JOURNAL OF AIRCRAFT
Vol. 45, No. 2, March–April 2008

Design, Integration, and Preliminary Assessment of a Takeoff Monitor Display

David Zammit-Mangion*
Cranfield University, Bedfordshire, England MK43 0AL, United Kingdom and University of Malta, Msida, MSD 06, Malta
and
Martin Eshelby†
Cranfield University, Bedfordshire, England MK43 0AL, United Kingdom

DOI: 10.2514/1.22967

The takeoff performance monitor is an instrument that monitors the progress of the takeoff and provides advisory information intended to support the crew in their decision to continue or abort the run. A critical component of the instrument is the display design. This paper reviews the requirements for, and constraints associated with, such a display and presents design criteria established at Cranfield University. The Cranfield design is then discussed, explaining the interpretation of the display in operation. Issues relating to the integration on board the flight deck and the reasoning behind critical design aspects are also described in detail.

Nomenclature

a	=	longitudinal acceleration
C_D	=	coefficient of drag
C_L	=	coefficient of lift
k_1, k_2	=	coefficients
M	=	coefficient
m	=	aircraft mass
S	=	wing reference area
T	=	thrust
V_R	=	rotation speed
V_g	=	aircraft ground speed
V_1	=	decision speed
v_w	=	headwind component of windspeed
W	=	aircraft weight
θ	=	runway slope
μ	=	runway rolling friction
ρ	=	air density

I. Introduction

TAKEOFF in a conventional, fixed-wing aircraft involves, in principle, the acceleration of the vehicle to a target airspeed that will allow it to lift off the runway and safely climb above the terrain and other obstacles. The maneuver must be completed within the runway constraints and consequently it is necessary to ensure that the runway length available is adequate. In practice, this is done through performance scheduling where, prior to departure, the runway length required for the particular flight is estimated and compared with that available. The runway length required depends on several environmental and operating conditions, such as dispatch weight, thrust setting, wind conditions, ambient temperature, and pressure. Several of these parameters are physically unknown, particularly because the performance calculations may be carried out hours before the intended departure. As a result, a certain degree of uncertainty is associated with the values of the parameters used. To mitigate this problem, studies were carried out in the early years following the second World War to model the effects of such variations. The variations in the parameters, that is, the differences between the expected values of the parameters used in the calculations and the actual values that were eventually prevailing during the actual takeoff maneuver, were assumed to be Gaussian in nature with a particular standard deviation identified for each distribution. Such an assumption is reasonable, because these variations are by definition random. The collective effect on the runway distance requirements was then also found to have a Gaussian distribution, with a standard deviation of 3% of the expected distance requirement about the mean [1]. In other words, the distances covered in separate takeoffs conducted in identical conditions can be expected to be normally distributed around the mean (net) performance, with a standard deviation of 3% of the expected (mean) distance requirement.

To achieve an acceptably low probability of the aircraft exceeding the estimated runway requirements in the eventual takeoff, scheduled performance introduces several leeways. The major leeways include the following:

1) The allowance for the contingency of an engine failure. To this effect, the takeoff is aborted if the engine failure occurs during the early part of the run and is continued otherwise. This effectively defines a decision speed V_1 beyond which the run should not be aborted. Calculations are carried out to determine runway lengths required for a) the all-engines-operative (AEO) takeoff, b) the one-engine-inoperative (OEI) continued takeoff, in which engine failure is assumed to occur at V_1, and c) the aborted run, aborted at V_1.

2) Conservative allowances for headwind and tailwind conditions. Only 50% of the expected (usually reported) headwind is taken into account, whereas tailwind components are increased by 50%.

3) Using expected values for the parameters used, the calculations will yield the average expected runway lengths required. This is termed the gross performance. 15% is added on to the gross performance in the AEO case. Because actual aircraft performance exhibits a normal distribution with a standard deviation of 3% of the expected (average, or gross) performance, a 15% allowance corresponds to 5 standard deviations. Consequently, the probability of an aircraft exceeding 115% of the calculated net performance is statistically of the order of 1 in 10^7 of all takeoff runs.

Following dispatch, the crew will carry out the takeoff assuming that the aircraft will indeed perform within the leeways allowed for in

Presented as Paper 6218 at the AIAA Atmospheric Flight Mechanics Conference and Exhibit, San Francisco, California, 15–18 August 2005; received 3 February 2006; revision received 18 April 2007; accepted for publication 18 April 2007.

*Lecturer, Department of Aerospace Engineering, School of Engineering; also Senior Lecturer, Department of Electronic Systems Engineering, Faculty of Engineering. Senior Member AIAA.

†Associate Fellow AIAA (Retired).

the predispatch calculations. Ensuring that the scheduled thrust is correctly set, the crew repeatedly scans the aircraft instruments during the ground run to ensure that the aircraft is actually performing normally and therefore should become airborne successfully within the runway constraints.

The takeoff run is a maneuver involving relatively high pilot workload, where the aircraft may be operating at the regulated limit of performance and events would occur in quick succession should an anomaly arise. Quick identification of any unfavorable conditions and the timely and correct decision to continue the run and become airborne or to reject the run are crucial to the successful completion of the maneuver in such circumstances. Success, in this context, refers to the completion of the takeoff maneuver without an accident. During the maneuver, the only objective means with which the crew can assess the progress of the run are the airspeed indicator, the speed-trend vector, and the engine instruments. While indicative of the performance of the aircraft and progress of the takeoff, the information assimilated from these instruments does not explicitly indicate whether the takeoff will actually be successful or not. As a result, the crew is obliged to assume that it will be successful and will normally also rely on their perception of acceleration, experience, and visual cues to confirm this assumption. The crew's real-time assessment of progress of the maneuver, therefore, is highly subjective.

From a regulatory perspective, scheduled performance provides a statistical protection against exceeding runway estimates by keeping the probability of exceeding the distances, and thus the probability of hitting obstacles at the end of the runway or beyond, adequately low. While successfully providing the protection from a statistical point of view, the mechanism fails to adequately protect the individual takeoff. Indeed, there are several loopholes that can result in failure of the maneuver. The most significant limitations are as follows:

1) Gross performance is allowed for in the OEI case. This implies that if the takeoff is to be aborted at V_1 for any reason, there will be a 50% chance of the aircraft overrunning a limiting runway. This also assumes the aircraft will have average, or normal, performance during its acceleration to V_1.

2) Only the well-defined OEI case of failure is allowed for. Other contingencies, such as tire bursts, which would significantly affect braking capacity, are not allowed for.

