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Takeoff Performance Monitoring System Display Options

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This article summarizes the development of head-up and head-down cockpit displays for an airplane takeoff performance monitoring system (TOPMS). Basic TOPMS displays provide pilots with real-time graphic information concerning their airplane's current and projected runway performance. The displays also indicate the status of associated airplane systems (e.g., flaps, engines) and optionally, they provide "GO/NO-GO" advice and a continually updated prediction of where the airplane can be braked to a stop. The displays have been developed and evaluated on the NASA Transport System Research Vehicle (TSRV) B-737 simulator by more than 40 government, airline, and industry pilots who rated the displays favorably and judged them easy to monitor. The TOPMS has also been flight tested successfully on the TSRV B-737. Based on these evaluations and on discussions with the commercial aircraft community, the displays have evolved to a baseline final configuration containing basic performance and system-status data to which GO/NO-GO advisory and predicted stop point information can be added as options.

Introduction

IN recent years, approximately 10% of all aircraft accidents occurred during takeoff and/or abort operations. According to National Transportation Safety Board (NTSB) records, over 4000 takeoff-related accidents occurred between 1983–1990, resulting in 1378 fatalities.[1]

Current flight management systems do not provide the pilot with timely knowledge of achieved acceleration relative to a nominal acceleration based on ambient conditions, proper thrust, and "nominal" execution of the takeoff maneuver. They also provide no explicit GO/NO-GO decision aids. Therefore, it was postulated that many serious takeoff-related accidents might be avoided or downgraded to relatively simple low-speed aborts if an appropriate takeoff performance monitoring system (TOPMS) were available to the crew.

TOPMS-type research[2-8] has been conducted and discussed for a number of years, but no satisfactory real-time system has been developed and implemented commercially. NASA Langley responded to this need by developing the TOPMS as a software/graphics program that could be installed on modern airplanes that are equipped with suitable computers, sensors, etc.; otherwise such equipment would have to be added. The host airplane for the TOPMS simulator and flight studies has been the NASA Transport Systems Research Vehicle (TSRV), a highly modified B-737-100 research airplane. Figure 1 shows a functional view of the TSRV.

Evolutionary development and evaluation of the TOPMS technology are summarized in the next several sections, followed by descriptions and research-pilot rankings of, and comments on, three selected display sets.

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TOPMS Algorithm

The TOPMS algorithm creates and manipulates a variety of performance, status, predictive, and advisory information. Prior to beginning a takeoff roll, the algorithm accepts input values representative of aircraft loading, ambient conditions, runway geometry, and runway surface conditions (viz., wet, dry, icy, etc.). From these inputs and other stored information, including airplane-specific data, the algorithm determines nominal values for such parameters as engine-pressure-ratio (EPR), GO/NO-GO decision speed (also called critical-engine safety speed) V_1, rotation speed V_R, and takeoff safety speed V_2. It also predicts locations on the runway where the airplane will reach V_1 and V_R relative to the selected start point and to a computed ground-roll limit line (GRLL). The GRLL represents the farthest position down the runway at which the airplane can reach V_R and still achieve the Federal Aviation Administration (FAA) required 35-ft-high screen height at the end of the runway after experiencing failure of the critical engine at V_1.[9] The algorithm then computes a nominal acceleration schedule based on existing conditions, achievement of correct thrust, and proper (normal) execution of the takeoff maneuver.

During the takeoff roll, TOPMS tracks measured acceleration for comparison. Then, based on this comparison and other pertinent runway parameters, constraints, and programmed criteria, the algorithm continually 1) determines whether the takeoff roll should be continued or abandoned (i.e., "aborted"), and 2) updates its prediction of where the airplane can be stopped when using maximum wheel and spoiler (aerodynamic) braking. No credit for using reverse thrust is included in the stop-point predictions; however, if both engines appear to be operating satisfactorily, reverse thrust can be used to shorten the stopping distance somewhat.

TOPMS Display Evaluation Studies

During display evaluation studies, TOPMS information was conveyed to pilots on electronic-screen head-down displays (HDD) and on simplified head-up displays (HUD) that were electronically superimposed on the TSRV simulator's out-the-window runway scene as shown in Fig. 2. Also shown in this photograph is a typical TOPMS HDD that appears on the TSRVs navigation display (ND) screen during the takeoff roll, but is replaced by regular navigation information after liftoff.

