survey.
10 The survey responses did not provide enough information to identify how often these methods are used in conjunction with each type of lead aircraft.
11 From the pilots’ textual comments accompanying some of the entries, it appears that slowing down, timing the turn and making S-turns were all used to increase the spacing.
However, concern was also noted regarding following large aircraft, and that heavy aircraft expressed concern about following other heavies, Boeing 757s, and even large aircraft.

Although the concerns as well as the methods used to mitigate concerns were listed, the survey was not detailed enough to determine whether flight crews always utilized the mitigation methods listed when they were concerned, and whether they utilized them equally with respect to all aircraft types for which they listed concern. It is possible that although a concern was listed with respect to several aircraft groups, that a mitigation strategy may be used more frequently against some than others. A more focused questionnaire may shed more light on this question.

It is remarkable that even though pilots indicate the need to gain spacing or gain vertical separation over their TTF’s glideslope as their primary mitigation strategy, today they have no means of precisely determining either their distance from the TTF, nor whether the technique they are using to gain altitude separation over their traffic on approach is likely to succeed, since they currently have no way of verifying how the lead aircraft is flying with respect to its glideslope. ADS-B and CDTI offer an effective means of determining these parameters of vital interest to pilots who are performing single stream operations and have assumed separation responsibility.

V. CDTI TOOL SET FOR IMC CAVS OPERATIONS

Fig. 6 depicts a possible basic toolset to support the IMC CAVS applications described here. Key features include track referenced target chevrons (cyan), with orientation depicting current track; selected target highlighting with color coding for selection (green outline) and application coupling (magenta); selected target datablock with range to target, flight identification, wake category, and groundspeed; and when certain relative track and heading constraints have been satisfied, closure rate display with a directional arrow. A vertical situation display depicting the vertical relationship between TTF and Ownship is also provided.

12 Except by reference to the TCAS display for an approximate estimate.
Pilots in prior studies have indicated that this toolset is sufficient to perform the pilot provided separation task on approach by reference to the CDTI ([18] [19], [24]), including operations in which a portion of the flight occurs in IMC. However, to address the previously described concerns about wake encounter in IMC, wake situation awareness displays have also been provided to indicate ownship’s relationship to the actual vertical trajectory flown by a selected target lead aircraft. (See [22]). This information is provided by a combination of two display features: a lead glidepath reference display which shows the position of the selected target to follow (TTF) in relation to the glideslope when it was at current Ownship position (see Fig. 7), and a vertical situation display showing the vertical relationship between Ownship trajectory and TTF trajectory (see Fig. 6, lower left area). The glidepath reference display is implemented as a supplemental “caret” displayed with Ownship glideslope deviation on the primary flight display. Previous research on wake avoidance displays indicates that lead past position effectively provides pilots with useful information with respect to wake risk [22].

With this combination of features the pilot of Ownship could be aware of whether their current position, in relation to the trajectory of the TTF, is such that a wake risk exists. A pilot may then choose to adjust the flight path to a more advantageous position with respect to wake avoidance, while recognizing that the minimum altitudes specified in the instrument approach procedure and stabilized approach criteria must be respected.

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The pilots were asked “Please select the aircraft categories that cause you to consider wake when maintaining visual separation behind an aircraft you are following to the same runway.” They were told to “Check all that apply,” which resulted in counts greater than the number of pilot respondents.

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**Table 2. Aircraft types with respect to which wake concern was indicated**

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>Number of Pilots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy (80)</td>
<td>12</td>
</tr>
<tr>
<td>B 757 (39)</td>
<td>213</td>
</tr>
<tr>
<td>Large A (1:16)</td>
<td>359</td>
</tr>
<tr>
<td>Large B (142)</td>
<td>382</td>
</tr>
<tr>
<td>Small AC (54)</td>
<td>325</td>
</tr>
</tbody>
</table>

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Figure 5. Methods Employed by Pilots in Avoiding Wakes on Approach to Single Runways: Subjective Results by Ownship Category and Mitigation Method
VI. IMC CAVS FOR SINGLE RUNWAY APPROACHES: OPERATIONS CONCEPT ILLUSTRATION