3) Scheduled performance does not allow for errors in the calculations and parameter entry, nor does it allow for erroneous thrust settings or instrument failure. If, for example, the aircraft is dispatched heavier than estimated, not only will the runway allowances be inadequate, but the decision, rotation, and climb safety speeds will be too low and second-segment climb performance may be compromised.

The limitations of the mechanism have been demonstrated in a number of accidents over the years, but more significantly, as no substantial improvement has been introduced to mitigate them, it is reasonable to expect that it is only a matter of time before another accident will occur. Indeed, the authors are of the opinion that inadequate performance during takeoff may be occurring more frequently than believed, but these situations go unnoticed mainly because no objective means is used with which the crew or operators —even through postflight analysis—can assess the actual aircraft performance. Also, aircraft often operate from long runways and the leeways allowed for contingencies that do not occur on the specific run prove to be adequate, so it is very possible for poor takeoff performance to go unnoticed.

The takeoff monitor is an instrument intended to mitigate this problem by monitoring the performance of the aircraft during takeoff and providing an output that will significantly enhance the crew's situational awareness and thus contribute to the successful completion of the maneuver. The concept has been first suggested nearly half a century ago and there have since been several proposals, none of which has yet been successful commercially.

II. Aerospace Standard 8044

Society of Automotive Engineers (SAE) Aerospace Standard 8044 [2], released in 1987, defines a minimum performance standard for takeoff performance monitors.[‡] It also defines the scope of a performance monitor to "monitor the progress of the takeoff and to provide advisory information which the crew may use in conjunction with other available cues to decide to continue or abort the takeoff" and explicitly specifies that a performance monitor may not automatically initiate action to abort a takeoff.

The standard defines three types of performance monitor, namely, types 1, 2, and 3. Type 1 monitors are those which compare the achieved aircraft performance to its scheduled counterpart. Such monitors do not have any predictive capacity. Type 2 monitors are defined as those which, apart from providing the comparison and indication of type 1 systems, also predict the continued takeoff situation (parameters such as the location where the takeoff is complete, the effect of a critical engine failure, etc.). Type 2 monitors do not predict stopping distance. Systems with such a predictive capacity are classified as type 3. They perform this prediction on the basis of the current speed and position of the aircraft on the runway.

Of major relevance to this discussion is the standard's reference to display requirements. The standard requires displays to the following:

1) "Utilize natural and meaningful symbology readily understood by the crew."

2) "Indicate to the crew in a timely manner the deviation between airplane reference performance and the achieved airplane performance . . . ."

3) "Provide information immediately discernible to the crew such that there is no need to watch the display for a period of time to observe rates of change or relative motion."

4) Avoid the sole use of binary, noncontextual signals.

Instrument accuracy is fundamental to reliability in operation and AS-8044 addresses the matter accordingly. Of relevance to this discussion is the requirement that, besides the accuracies specified, the probability of the system presenting hazardously misleading guidance information to the crew because of an unidentified system failure needs to be shown to be less than 10^{-5} for a part 25 certified aircraft.

III. Monitoring Takeoff Performance

The fundamental question associated with the takeoff maneuver is whether the aircraft will become airborne within the runway constraints. It is therefore expected that performance monitors would attempt to predict the actual distance that will be covered during the run. This, however, is not a trivial task. Indeed, for the purposes of calculating runway distance requirements, the takeoff maneuver is segmented in a number of phases as follows [3]:

1) The *acceleration* phase, during which the aircraft is accelerating along the runway with the nose wheel on the ground. The attitude of the aircraft is essentially constant in this phase.

2) The *rotation* phase, during which the aircraft is rotated to the appropriate attitude to support liftoff.

3) The *transition* phase, during which the aircraft is airborne and pitching up, prescribing a curved path in the vertical plane.

4) The *climb* phase, during which the aircraft is climbing at a steady pitch angle and climb gradient. As the takeoff is considered complete at 35 ft above the runway datum, the climb phase may or may not be included in the takeoff maneuver.

5) In the case of a rejected takeoff (RTO), the *deceleration* phase, during which the aircraft is decelerating to a halt following the rejection of the run.

The distances covered during the rotation, transition, and climb-out phases are highly dependent on piloting technique and therefore cannot be estimated with an accuracy that is adequate for monitoring purposes [4]. Also, the distance covered during the deceleration phase is highly dependent on tire status, brake performance, and runway condition, while the time between the acceleration and deceleration phases, during which the crew will be reacting to the failure, depends on crew response time and coordination. As a result, any estimate of these distances would also be inadequate.

[‡]TOPM refers to the Cranfield takeoff performance monitor in Table 1.

The inference from this discussion is that only the acceleration phase can be used to provide an estimate of *actual* performance based on the true operational and environmental conditions. During this phase, the aircraft is accelerating at essentially a steady attitude and thus the drag profile is readily characterized and predicted. Any estimate of performance in the later phases can only be as accurate as scheduled performance, because any attempt to predict such values involves, in essence, the recalculation of scheduled performance. The authors consider the value and merit of such a recalculation questionable. The arguments supporting this statement are presented in Sec. V.

The major question associated with takeoff monitoring, therefore, is how, given the constraints discussed, can the progress of the run be reliably and timely quantified in terms of the expected outcome in a manner that is unambiguous and conducive to the safe execution of the decision to continue or reject the run.

IV. Past Design Proposals

A. Earlier Designs—Electromechanical Era

Before the advent of digital computers on the flight deck, the available technology generally restricted designs to depend on simple monitoring techniques. The modeling of the equations of motion was too complex to implement in electromechanical technology to a level of accuracy that is adequate for the useful application in takeoff performance monitoring. As a result, many systems were designed to measure *achieved* or *instantaneous* performance up to that moment, rather than attempt to predict the performance of the remainder of the run on the basis of that achieved. This classifies them as type 1 instruments under the AS-8044 classification.

Many early nonpredictive devices were based on acceleration monitoring or on measuring achieved airspeed as a function of either time or distance gone. The most basic of indications used with such systems were discrete go/no-go indicators or warning lights [5]. This has, however, been long before the introduction of AS-8044 considered to be an unfavorable indication and consequently quantitative displays have emerged. Numeric quantitative displays have been proposed, particularly to indicate runway distances [6,7], but the value (with respect to the decisional capacity of the crew) of this information provided alone in the said format is questionable. Analog (graphical) displays have, in fact, been favored by many designs. A common analog display concept is that based on the analog meter. The NACA [8] and Doman [6] (Fig. 1) designs, which measured achieved acceleration, are among those based on this concept. The actual acceleration measured was factored to compensate for the droop in acceleration as the run progressed, resulting in an indication that should remain steady under theoretical and normal conditions. A minimum threshold, or reference acceleration value, was also displayed to provide comparative information to the crew. The display of instantaneous acceleration, however, does not directly translate to a measure of the runway distances expected to be covered, as this involves the double integration of the parameter to provide positional information. As a result, the interpretation of this instrument in terms of takeoff performance can, in dynamic and limiting conditions, be misleading. For example, if the acceleration fluctuates resulting in an indication that crosses the minimum (threshold) limit, it is unclear whether the performance is adequate and within scheduled allowances.