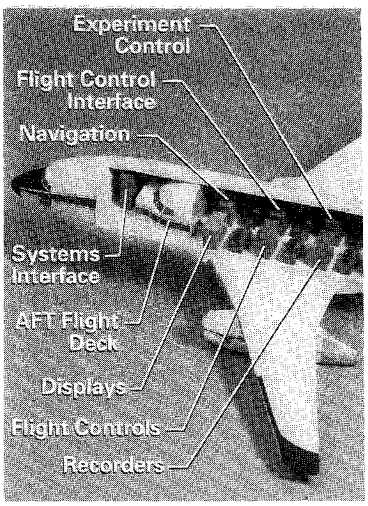

Fig. 1 Cutaway view of the TSRV.

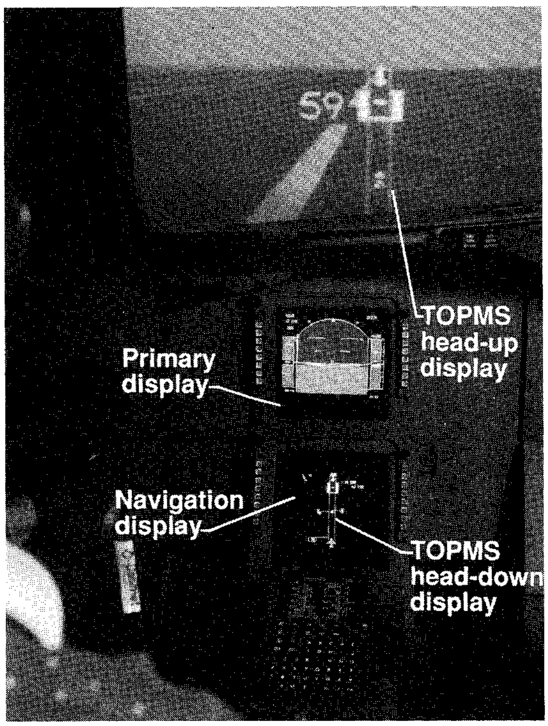

Fig. 2 TOPMS displays in simulator.

The primary display (PD), showing attitude, altitude, and other information, is located just above the ND. No HUD was available during the flight test study.

TOPMS Initial Simulator Experience

The simulator flight crew consisted of a "pilot-flying," who controlled the takeoff and made the GO/NO-GO decisions, and a "pilot-not-flying," who had primary responsibility for monitoring the TOPMS display(s). Each pilot subject spent approximately 2 h in the simulator—1 h in each role.

HDD symbology for the early TOPMS displays is defined in Fig. 3. This sketch portrays an airplane advancing at 97 kt toward two triangular symbols. The apex of the unshaded triangle marks where the airplane's speed was initially predicted to reach V_R. The apex of the dark triangle marks the updated expectation of where V_R will be reached. Advancement of the dark triangle relative to the unshaded (fixed) one provides fundamental performance information. In this case, it indicates that along-track acceleration is seriously deficient, and thus, the airplane will require significantly more distance to reach V_R than initially predicted.

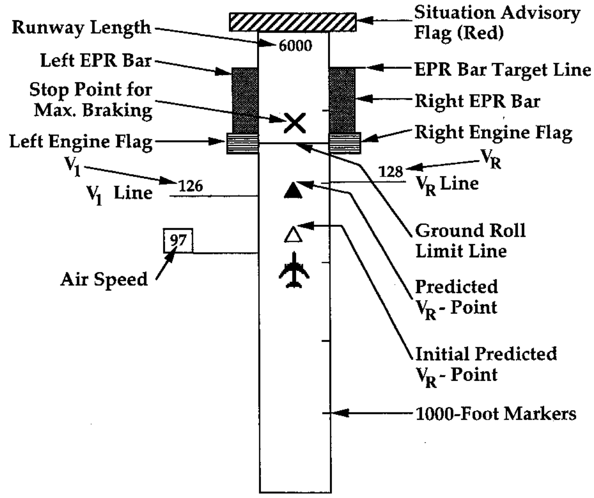

Fig. 3 Early TOPMS display symbology.