Figs. 8 and 9 show a sequence of proposed tasks and notional CDTI display to illustrate the IMC CAVS procedure during approaches to a single runway, in this case following a hypothetical RNAV runway transition. In Fig. 8 two aircraft are inbound to Los Angeles International Airport (LAX) via an RNAV Transition1 to the ILS to runway 25L. ATC points out traffic to Ownship using phraseology that includes the traffic aircraft identification (ACID), and asks the crew to report when it is identified. The pilot locates the intended TTF on the CDTI, selects it to display its data block, and reports “traffic identified” to ATC. ATC advises “maintain CAVS separation” and issues clearance for RNAV Transition1 to the ILS for Runway 25L. The pilot is now free to adjust the speed as desired to maintain a safe interval. As both aircraft proceed inbound, Ownship continues to monitor traffic ahead, adjusting closure rate to a comfortable value. When established on final approach (Fig. 9), Ownship continues to monitor deceleration of TTF, recognizing that about 2 NM separation at the threshold would be a practical minimum to assure that TTF has time to clear the runway. If wake is a concern, wake situation awareness is provided by a display of stored vertical position of the lead with respect to the glide slope and the pilot would adjust in trail threshold separation accordingly. The wake situation awareness caret displays the lead aircraft’s relative altitude when it was at Ownship’s current position, effectively indicating the lead’s deviation from the glideslope. The vertical situation display provides information about the expected position of Ownship with respect to the lead aircraft’s vertical path, based on Ownship’s current trajectory. Based on this information, Ownship adjusts its path or spacing as needed as it continues its approach. Once the TTF lands, responsibility for runway separation reverts back to ATC. However, Ownship continues to monitor the lead TTF, now slowing down to exit the runway, to make sure that the runway is clear prior to landing.

VII. SIMULATION STUDY OF IMC CAVS FOR SINGLE RUNWAY APPROACHES

An exploratory simulation was conducted by MITRE/CAASD in the summer of 2008 to better understand the factors, performance, and feasibility of conducting an IMC CAVS for single runway arrivals procedure with these CDTI tools, when the initial identification of and spacing behind TTF is fully conducted by reference to the CDTI while operating in IMC. These conditions extend the currently approved VMC CAVS procedures ([18] and [19]) into less than visual approach conditions. The simulation included the CDTI displays and vertical situation display tools illustrated in Figs. 6 and 7. Weather conditions were set to a 1500 feet (ft) ceiling and visibility of 3 mi, requiring pilots to use the CDTI information to manage spacing in IMC until passing the final approach fix. Initial visual contact with the traffic was not required.

15 These call out procedures are being investigated in other research. See, e.g., [25]
Eight commercial airline pilots flew two baseline visual approaches with no CDTI available, and 14 ILS approaches using the CDTI during which spacing data was collected. Two demonstration departure scenarios were also performed using the CDTI for spacing. One of the baseline approaches and 3 of the ILS approaches were behind Heavy TTFs. Pilots provided their own separation from TTF either visually, in the baseline approaches, or by reference to the CDTI in IMC approaches and departures. The behavior of all traffic except the subject cockpit was prerecorded and ATC communication was simulated. No controllers were actually controlling traffic. Selected results are reported below for the approach scenarios.

Each began with Ownship established on a 20 nmi final approach with an initial spacing of about 3 or 4 nmi behind a large weight category TTF and 5 or 6 nmi behind a heavy TTF.

A. Spacing Performance

1) Spacing Behind Large Aircraft

Fig. 10 shows the spacing performance observed in the simulations behind large aircraft.