Other indication methods proposed include the display of the current performance leeway in terms of the excess airspeed achieved at that particular instant during the run [9] (Fig. 2). In this type of display, the expected and minimum allowable airspeeds at that moment during the run were superimposed on the airspeed indicator (ASI). This instrument effectively computed these values continuously and the indicators, or bugs, moved along the display with the airspeed needle. The relative position of the airspeed needle with respect to the two bugs would provide an indication of whether the achieved airspeed was adequate. Although significantly more representative of aircraft performance than the acceleration monitor, such a display still fails to provide unambiguous indication of whether the aircraft will complete the takeoff maneuver within the runway allowances. Yet other designs were based on the representation of the runway and indication of runway distances or positions displayed on tape indicators [10].

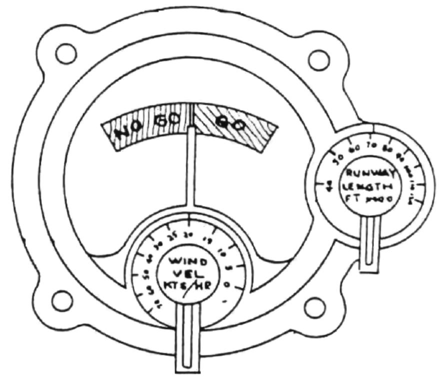

Fig. 1 The analog meter indicator is a Doman display indicating acceleration superimposed on go/no-go areas derived from scheduled performance. Some designs have adopted a classical-ASI type of display to indicate achieved acceleration (reproduced from [6]).

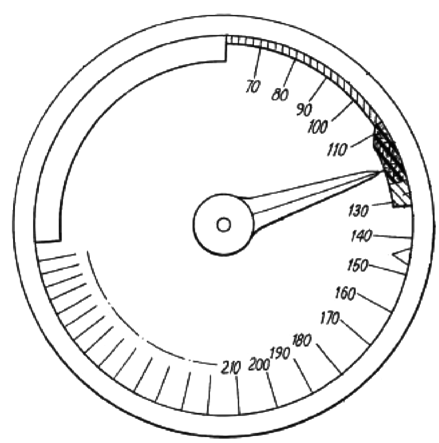

Fig. 2 The analog indicator superimposed on the ASI is an analog display indicating a comparison of achieved airspeed with scheduled airspeed (reproduced from [9]).

A significant limitation of the nonpredictive approach adopted by many of the earlier designs is, however, identified. The value of nonpredictive monitoring is limited, as a particular indication does not translate to the specific outcome of the run. Furthermore, the comparison between an instantaneous situation and scheduled performance implicitly assumes a "reference" performance profile, but no such profile exists. This is because scheduled performance calculations only calculate runway allowances and are not directly related to any "reference profile." This has indeed been pointed out by the British Civil Aviation Authority in 1984 [11]. As a result, predictive monitors are preferred.

B. Later Designs—Digital Computer Era

The advent of digital computers supported the advanced modeling of aircraft dynamics and introduced a new dimension to the scope of displays with the introduction of the glass cockpit. As a result, many of the later designs attempted to model aircraft performance using appropriate performance calculations to predict the actual distance requirements of the run. With the hurdle of accurate modeling over, the difficulty of accessing the required parameters was encountered. Access may be limited due to the particular avionic system installation limitations (such as availability of air data) or the intrinsic difficulty of measuring the parameter with reasonable confidence (such as aircraft weight and runway friction). Notwithstanding the uncertainties associated with predictions of postrotation perform-

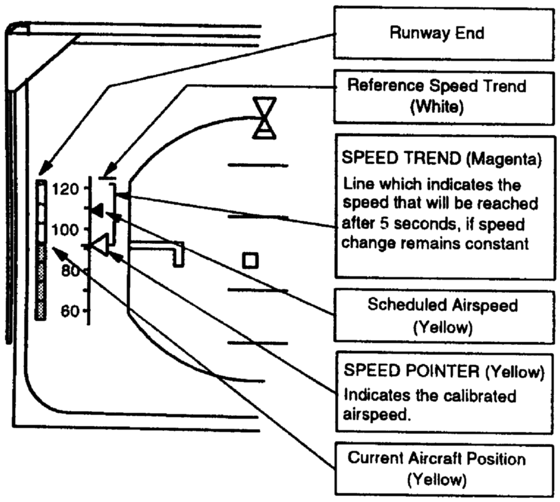

Fig. 3 The simplest display studied by the NLR, referred to as type 1 (reproduced from [14]).

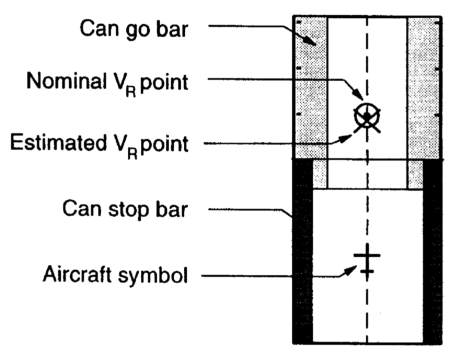

Fig. 4 The most complex display studied by the NLR, referred to as type 3 (reproduced from [14]).

ance, various proposals also attempted to predict runway distance requirements to the completion of the run.

Display designs in general also became more complex. Many favored the representation of the runway on the display. Such designs include those proposed by NASA [12], Boeing [13], and the National Aerospace Laboratory (The Netherlands) (NLR) [14]. NASA developed versions of their design for both head-down display (HDD) and head-up display (HUD) technologies. Whereas NASA conducted studies on the optimization of their basic configuration [15], the NLR compared three models to study the usefulness of increased information at the expense of display complexity. Both organizations have concluded that the runway representation method was favorable. In their study, the NLR considered the implementation of the three types of monitor defined by AS-8044 and concluded that their nonpredictive (type 1) monitor implemented with a display as in Fig. 3 provided little improvement in overall safety, while their predictive (type 3) system, illustrated in Fig. 4, provided optimal safety advantages [14].