During the initial simulation study[6] only the TOPMS HDDs were available to the crew. These HDDs contained all of the symbology shown in Fig. 3 except the EPR bars (which were added for Ref. 7 and subsequent studies). Consequently, the cause of the large acceleration deficiency depicted in Fig. 3 would not have been immediately apparent to pilots during the initial study. The green engine flags (rectangles at the base of EPR bars) would have ruled out engine failure, but would not have indicated whether the performance of either engine was marginal. Thus, the pilot-flying would have to make the GO/NO-GO decision without knowing whether the acceleration deficiency was being caused by low thrust, excessive drag, or some of each.

The displays were evaluated with the assistance of a detailed TOPMS-display rating diagram and an associated questionnaire. The diagram contains various display criteria tied to a 1–10 rating scale, where "1" denotes "satisfactory—excellent." In the initial study,[6] 32 experienced government, airline, and other industry pilots, operating as 2-man crews, gave the HDDs an average rating of "3" (characterized as "satisfactory—good"). The pilots' general perceptions were that the TOPMS HDDs were easy to monitor and provided valuable status, performance, and advisory information (most of which is currently unavailable in their cockpits.) They recommended continuation of TOPMS research and offered the following suggestions: 1) develop and implement a simplified TOPMS HUD (to complement the HDD); 2) provide an analog display of measured EPR relative to an EPR target value (i.e., the "scheduled" or nominal value obtained from the airplane's flight manual); and 3) display along-track-acceleration error as a prominent analog symbol.

Modified HDD/HUD Experience

In a follow-on simulation study,[7] a modified HDD and a simplified HUD were implemented on the TSRV simulator. The modified HDD contained all of the information shown in Fig. 3. For the deficient-acceleration situation portrayed, the fully extended (to target mark) EPR bars indicate that nominal thrust is being delivered by both engines; thus the acceleration deficiency suggested by the separated triangles can be attributed to some type of excess drag. The red situation advisory flag (SAF) at the end of the runway graphic indicates that acceleration performance is unacceptable by TOPMS standards, and "NO-GO" is the "recommended" (not "required") control action.

Whenever a takeoff is abandoned (i.e., when an abort maneuver is initiated by retarding the throttles to "idle"), all takeoff-related information on the HDD disappears from the graphic runway display, leaving only 1) the airplane symbol (denoting the airplane's position), 2) the speed box (in which groundspeed replaces airspeed), and 3) two predicted stop

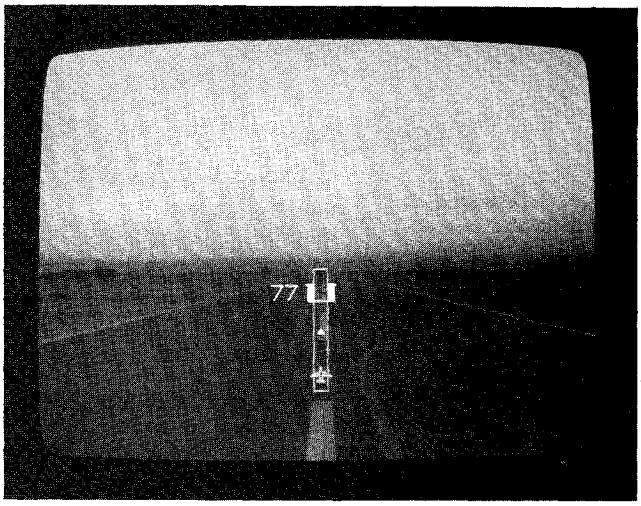

Fig. 4 TOPMS HUD during normal takeoff roll.

points, one based on the application of maximum braking, and the other based on maintaining the currently measured level of deceleration for the remainder of the maneuver.

Figure 4 shows the TOPMS HUD superimposed on the simulator's runway scene during a normal, no-error takeoff roll. In this case, the two triangles are coincident and the EPR bars are extended to the proper length. Airspeed is shown as large numerals beside the runway graphic. The other symbols defined in Fig. 3 are not included on the HUD. In Ref. 7, the evaluation pilots provided separate ratings for the HDDs and the HUDs. The HDDs again were given an average rating of 3, but the HUDs received an average rating of "2" ("satisfactory—very good"). The pilots again made several suggestions for display improvement, from which the following were selected and implemented for further study:

1) Delete the engine status flags (see Fig. 3); the EPR bars vis-a-vis the EPR-target marks provide adequate alternative information.