The baseline case (in red) represented performance with visual cues only, without access to the CDTI tools, but with

TCAS traffic as typically displayed on the Navigation Display (ND). The IMC CAVS performance is represented by the blue bars. Due to time limitations of the experiment, only 8 baseline cases were available, one for each subject which precluded a robust statistical analysis. However, visual inspection of the two distributions suggests that they are roughly similar. Mean spacing in the baseline was about 2.7 nmi and during the IMC CAVS approaches about 3.0 nmi. The slightly closer spacing for the baseline case is not unexpected, given that these trials were conducted early in the simulation when pilots were still learning the deceleration characteristics of the simulator and with substantially less information about TTF, since the CDTI information was not available. The rough equivalence suggests that pilots may be able to provide spacing at threshold during IMC CAVS operations that approximates that achieved in visual operations.

The spacing performance found in these simulations is consistent with that found in past CEFR simulations conducted in 2003. ([18], [19], [24]). In those earlier simulations, the emphasis was on the feasibility of conducting CEFR operations, and not on spacing performance. In addition to demonstrating the feasibility of the procedure, those simulations indicated that the spacing achieved over the threshold was highly correlated with the initial spacing provided by ATC. The minimum spacing values achieved in those simulations were also comparable to those achieved in visual operations. It was conjectured then, that at busy facilities, ATC may be able to realize visual-like performance in a CEFR operation by using tight spacing to achieve sustained demand to the runway combined with pilot managed separation using the CDTI. The simulations reported here specifically utilized tighter initial separations in order to build on these previous results.17.

2) Spacing Behind Heavy Aircraft

Fig. 11 shows the spacing performance observed behind heavy aircraft. It can be seen, that although the minimum IMC CAVS separations achieved behind heavy aircraft were similar to those achieved in the baseline visual cases, there was more variability in spacing behind heavies. Part of this may be the effect of having more information about lead behavior than was available using out the window cues, even when combined with TCAS range information. The closure rate information and closure direction arrow may have cued pilots to adjust speed earlier than they did in the baseline trials. In addition, it is conceivable that, due to the common requirement to ensure a stabilized ILS approach, the participants may have used “increased spacing” as the primary method of flight path

17 The mean spacing over the threshold observed in the IMC CAVS simulations (3.0 nmi) is considerably less than the mean spacing reported in the operational data (4.4 nmi) for approaches during visual conditions. This is most likely an artifact of the simulation initial conditions which used a consistent and relatively close initial spacing, as compared to the broad range of initial (and final) spacing in the observed operational data. As mentioned earlier, this simulation specifically used close initial spacing in order to study the potential performance in a busy ATC environment.
adjustments behind heavies rather than the more frequently reported method in Fig. 5 of “flying high, landing long”. More detailed investigations of these factors are recommended for subsequent studies. It is also recommended that such future studies also consider the possibility of providing methods of stabilized approaches at higher glide paths to flight crews if they should choose to use them.

B. Pilot Acceptability

Pilot acceptability of the IMC CAVS procedure was assessed in two ways. At the conclusion of each scenario pilots provided an estimate of their overall workload using the Bedford Workload assessment form. [23] This assessment uses a decision tree structure to categorize the workload experienced during a trial. Scale values range from 1 (workload insignificant) to 10 (Task abandoned). Values of 3 or lower are considered to be acceptable without requiring task redesign. Mean workload by scenario trial is reported in Fig. 12. All mean values were 3 or less, and trended lower as pilots became more experienced using the CDTI for the spacing task.

![Figure 11. Observed spacing over the threshold behind heavy aircraft: IMC CAVS vs Baseline](image)

![Figure 12. Mean Bedford workload score by trial number](image)

After all trials were completed pilots provided additional input on their assessment of IMC CAVS operations using a questionnaire. Pilots indicated their degree of agreement or disagreement with a series of statements about the IMC CAVS operation, using a five point scale from Strongly Disagree (SD) through Strongly Agree (SA). Mean responses on a selection of key questions is presented in Fig. 13. The message in these questions is general agreement that the IMC CAVS procedures were judged to be acceptable by pilots both for arrivals and departures, and that pilots would be willing to accept separation responsibility using a CDTI with the display features outlined above. In addition pilots disagreed that performing the IMC CAVS spacing task compromised the safety of the operation. These findings are consistent with pilot responses to similar questions in the earlier CEFR research ([18], [19], [24]).