V. Cranfield Philosophy

The philosophy adopted at Cranfield University was to adopt an integrated approach during conceptual design. In this stage of the design, an in-depth multidisciplinary study was carried out addressing the following: 1) the operational scenario during takeoff, 2) the practicalities and difficulties associated with reliably quantifying takeoff performance, 3) acceptance on the flight deck, 4) certification considerations, 5) avionics integration limitations and considerations, 6) human factors issues associated with display considerations, and 7) the information the system is intended to display.

This exercise then supported the identification of the optimal balance between the associated tradeoffs and the integration of all issues in the forming of the philosophy adopted at Cranfield University.

A. Operational Scenario During Takeoff

Takeoff is a relatively high-risk maneuver conducted in the vicinity of obstacles, and aircraft performance is often balanced between higher dispatch weights driven by economic drivers and runway leeways driven by safety requirements. The risks associated with safety during takeoff include the following: 1) failure to become airborne, resulting in a high-speed runway excursion (overrun); 2) collision with obstacles at the end of the runway due to poor acceleration and late liftoff; 3) overrotation and the risk of the event of a tail strike and its associated effects; 4) failure to achieve or maintain positive climb following liftoff; 5) stalling on or soon after liftoff. Stalling in these circumstances is generally not recoverable. 6) Poor second-segment climb and the associated risk of collision with obstacles and failure to meet minimum climb gradients; 7) low-speed runway excursion (overrun) following the rejection of a run; 8) damage to aircraft (brakes, tires, and undercarriage) following a high-energy (high-speed) rejection of a run; and 9) operational delays following a rejected takeoff. Even if no damage is suffered, a high-energy rejection may require a return to stand to allow for the brakes to cool before the takeoff is attempted again.

The fact that, statistically, a rejection from the decision speed V_1 has a 50% probability of ending in a low-speed overrun must also be taken into account. The reason behind this is that the probability of rejection *at* V_1 is assumed to be acceptably low and the introduction of further leeways would compromise performance (in terms of dispatch weights, and thus commercial returns) unnecessarily. Consequently, a high-energy rejection (close to V_1) constitutes a high-risk maneuver and should be avoided unless necessary. Accordingly, an 80-kt call out beyond which the run is aborted only if a failure (or anomaly) that can compromise the safe continuation of the run is normally adopted. Rejection below 80 kt normally only results in the slight operational delay of resequencing the aircraft for takeoff. On modern aircraft nonessential alerts and warnings that are not associated with the takeoff maneuver are suppressed during takeoff to avoid distracting the crew.

The thrust-to-weight ratio of large transport aircraft is of the order of 0.3 for two-engined aircraft and about 0.25 for their four-engined counterparts. The duration of the acceleration phase, therefore, is highly dependent on the rotation speed V_R. In practice, this is of the order of 20–30 s for commuter jet aircraft and single-aisle aircraft of the size of the Boeing 737 and Airbus A320 and up to 60 s for large, four-engined aircraft of the size of the Boeing 747. As a result, the time in which the crew can identify an anomaly, decide to take action (reject the run), and actually take action is very short. During this period, the pilot handling the aircraft (PH) will be guiding the aircraft and essentially looking outside the cockpit, while the pilot monitoring (PM) scans the displays to monitor the progress and health of the aircraft. In this latter task, the airspeed indicator, speed-trend vector, and engine instruments are scanned to ensure that no anomaly exists, otherwise the run would normally be aborted. A decision to abort on the grounds of performance is normally based on the identification and separate confirmation of the anomaly. For example, an engine failure would be identified and confirmed by two separate instruments. Other anomalies could be more difficult to confirm and may even depend on personal perception.

Following the previous discussion, the reluctance of crews to abort in the vicinity (even up to 10 kt before) of V_1 is readily understood. This is aggravated by any hesitation in the decision due to absence of sufficient confirmation of a perceived anomaly.

This analysis of the operational scenario during takeoff has contributed to the Cranfield philosophy by resulting in the identification of the following requirements:

1) The instrument needs to provide early, timely, and reliable indication of performance.

2) The probability of the instrument causing an unnecessary rejection needs to be acceptably low. Because of the nature of the situation and the device, the performance monitor *should* increase the number of rejections, but these must be justified. An unnecessary rejection is considered to be a wrong decision in the circumstances.

3) The instrument needs to be predictive to provide an early indication of the outcome of the maneuver based on the developing conditions.

B. Quantifying Takeoff Performance

The quantification of takeoff performance needs to be adequately reliable for the purposes of takeoff performance monitoring. On the basis of the analysis of previous works, it is evident that for performance assessments to be useful in real time, they need to be made on the basis of runway distance predictions. Consequently, the Cranfield concept is based on runway distance predictions.

Considering the three types of monitor defined in AS-8044, it would appear that type 3 should be the preferred choice for monitor design. The discussion in Sec. III, however, clearly illustrates how any postacceleration-phase distance predictions are, in essence, recalculations of scheduled performance. As a result, any attempt at developing a type 3 monitor would essentially result in distance predictions that are the sum of individual predictions of the different phases of takeoff, with all postacceleration distance estimates being taken from scheduled performance. The process of comparing actual performance estimates with scheduled performance, then, is, in essence, reduced to a comparison between the performances of the acceleration phase, because the postacceleration-phase distances are, by definition, equal.

Such an approach is conservative. If an aircraft is performing well, it will achieve V_1 before the scheduled allowance. This not only provides a leeway in the distance margin, but also provides an indication that the post-V_1 performance—including the second-segment climb performance—should also be within scheduled limits. The greater the leeway up to V_1, the greater the probability that the post-V_1 performance will be adequate.

The distance that will be covered to rotation can be estimated from the expression of acceleration in the acceleration phase [Eq. (1)]:

$$a = \frac{T - [\frac{1}{2}\rho S(C_D - \mu C_L)](V_g - v_w)^2 - W[\sin\theta - \mu\cos\theta]}{m} \tag{1}$$

A major limitation in the use of this equation is that several parameters such as engine thrust, aircraft mass (and weight), ground rolling friction, and the actual runway profile (slope) are not known and cannot be measured with adequate reliability with current technologies. As a result, a novel method of modeling aircraft performance in the acceleration phase had to be invented at Cranfield University to support the reliable prediction of aircraft performance during takeoff.

This method is based on the capture of data from the history of the particular run and using it to forward predict the performance up to V_1. Accordingly, the ground speed of the aircraft is monitored as a function of time and this is used to estimate actual lumped parameters representative of the actual parameters in Eq. (1).