2) Do not display a green "GO" SAF when a takeoff is proceeding satisfactorily; only display it in cases where continued takeoff becomes the only viable option (e.g., when the predicted stop point is beyond the end of the runway).

3) Make the GO and NO-GO SAFs different sizes and/or shapes so that they can be easily distinguished in poor lighting conditions, without dependency on color.

TOPMS Tests on TSRV

TOPMS software for the HDD displays was implemented on the flight computer in the console labeled "Displays" in Fig. 1. In this airplane, there are no provisions for installing either HDDs or HUDs in the regular forward flight deck, or provisions in the aft flight deck for braking or showing HUDs and/or out-the-window runway scenes (real or computer-generated). Consequently, the experiment was conducted using the following procedures:

1) A pilot-flying controlled the airplane from the left seat of the forward flight deck.

2) A "TOPMS-pilot" monitored the TOPMS display on the ND screen in the research (aft) flight deck and via the TSRVs regular intercom, he periodically informed the pilot-flying of the observed progress of the takeoff roll and immediately reported significant anomalies, such as a failed engine or a large acceleration deficiency.

3) A "safety-pilot" performed normal copilot duties from the right seat of the forward flight deck.

The TOPMS flight tests were conducted at five different airfields under a variety of ambient conditions and on several dry runway surfaces, including asphalt, smooth concrete, and concrete with longitudinal and lateral grooves (1/4 in. depth and width). No wet or icy surfaces were encountered.

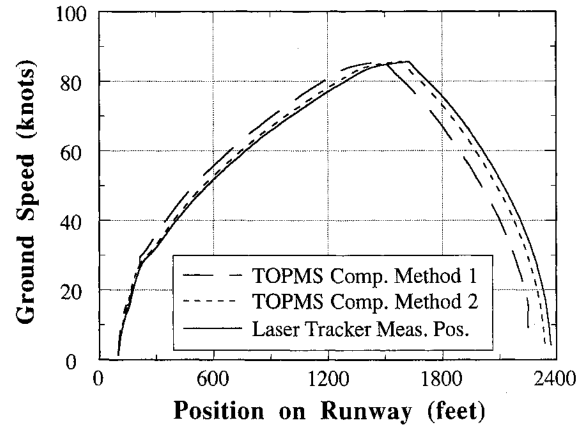

Fig. 5 Takeoff/abort travel distance as determined by three methods.

The distance-prediction accuracy and computation of the airplane's instantaneous location on the runway were checked during several runs at the NASA Wallops Flight Facility (at Chinquoteague, Virginia) using a highly accurate Laser Oblique Radar Tracker.

Figure 5 shows a typical takeoff roll to 80 kt, where the TOPMS-pilot called for an abort. The pilot-flying responded and stopped the airplane in the distance shown using maximum wheel braking and fully deployed spoilers (but no reverse thrust).

The airplane's positions on the runway were determined by three methods: 1) ground-based laser-tracker measurements, 2) double integration of the along-track acceleration, and 3) single integration of the groundspeed. In Fig. 5, the laser-tracker data showed that the airplane stopped approximately 2400 ft down the runway. The algorithm, after filtering and double integrating the measured acceleration (method 1), computed the stop point to be approximately 200 ft (i.e., two airplane lengths) short of the laser-tracked position (although the accelerometer may have ceased operation just prior to reaching the stop point). During postflight analysis it was determined that if the independently measured/filtered groundspeed signal (available on this research airplane) had been single-integrated (method 2) over this range, the airplane's position would have only been approximately one-half an airplane length short of the laser tracked position. This same trend occurred for an abort at 100 kt.

Overall, the TOPMS algorithm and the HDDs performed well in the noisy, vibrating real-world environment of the test airplane. The TOPMS-pilot, who had actively participated in the project since its inception, judged that the displays had performed as expected, and in his opinion the TOPMS simulator-developed technology had been transferred in working order to the TSRV B-737 test airplane.

TOPMS Workshop

The TOPMS concept and display-evaluation results were presented at a national workshop for airline-pilot organizations, airline management representatives, avionics systems manufacturers, and officials from the FAA, the National Safety Board (NTSB), and the Flight Safety Foundation. The overall reaction was that TOPMS was the type of cockpit technology that potentially could aid the pilot in making proper GO/NO-GO decisions during an abnormal takeoff roll. Several attendees, however, felt that the displays may contain more information than necessary or desirable. In particular, advisory flags and predicted stop-points were identified as potential problem sources, particularly if the runway surface contained wet or icy patches.