C. Display Assessment

Finally, pilots were asked to rank the utility of the 12 display features that were available to support the IMC CAVS operation. Pilots were asked to rate the most useful feature as 1 and the lowest rated feature as 12. The ranking results are presented in Fig. 14. The basic data related to TTF used for the spacing task (range, weight category, groundspeed, closure rate) were rated highest. The vertical situation display features which would have the highest utility when following a Heavy TTF were rated lowest. This is an interesting finding since the wake awareness questions in the post scenario questionnaire also indicated that pilots judged them to be useful, with aggregate scores of 4.375, (i.e., between Agree and Strongly Agree) for utility when following a heavy jet, and 4.0 (Agree) when following a large jet. It is possible that due to the novelty of the features and the relatively small number of scenarios provided for following heavy jets that the other features were simply judged to have more utility on a comparative basis.

![Figure 13. Mean response to selected post scenario questionnaire items](image)

VIII. DEPARTURE IMC CAVS: CONCEPT OF OPERATIONS

Constraints over departure paths can reduce airport efficiency when conditions drop such that visual operations cannot be conducted. Fig. 15 shows departures for LAX over a one hour period when visibility was 10 mi and ceiling was unlimited. It can be seen that most departures must go straight out for nearly 8 NM due to environmental restrictions. When conditions are visual, the tower clears aircraft for visual separation from the lead aircraft. Visual separation is maintained by flight crews until the courses diverge. This also enables an application of the more efficient visual separation rules from the airport. Because of the long straight out climb, tower-provided visual separation is not possible and the ceiling must be quite high for pilot provided visual separation to be used. When visual separation cannot be used on the departure tracks, radar separation rules apply, and the airport departure rate drops by nearly 20%. Use of IMC CAVS over such departure tracks could enable a recovery of this lost capacity. Figs. 16 and 17 show the potential use of departure CAVS.

In the example shown, ATC identifies an opportunity to use CAVS for separation between departures on the same runway,
and advises the trailing aircraft to expect CAVS separation behind the lead aircraft. The pilot of the trailing aircraft identifies the TTF and selects it to display its data block, and reports “traffic identified” to ATC (Fig. 16). Applying standard departure separations, when the lead aircraft is at least 6000 ft ahead and airborne, ATC advises lead aircraft’s direction of flight, states “maintain CAVS separation” and issues takeoff clearance to the trailing aircraft. Since the lead is accelerating, initial spacing at departure is increasing until Ownship matches speed. The pilot of the trailing aircraft maintains safe separation from leading aircraft as the lead traffic climbs into IMC (e.g., the marine layer). The departure CAVS procedure ends when other separation, such as altitude, divergent headings, or radar separation is achieved (Fig. 17).

The visual procedure is also used at LAX between departures from the two complexes and the operation is affected in the same manner when visual separation cannot be used. Departure CAVS could be used to regain this lost capacity in the same manner as described above. It should also be noted that the use of RNAV routes would significantly enhance this procedure.

Similar opportunities for applying CAVS separation have been identified at other major facilities such as ATL, ORD, and DFW.

Two departure scenarios using CAVS separation were conducted to gather initial pilot feedback on the feasibility of the procedure. One trial was a departure behind an aircraft on the same runway, and the other behind an aircraft on the opposite side departure runway. Pilots provided their feedback on the post simulation questionnaire. For the limited trials conducted, pilots indicated that they would be willing to conduct such an operation with the tool set provided and described earlier, and that they did not identify significant operational or safety issues.

Like IMC CAVS for single runway arrivals, this procedure, though less mature, also appears to be highly beneficial and potentially feasible. It is recommended that further
IX. SUMMARY AND RECOMMENDATIONS

This paper presented initial operational concepts, potential benefits and potential CDTI tools for two IMC CAVS applications

- IMC CAVS for single runway arrivals using instrument approaches, and
- IMC CAVS for departures

The paper showed that data exists to suggest that procedures for IMC CAVS for these two applications could be developed and the requirements (such as the CDTI tools necessary) to conduct them could be derived with additional focused analysis and simulations. The data also indicates that significant benefits may be achievable with these procedures. It is recommended that appropriate analyses, simulations, and coordination, required to develop these concepts, be conducted within the framework of an appropriate group of stakeholders.