It can be shown that, from Eq. (1), the ground speed can be expressed as a function of time [16]:

$$V_g = \frac{M\{1 - e^{k_1 t}\}}{1 + k_2 e^{k_1 t}} \tag{2}$$

where M, k_1, and k_2 are coefficients and functions of the parameters of Eq. (1). For values of M, k_1, and k_2 within the normal operational envelope of jet aircraft, the expression in Eq. (2) can be closely approximated to a second-order polynomial function of time. This polynomial is then used to forward predict the distance that is expected to be covered by the aircraft up to V_1, assuming that prevailing conditions remain unchanged. This distance estimate is compared with its scheduled counterpart, and the leeway, in terms of a percentage, is then used to drive the Cranfield display.

This method of performance prediction essentially results in the estimation of coefficients with an adequate accuracy for the purpose of predicting performance up to V_1. Results demonstrating this have been published by the authors [17].

C. Acceptance on the Flight Deck and Certification Issues

The aviation community is essentially divided over the merits of takeoff performance monitoring. Although it is generally accepted that the concept would be beneficial and could contribute to improved safety during takeoff, there is a significant sector, including regulatory bodies, that holds strong reservations based on concerns on reliability and its detrimental effect on safety. There are also the added complications of commercial value and legal implications. It is difficult to objectively associate a commercial value to additional safety. Furthermore, from commercial and operational points of view, airlines are only required to meet current standards of operation and associated requirements because this, legally, is sufficient to support safe operation. Despite the fact that many in the community, including a number of national safety boards, are aware of the shortcomings of the current procedure, admitting to it is often perceived as admitting to operating unsafely, resulting in a "catch-22" situation.

From a certification perspective, the major issues are associated with the probability of increasing the risk of accident. Because of the nature of the takeoff maneuver, any information that may mislead the crew into taking inappropriate action in the circumstances may readily result in an accident. The regulatory bodies are also reluctant to introduce a system if it would require a change in, or be in conflict with, current procedure (unless safety is enhanced).

The form of instrument required to display takeoff performance information to the pilot needs to take into consideration its effect on pilot workload. The most important criterion is that pilot workload shall not be increased by the introduction of an addition to the instrument panel. Takeoff is a critical maneuver in which the pilot handling and pilot monitoring have well-defined procedures that must not be changed by the introduction of the takeoff monitor. Thus the monitor must integrate seamlessly with current procedure and practice.

To overcome the hurdle of acceptance and satisfy certification considerations, therefore, the requirements established for the Cranfield design also include the following:

1) The need to seamlessly integrate the system with current procedures in the cockpit, avoiding the need for any changes.

2) The need for the system to provide situational awareness information and not advisory information.

3) The need for the system to focus on *complementing* current performance, to protect against scenarios that are not adequately addressed in current procedure.

4) The need for the display to provide quantitative information of the information displayed.

D. Integration into the Aircraft

The takeoff performance monitor was intended to be integrated onboard current-technology aircraft. Such aircraft are assumed to have a glass cockpit, be equipped with an inertial navigation system (INS), a digital air data system (ADS), and a flight management system (FMS) linked together with an ARINC-429 bus. To facilitate the integration onboard the aircraft, the algorithm was required to interface with a minimal set of avionic equipment, thus comprising the ADS, FMS, and INS. This requirement indirectly affected the display design, as it conditioned the type of performance-related information that could be accessed or estimated. Such constraints may affect the size and positioning of the display.

E. Human Factors and Information Displayed

On the analysis of previous display designs, it becomes clear that a successful display is required to present information that is easily assimilated, while providing an unambiguous indication of the eventual outcome of the takeoff. These two requirements have

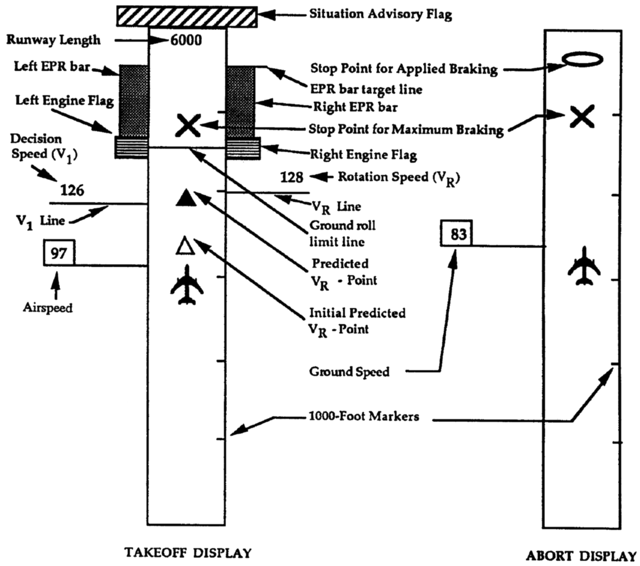

Fig. 5 The HDD proposed by NASA. Most of the symbols are dynamic during takeoff, and viability of the options available during takeoff is represented by the relative position of the pointers (reproduced from [15]). EPR: engine pressure ratio.

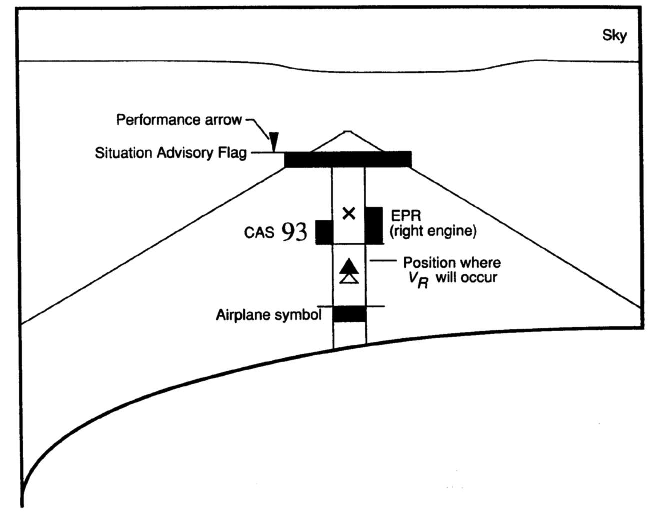

Fig. 6 The HUD proposed by NASA. Most of the symbology is identical to the HDD (reproduced from [15]).

generally not been satisfied simultaneously by previous designs. The displays presented in Figs. 1 and 2, for example, are easy to assimilate but fail to provide an unambiguous indication of the eventual outcome of the takeoff. In contrast, Fig. 5 requires continuous monitoring and is more complex to interpret and is therefore, in the authors' opinion, more demanding on crew workload. Figure 6 presents the head-up display version of the display illustrated in Fig. 5.