To address these concerns, a number of alternative takeoff performance display formats were subsequently investigated. The remainder of this article describes experiments conducted in the TSRV simulator to evaluate three of the most promising configuration sets (i.e., "Display Options").

TOPMS Display Options—Description and Evaluation

Three selected TOPMS display options were shown to five research pilots, and one airline pilot, who each flew solo in the TSRV simulator and experienced each option for a variety of conditions. All six pilots had participated in at least one of the previous studies. The selected display options are described below.

Option 1 displays contain basic performance and status indicia, but lack GO/NO-GO advisory flags and predicted stop-point information; however, during the abort maneuver (only), the displays exhibit a predicted stop-point based on double integration of the measured/filtered acceleration. (This symbol is common to all three options.)

Option 2 expands option 1 by including GO/NO-GO advisory flags and a second predicted stop-point, based on the use of maximum wheel and spoiler braking, but no reverse thrust. This option comprises the displays that evolved from the earlier simulation studies and it is essentially the set of displays that were flight tested.

Option 3 expands option 2 by providing a preliminary or "abort-warning" advisory flag (octagonal) whenever degraded acceleration exceeds a preliminary unacceptability threshold (denotes unsatisfactory, but still acceptable). If the acceleration continues to degrade and the error exceeds a second threshold ("unacceptable"), the advisory flag's interior becomes filled with red—mimicking a STOP sign. Symbology for these three options is shown in Fig. 6, for similar acceleration-error conditions.

Option 1 is illustrated by the sketch on the left in Fig. 6. At 97-kt airspeed, measured along-track acceleration has become quite deficient, as evidenced by the length of the acceleration-error arrow. This arrow is not displayed when the error is less than 5%; above 5% a white arrow appears and grows until its length exceeds limit 1 (shown as a large tick mark beneath the acceleration-error arrow). Beyond limit 1, the arrow turns amber; when it reaches limit 2 (unseen tick mark superimposed on the GRLL) the arrow turns red. [The limit 2 tick mark has no relationship to the GRLL; in this study, its value was scaled and arbitrarily placed on the GRLL to preclude the need for another (visible) tick mark.] As a result of the large acceleration error, the dark triangle, marking the current prediction of where the airplane will reach V_R, has moved farther down the runway—considerably ahead of the stationary unshaded triangle. The size of this separation indicates that acceleration is and/or has been considerably below nominal. Looking further, both EPR bars extend up to the EPR target line, indicating that both engines are providing the desired nominal thrust. Consequently, the acceleration deficiency is attributed to some type of excess drag (e.g., aerodynamic and/or frictional). Even though takeoff remains a viable option as long as the dark triangle does not cross the GRLL, an abort should be given strong consideration—particularly if the acceleration-error arrow approaches limit 2. No situation advisory flags are provided in option 1, but limit 2 could be considered the acceptability/unacceptability (or abort) threshold.

Option 2, depicted by the middle sketch in Fig. 6, adds SAFs and a predicted stop-point "X" based on immediate abort and use of maximum wheel and spoiler braking. The situation is similar to that for option 1, except that the acceleration-error arrow has exceeded its single programmed unacceptability limit (could be either limit 1 or 2) and has disappeared from view. Simultaneously, an abort SAF (STOP sign) has appeared, advising an immediate abort, which can be terminated at the X symbol. (If the X were beyond the end of the runway, a large green forward-pointing arrow (GO advisory flag) would have appeared in place of the STOP sign.)

Option 3, portrayed on the right side of Fig. 6, is a variation of option 2. The situation and the acceleration-error limits are the same as for option 1. However, the display is showing an abort-warning flag (octagon), indicating that the acceleration error has exceeded limit 1.