In the study reported here, no controllers were used to set up traffic. It is expected that efficient traffic flow will require that controllers issue the CAVS clearance at an appropriate time to ensure a smooth arrival flow. Additional simulations should include real time ATC to examine the effects on threshold spacing when CAVS separation is available to ATC. This would also provide a greater variety of initial spacing at clearance that might more closely replicate actual traffic flows, and permit more accurate comparison with real world track data.

Future simulations should also be designed to determine whether the wake situation awareness tools are in fact required rather than just "nice to have" for safely performing the IMC CAVS operation behind wake generating aircraft. This may be driven in part by the weather minima to be approved. For example, at high weather minima (such as those used in this simulation) pilots may have sufficient time after breaking out of the clouds to visually adjust their flight paths during the last stages of the approach as they do today during visual approaches. In this case the wake situation awareness tools may be perceived to be less useful. Conversely, the wake situation awareness tools may be considered more important for cases where direct visual assessment of TTF trajectory is not feasible and procedures approved for using these tools in IMC have been tested and determined not to have de-stabilizing effects on the approach trajectory.

Pilot feedback on path adjustment during instrument operations indicated that airlines practices require pilots to fly a stabilized approach for the final several miles (the actual requirements vary somewhat from carrier to carrier). In order to conduct IMC CAVS operations with the efficiency found in visual conditions, means would have to be found to enable pilots to fly their wake mitigation techniques of choice (such as fly high) yet still be in compliance with the carrier’s requirement to “fly stabilized approaches.” The possibility of using alternate glide slopes offered by RNP or LPV approaches may provide some potential solutions. Limiting the IMC CAVS procedure to higher minima (e.g., 1500 ft) may also mitigate some of this requirement, permitting pilots to begin making glide path adjustments after breaking out, supported by displaying the actual altitude history of the lead, rather than begin confined to visual estimates.

Regarding runway occupancy, for visibilities down to say 2 or 2.5 miles, flight crews could determine visually that the airplane they were following had safely cleared the runway. In lower visibility cases, specific additional information may be deemed necessary for crews to be able to determine whether the traffic to follow is vacating the runway. These future studies should therefore consider operations down to various ceilings and visibilities, such as 1500 ft & 3 mi, 800 ft & 3 mi, and 200 ft & 0.5 mi, to identify any additional display features that might be required to support determination of runway occupancy. Various solutions may be possible, including direct visual observation after breaking out of instrument conditions,
to indications on the display. A range of these mitigations should be explored.

Although it may ultimately be the goal of the IMC CAVS procedure to conduct single runway approaches down to 200 ft ceiling and \( \frac{1}{2} \) mi visibility (Category I minima), a phased approach is suggested for establishing the minima to which IMC CAVS operations would be conducted. For example, in implementation phase I, the community could consider conducting IMC CAVS with ceilings no lower than 1500 feet and visibility no less than 3 mi, then in subsequent phases reduce the weather minimums to allow the procedure with ceilings of 800 feet and 2 mi eventually to down to category I minima. It is worth noting that visual approach operations are often terminated at relatively high VMC, when reliable visual acquisition begins to break down. Significant benefit could still be derived from CAVS approvals at weather conditions that are still technically VMC.

The IMC CAVS applications described here are only two of several possible IMC CAVS applications. This potential larger set of IMC CAVS applications should be kept in view while developing the procedures and requirements for the two procedures presented here. It is recommended that a more generalized IMC CAVS capability be developed. It is conceivable that additional CDTI tools may be required for this more generalized IMC CAVS capability. Integration with RNAV procedures is also expected to enhance, and in some cases enable, such new procedures. A seamless design of CDTI tools, integrated with advanced navigation capabilities and ATC procedures applicable in the NAS should be the goal of such IMC CAVS development.

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