VI. Cranfield Display

The basic question the takeoff performance monitor attempts to answer is whether the performance of the aircraft is sufficiently adequate to allow the takeoff to be completed successfully within the runway constraints; this information would optimally complement the current procedure by effectively closing the loop in accident mitigation. Scheduled performance calculations before takeoff ensure that runway distances *will* be adequate, while real-time performance monitoring then *confirms* that the actual performance is adequate.

A simple "go/no-go" indication that indicates whether or not the runway distances are adequate has long been considered inappropriate as it does not permit judgment to be exercised by the pilot; it is, in effect, an executive device. The quantitative display of information is therefore preferred. Indeed, it is evident that crews would want to know how close to the limit the aircraft is operating. This is because the actual leeway is directly related to the probability of success of the maneuver and is thus also a measure of the risk of accident. Such information would optimally complement the crew in their decision to continue or reject the run by providing objective information on the risk associated with either decision. However, the display needs to be very simple to read and assimilate if additional workload is to be minimized. For this reason, it was decided that there should be no alpha–numeric information displayed as this needs to be read and remembered by the pilot. Furthermore, the information displayed should be in a fully integrated form that requires no mental processing or continuous monitoring by the crew. In concept, the display should be as easy to read and assimilate as the fuel gauge of a car. In most cases the fuel gauge has no calibration other than "full," "half full," and "empty," an exact fuel quantity remaining being irrelevant from a tactical point of view, and one brief glance at the gauge tells the driver that there is sufficient fuel for the journey or otherwise; such a display is intuitive in operation. By positioning the display within the normal scan pattern of the instruments, preferably close to the airspeed indicator, there is no need to alter the current scan practice and the workload is not increased. Indeed, the confirmation that progress is satisfactory will reduce concern about the acceleration and may reduce the workload by eliminating the need to estimate the distance gone by other means. Another critical consideration is that any information displayed on the progress of the takeoff should not be able to jeopardize safety. The principle of engine failure accountability is that the takeoff must be continued once the decision speed V_1 has been exceeded and any performance information is, therefore, redundant after V_1 so that the display should be canceled at that speed.

The Cranfield display concept was, therefore, built around the fundamental requirement to provide minimal information that is easily assimilated while presenting an unambiguous picture of the situation to the crew. It was thus decided to display takeoff performance in one parameter in such a form that the implications of the displayed parameter are readily assimilated by the crew. Accordingly, the Cranfield display presents one quantity, namely, a graphical representation of the relative performance of the aircraft. The authors are of the opinion that the presentation of relative information is more appropriate than that of absolute information, as suggested by the fuel gauge analogy. This approach also ties in with the concept of net and gross performance. As takeoff performance is expected to have a standard deviation of 3% and net performance introduces a 15% leeway to cover 5 standard deviations (all but 1 in 10^7 of cases), a graphical measure of the *actual* percentage leeway available during the run can provide the crew with an indication of how the takeoff is progressing. Indeed, it is the percentage leeway of performance and not the absolute leeway that is a direct measure of the probability of success of the maneuver. For example, the performance may be better than average, less than average but well within limits, borderline, or inadequate. The authors consider the provision of such information more appropriate than, for example, absolute distances. This is because the probability of success of the maneuver (and thus also the risk of collision) is linked directly to the percentage leeway and not the absolute leeway. Indeed, a 300-m leeway provides a smaller margin for a heavily laden aircraft than a lighter counterpart.

As a result, the Cranfield display presents the percentage leeway in the form of a bar extending from the reference line of the ASI. The length of the bar is a linear function of the performance leeway with respect to the scheduled performance. The display is located adjacent to the ASI as the ASI is the most critical instrument during takeoff and is currently also used to measure performance. The extension from the reference line of the ASI was a natural choice, as this concept is standard in primary flight display presentation. A number of graduations next to the displayed bar provide a standard scale to support the correct assimilation of the quantitative information. The Cranfield display is presented in Figs. 7–13. One graduation in line

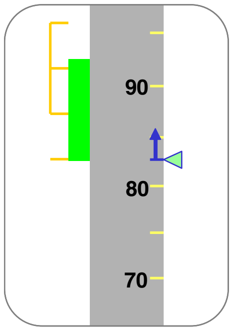

Fig. 7 Normal performance: The performance of the aircraft is slightly above average (gross) performance.

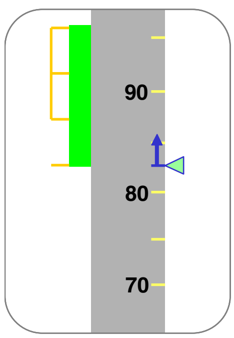

Fig. 8 Abnormally high performance: The performance of the aircraft is well above average (gross) performance.

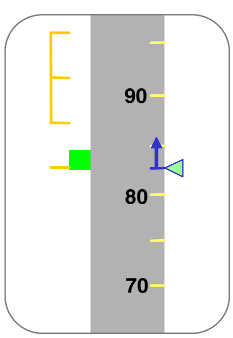

Fig. 9 Low performance: The performance of the aircraft is well below average but still within scheduled (net) allowances.

with the reference line of the ASI coincides with net performance, which is also the reference threshold of performance. If the aircraft's performance is adequate and therefore a leeway is available, the bar extends upward from this graduation. It is colored green, denoting adequate performance. The size of the green bar is a measure of the excess leeway, or the safety margin associated with the maneuver.

Three other graduations are linked by a vertical bar, forming a bracket in the shape of an "E." The middle graduation denotes gross performance. If the green bar extends to this mark, the aircraft would have average performance and have a 15% leeway from the scheduled threshold. The bracket extends on either side of the gross performance mark and denotes the boundaries of "normal performance." These boundaries are nominally set at ±2.5 standard deviations, with the bracket statistically covering just under 99% of all runs. The reasoning behind this choice of limits is presented later.

When performance is less than the scheduled threshold, the bar extends below the reference graduation and is colored red. The length of the bar is proportional to the amount of excess runway being covered. No graduations are displayed in this area, as the performance is inadequate and there is no scope of quantifying the inadequacy other than by the length of the bar to quantify the gravity of the situation.

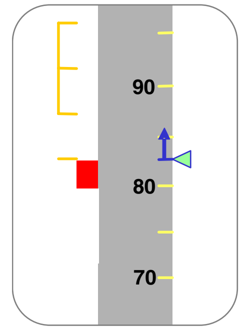

Fig. 10 Inadequate performance: The performance of the aircraft is just outside scheduled (net) performance.

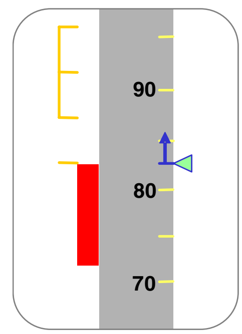

Fig. 11 Inadequate performance: The performance of the aircraft is well outside scheduled (net) performance.