The TOPMS displays (head-up and head-down) in Fig. 2 portray an acceptable excess-drag situation in which the resulting acceleration error is less than the limit 1 value. If the acceleration error increases and just exceeds this limit, the head-down option 3 display would appear as shown in Fig. 7, where the outline of an octagon has appeared at the end of the runway graphic. An X (predicted stop-point), based on maximum braking has appeared and is positioned almost on top of the dark V_R triangle. If and when the error arrow reaches limit 2, the arrow will disappear from the display and the octagon outline will convert to a full abort advisory flag

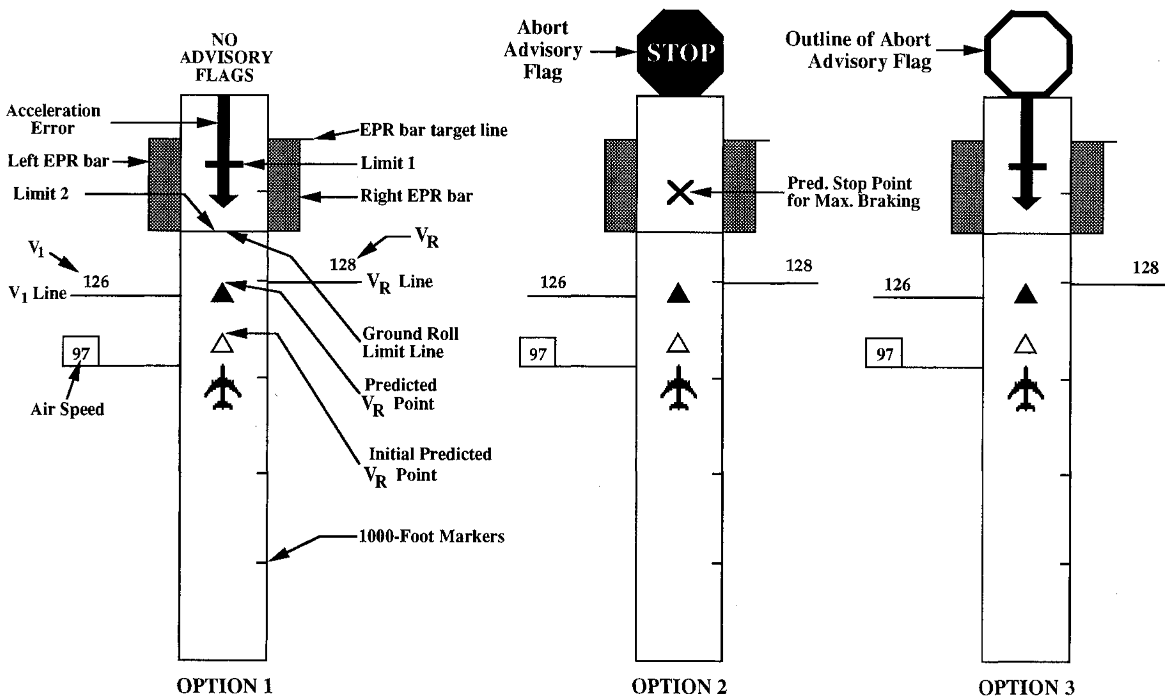

Fig. 6 Symbology for three display options.

Table 1 Pilot rankings of display options

Pilot	Option 1	Option 2	Option 3
1	3	2	1
2	1	3	2
3	3	2	1
4	1	2	3
5	3	2	1
6	3	2	1

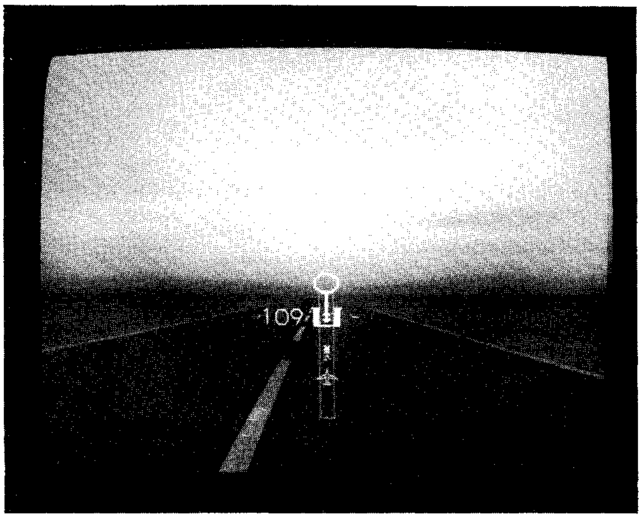

Fig. 7 Option 3 HUD showing marginally acceptable acceleration error.

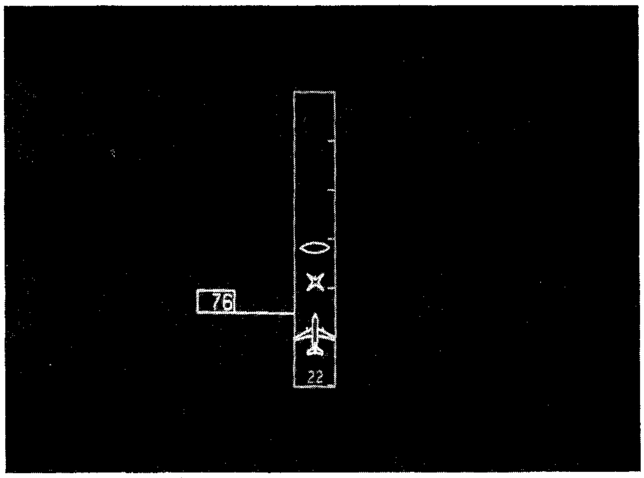

Fig. 8 TOPMS abort display.

(viz., a STOP sign). For this situation, the option 3 display has the same appearance as the option 2 display.

Once an abort has been initiated while using any of the display options, all of the symbology related to takeoff is deleted. However, the airplane (position) and stop-point symbol(s) are retained, as shown in Fig. 8. Groundspeed has replaced airspeed in the speed box. This figure depicts option 2 or 3 displays, which contain both predicted stop points; the option 1 displays contain all the symbology except the X stop point.

The pilots in this study flew (in the simulator) alone; thus, having to monitor the HDD, the HUD and the runway scene as necessary. They were not asked to perform a rigorous evaluation of the displays as they had in prior TOPMS studies[6,7]; instead, they were asked to rank the three options according to preference and then answer a short questionnaire supporting their choices. Their rankings are presented in Table 1, and a summary of their comments is as follows.

Pilot 1

Pilot 1 preferred option 3 over option 2 because of the way the acceleration-error degradation is depicted: 1) the appearance of the octagon appropriately warned and mentally prepared him for a potential abort situation; 2) he felt that option 3 symbology is less dictatorial than option 2, where a STOP sign suddenly appears whenever acceleration error exceeds a specified acceptability limit, 3) he would have preferred having more display information than is provided by option 1, thus preferring option 2 over 1; 4) he would likely decide to abort less quickly when using option 1 displays because the acceleration-error arrow color changes are less noticeable than the appearance of the outline-octagon in option 3 and the STOP sign in options 2 and 3; and finally 5) he would have preferred having both stop-point symbols appear in all abort displays, including the option 1 abort displays.

Pilot 2

Pilot 2 preferred the option 1 displays (but not strongly); he liked certain features of each display: 1) he preferred options 1 and 3 over option 2 during degraded acceleration-performance situations because their displays provide enhanced indications of the acceleration degradation; and 2) he judged option 1 to provide generally adequate information at low and moderate speeds, but at higher speeds, preferred having "a second opinion" (GO/NO-GO SAFs) to reinforce his abort decisions; 3) in addition, he would like SAFs to remain on the screen longer during the abort-initiation maneuver, preferred seeing the maximum braking stop point, X, during high-speed aborts, and preferred that stop-points not be displayed during normal takeoffs, not even near V_1.

Pilot 3

Pilot 3 considered all three display options satisfactory and desirable and felt that, with proper training, all could be used comfortably and correctly: 1) he preferred displays providing the most information, hence, his options-preference order was 3-2-1; also he 2) judged option 1 to provide generally adequate information. However, for problems at high speeds, lack of a SAF might cause loss of valuable time "visually trouble-shooting" while the airplane was rapidly running out of potential braking space.

Pilot 4

Pilot 4 judged all options to provide adequate and timely information and found the displays to be simple, intuitive, and easy to monitor: 1) he preferred option 1 because of its simplicity and felt that he could recognize potential abort situations with it about as quickly as with the options containing abort SAFs; and 2) he recommended that the "Must-GO" SAF (large green forward-pointing arrow) also be added to option 1—to quickly alert the pilot whenever continued takeoff becomes the most viable control choice.

Pilot 5

Pilot 5 judged the symbology for all three options to be satisfactory and operationally acceptable, and judged abort conditions at low speeds to be obvious; therefore, the simplest display was sufficient: 1) he preferred options 2 and 3 at high speeds because the SAFs provide a definite indication of serious problems, and 2) he preferred option 3 overall, but not strongly.