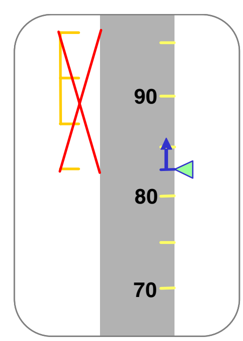

Fig. 12 System failure.

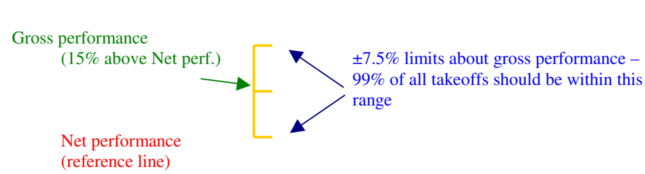

Fig. 13 The interpretation of the display graduations.

A. Display Operation and Interpretation

The display suggests the classification of performance into four categories, namely, normal, above normal, subnormal, and inadequate. In normal performance, the green bar would extend to a level within the bracket. This level of performance indicates a healthy situation with no real concerns regarding the risk of overrun, as the decision speed V_1 will be reached before the scheduled distance down the runway, thus allowing a greater leeway for braking or to become airborne.

If the (green) bar extends to the center graduation, then aircraft performance would coincide with average performance. If, in comparison, the bar extends to the upper half of the bracket (Fig. 7), the performance would be better than average but still considered normal. A bar extending only to the lower half of the bracket would likewise indicate that performance would be less than normal. Such a situation would not, however, be alarming as reasonable leeway would still be available. There are two reasons for selecting 2.5 standard deviations as the limits of extension of the bracket from gross performance. The first is that this is half the leeway to net performance, which is the minimum allowed performance at 5 standard deviations from the average. This results in four graduations being equally spaced apart, which is, from a visual point of view, desirable. The second reason is that if the bar extension falls outside the bracket, the performance can be classified as "abnormal" because it would happen on only 1% of all runs.

Subnormal performance would be indicated by a (green) bar extending to a level below the bracket (Fig. 9). Although the aircraft would be performing better than the scheduled limit and therefore theoretically within the acceptable level of risk of accident, leeways are now low and the aircraft would be performing in the 0.5 percentile bracket. From a regulatory point of view, the aircraft is still performing better than the minimum limit, suggesting that the aircraft will successfully clear obstacles and therefore the run need not be aborted. As a result, the decision to continue or reject the run is considered a matter of airline procedures at this stage. Procedure may, for example, require the rejection of the run only if the performance indication is "subnormal" below 80 kt, where the risk and implications associated with rejection would be less than those associated with continuing the run.

Above normal performance, where runway leeway is in abundance, is indicated by the (green) bar extending beyond the bracket (Fig. 8). The length of the bar correctly suggests a low risk associated with the maneuver and good performance "health." Such circumstances, however, unless deliberately conditioned with, for example, excess thrust application, would be expected on only 0.5% of all runs and this suggests that the cause of such performance should be investigated after takeoff. Indeed, such circumstances may be the result of situations of incorrect fuel loading, which may jeopardize the continued safety of the flight.

Inadequate performance is displayed by a (red) bar extended down from the reference line (Figs. 10 and 11). The implications of such performance are that the continued run is not viable and that rejection of the run from V_1 is likewise not viable. Viability, in this context, refers to whether the run will exceed the scheduled distances which, in the limiting case, will result in the collision with obstacles at the end of the runway. The implication in such situations is that the run should be aborted as early as possible to reduce the risk of low-speed overrun. The longer the (red) bar, the earlier the run needs to be aborted if the risk of overrun is to be kept low.

If the system fails or is unavailable, a clear indication of the status is presented, such as is shown in Fig. 12.

The display is not required beyond the decision speed V_1 and following a decision to abort the run, because the crew cannot elect to change their minds beyond the points in question. Consequently, the display is only available during the acceleration phase and is removed on transiting V_1 and on the initiation of a rejection, which can be typically identified by the moment when the thrust levers are retarded.

In addition to its use as a performance monitor during the takeoff run up to the decision speed, the display can be used to monitor the health of the aircraft and to identify situations in which there is the potential for the aircraft to exceed scheduled performance limits. If, during normal operations, any indications of performance in the regions outside the "E" bracket are logged, they can be investigated and used as a means of monitoring the general health of the aircraft, but particularly the health in the takeoff condition. Indications from an individual aircraft in the regions outside the range enclosed by the "E" bracket may fall into two categories as follows:

1) *Occasional, isolated occurrences:* Such indications suggest that, although the general performance of the aircraft is not a cause for concern, certain operations may be. These should be investigated for the common operating anomalies listed below. It is likely that such indications will not be confined to one aircraft.

2) *Repeated, consecutive occurrences:* If a number of indications occur in a consecutive, or near consecutive, series, and which are from a random spread of operations, then the health of the aircraft should be investigated, as this may indicate chronic performance degradation.

Operating anomalies, other than aircraft performance degradation, that may cause the indicator to indicate performance outside the $\pm 2\frac{1}{2}$ standard deviation range include:

a) *Aircraft weight* being greater/less than that assumed in the performance planning. This may be as a result of incorrect fuel uplift or a payload weight error. Although hold baggage and cargo may be weighed before loading, passengers are generally taken to be a standard weight. The variation in the weight of individual passengers from different ethnic, cultural, or national groups may vary considerably. Also, passenger hand baggage, permitted as cabin baggage, is frequently of excessive weight. Duty-free and tax-free sales made after check-in are not normally subjected to any weight checks. The actual passenger payload may, therefore, vary considerably from that assumed in the planning process.

b) *Environmental variables:* There may be significant differences between the environmental variables assumed in the flight planning procedure and those occurring at the time of takeoff. Pressure, temperature, and head/tailwind components may vary during the period between the completion of the flight planning procedure and the takeoff, particularly if a delay is experienced.

c) *Runway slope:* Although the mean slope of the runway is included in the takeoff calculations, it is based on the difference in heights between the ends of the runway. Thus, a runway with both ends at the same height will be considered as being level, although it may be humped or dished along its length. If the runway is humped, then the aircraft will perform an uphill acceleration, which will reduce acceleration. A dished runway will improve acceleration. Anomalies in performance on such runways are likely to be common and a warning could be included in the airfield information.

d) *Runway condition:* Surface roughness and friction characteristics vary between runways and will affect the acceleration. A note concerning runways with notably high-friction surfaces could be included in the airfield information. The effect of contamination (water, snow, and ice) on runway friction is also variable. Although the takeoff planning includes consideration of the effects of a reference-wet runway, the degree of wetness at the time of takeoff cannot be evaluated. The indicator would provide a direct indication of the effect of a contaminated runway and permit appropriate action to be initiated early in the run.