Pilot 6 (Airline Pilot)

Pilot 6 judged that with very little training, he could fly all three options equally well: 1) he preferred having as much information as possible available in case of need; he 2) judged the predicted maximum braking stop point (X) during abort to be a useful cue in determining the amount of pressure on brake pedals that was required to produce full braking, and 3) he felt that the amber acceleration-error arrow (option 1) and the octagon outline (option 3) do not remain on the screen long enough and recommended using a 10% differential between limits 1 and 2 instead of the 5% used in this study.

Pilot evaluation results are summarized and discussed by display-option in the following paragraphs:

Option 1 was favored by two of the six pilots. In their opinion, this option provided all necessary information: i.e., runway locations where V_1 and V_R would be reached; measured acceleration-performance relative to predicted performance; critical-engine status and performance information; and a pictorial indication of the minimum field length required for takeoff. Lack of explicit GO/NO-GO advice or an indication of where the airplane could be stopped in case of abort were not considered display weaknesses by these two pilots. The other four pilots did not dislike this option; however, it was generally ranked third because the least amount of information was provided.

Option 2 provided the same information as option 1 plus GO/NO-GO advisory cues and predicted maximum-braking stop-point information. Because it provided this additional information, five of the evaluation pilots rated it their second preference. It was ranked third by the other pilot because it lacked the acceleration-error enhanced degradation symbology provided by options 1 and 3.

Option 3, being very similar to option 2, adds an advance-warning abort SAF (octagon) to indicate the existence of acceptable, but less than desirable acceleration. This option was preferred by four of the six pilots, primarily because this feature allowed them extra time to mentally prepare for a potential abort.

Even though the pilot evaluators in this study were only asked to rank the TOPMS display options, it was clear from their verbal and written comments that all of the displays contained readily comprehendible, easy-to-learn/easy-to-use cockpit technology. Any of the three display options investigated were judged to be satisfactory from a control-decision standpoint and, with suitable training, each could be used comfortably and confidently. Although each pilot had certain display preferences, the consensus judgment was that providing any appropriate set of performance and status information during takeoffs/aborts is far better than that provided by current cockpit technology. The pilots in the current study judged that providing predictive and advisory information was appropriate and useful, but that the TOPMS displays would have considerable merit with or without such information. Similar comments were made at the end of each of the prior TOPMS simulation studies.[6,7]

Concluding Remarks

This investigation concludes the TOPMS formal research and evaluation program at NASA Langley. In prior NASA TOPMS studies, many display elements were viewed, "flown," and evaluated by 41 Air Force, airline, and research pilots. They recommended elimination of symbology considered to be of limited value, and the inclusion of other symbology which might provide useful cues. Many of the recommended features were implemented. The algorithm has been judged to provide valuable and appropriate takeoff/abort performance and advisory information. The TOPMS head-up and head-down information displays have evolved to an expandable "final" configuration set comprised of a baseline array of elemental information, with options to include certain advisory and predictive features. The three options investigated in this study were all judged to be acceptable by six evaluation pilots. However, there was not a consensus on the preferred option. In particular, four pilots preferred the option (option 3) that provided the most information, i.e., all of the elemental, predictive, and advisory information. The other two pilots selected the option 1 displays, which provided only enhanced elemental information. Option 2, which provided both elemental and advisory information was selected as a strong second choice by five of the six pilots.

As a consequence of this study and earlier concerns expressed by the broader aircraft community, it seems prudent to recommend a final TOPMS configuration comprised of a baseline set of displays to which advisory and predicted stop-point data/symbology could be incorporated. Thus, potential users could select the features that best suit their needs and operations philosophy. Their "selected configuration" might be one of the configurations investigated in this or prior TOPMS studies; or it may comprise some other combination of the above discussed features; or it may only contain part of them. The most important finding is that each of the three display options provide the pilots with valuable and timely new cockpit information regarding how well their takeoff is proceeding, particularly when abnormal conditions are occurring.

In the opinion of the evaluation pilots, there would be no problem learning to use any of the display options shown in this study, and that each could be used confidently, comfortably, and successfully. Each pilot emphasized that use of any one of the options was far better than having no TOPMS-type information in the cockpit. The TOPMS algorithm is designed to service any of these and many other options. Consequently, additional display features such as advisory or predictive information could be readily incorporated.

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