The reporting of anomalies will enable operators to identify airports, routes, and conditions that may need special consideration to avoid inadvertently exceeding performance limitations.

B. Pilot Assessment

The display was demonstrated to, and assessed by, line pilots during the evaluation of the complete takeoff performance monitoring system carried out by Purry [18]. In this study, 12 volunteer pilots with a range of flying experience on Boeing, Airbus, and Fokker aircraft were allowed to conduct takeoffs in Cranfield's flight simulator with the takeoff performance monitor operational and were then asked to answer a questionnaire. The major results of the questionnaire are presented in Table 1.

VII. Discussion

Under normal conditions, the Cranfield display should display a bar of constant length throughout the run. This is because, in steady conditions, the performance of the aircraft would remain constant. The display of a steady quantity is conducive to the early, quick, and easy quantification of actual aircraft performance and it eliminates the need to continuously follow the instrument during the run.

The Cranfield display has been designed to integrate seamlessly with current practice and procedure without increasing pilot workload. No changes are necessary to the standard scan pattern of

Table 1 Main results of the questionnaire

Question	Agree	Disagree
TOPM will enhance safety	100%	0%
TOPM interferes with crew monitoring task	17%	83%
TOPM use does not need training	17%	83%
Drawn to look at TOPM	50%	50%
Drawn because TOPM novel	83%	17%
TOPM urges more frequent ASI scan	50%	50%
TOPM interrupts outside scan	33%	67%
TOPM interrupts flight instrument scan	8%	92%
Compelled to abort with marginal performance	25%	75%
Compelled to abort with inadequate performance	50%	50%
Confused TOPM with trend arrow	0%	100%
TOPM increases workload	42% marginally increases	50% no effect, 8% substantial decrease
TOPM shows indication of stopping distance left	17%	83%
Safe to continue with a red bar	8%	92%
Red bar compelling to stop without further confirmation	75%	25%
Safe to go with marginal performance	83%	17%
TOPM should be executive (connected to auto braking)	0%	100%
Pilot not flying to call out TOPM indication as standard operating procedure	58%	42%
Clear policy required for action on TOPM indication	100%	0%
TOPM part of master minimum equipment list	8%	92%
Simulator training required before TOPM use	83%	17%

the flight instruments as the display is located close to the ASI. The combination of the confirmation of airspeed rising at about 80–100 kt with the indication of acceptable performance relieves the pilot of the need to check progress against distance markers or other arbitrary means of performance estimation.

The display presents aircraft performance relative to scheduled performance. This form of interpretation displays takeoff performance in terms of actual performance compared with expected performance. The alternative of attempting to calculate whether or not the aircraft will accelerate to takeoff within the runway distances available ahead of the aircraft may, on long runways, permit a takeoff to continue although the aircraft is not performing to scheduled performance and may compromise second-segment climb health. The system is, in fact, optimized to detect the subtle underperformance that cannot be readily detected by the crew. By providing a fully integrated function to be displayed, the difficulties encountered with acceleration monitors and other single parameter systems that require mental processing are eliminated and pilot workload is not increased. The display colors are compatible with go/no-go decision but, crucially, the quantitative information optimally provides situational awareness and leaves the final decision to the crew. The display is also conducive to trend monitoring. It is very easy to follow a trend and quickly extrapolate a dynamic condition to determine whether the situation will become critical. Trend information in the Cranfield display is particularly valuable as it indicates how the predicted outcome of the takeoff is changing.

By measuring aircraft performance, the Cranfield system permits flexibility in flight operation by enabling, for example, the takeoff to be expedited by taking an early entry to the runway or a rolling takeoff. Thus dependence on starting the takeoff from a specified point or from brake release with takeoff thrust set is not a necessity. In this way, the need for a runway database is also eliminated and, together with that, the possibility of using invalid information from the database. Also, autonomy was considered to be an important feature so that there is no call for the crew to initiate the monitoring on each takeoff. This avoids another critical action on the crew at takeoff and avoids an additional workload action.

A salient feature of the display is that the inclusion of "secondary" information such as tire health and wind direction is not included. Although relevant to takeoff performance, the value of the provision of such information on the flight deck during the run is questionable and indeed can even mislead or distract the crew.

All these features lead to a takeoff monitor that is fully compatible with current practice and has the capability of alerting the crew to a systematic error in the takeoff that cannot otherwise be detected.

The results obtained from the assessment questionnaire suggest that the pilot community will respond positively to the introduction of the Cranfield display on the flight deck. The primary outcome is that all pilots considered that the instrument would enhance safety and therefore reacted positively to the Cranfield design. A significant majority did not consider the display to interfere with normal operations, which satisfies the basic design requirement that the instrument should integrate well with current procedure. In unofficial trials, the authors were aware that the display could be compelling, but were of the opinion that this was mainly due to the novelty of the instrument and that once it became a normal instrument in flight operations, crews would not be attracted by it unnecessarily. This belief was confirmed by the outcome of the questionnaire, where, although 50% claimed to be drawn to the instrument, 83% of these responded that this was because it was a novel display.

One of the requirements defined by the authors during the design of the display was that it should be informative in nature and not executive. The philosophy behind this is that the authors consider the performance monitor to be a situational awareness tool aiding the pilot in his decision to continue or abort the run, and not an executive device that would abort the run automatically. All pilots agreed with this approach and their response suggests that the display was interpreted correctly and thus aided them in making the correct decision.

The questionnaire also clearly underlines the importance of training before use. This was expected by the authors. Indeed, as in all cockpit displays, it is crucial that pilots clearly understand what the display is indicating to avoid misinterpretation. Misinterpretation, in the takeoff environment, can lead to inappropriate action and possibly an accident, which would defeat the purpose of the instrument. The authors are of the opinion that the interpretation of the display, particularly in the case of marginal performance, should be an airline standard operating procedure inline with guidance interpretation from the manufacturers or authorities. This would reinforce the proper interpretation of the display and reduce the possibility of individual interpretation in marginal conditions.

VIII. Conclusions

The Cranfield display has been designed to meet the requirements of Aerospace Standard AS-8044 and the more stringent inhouse requirements that have been specified to ensure acceptance on the flight deck. Accordingly, this paper has provided solutions to two critical problems that have hitherto prevented the design of an acceptable takeoff monitoring system.

The first solution is the provision of a reliable and accurate measure of the performance of an aircraft during the critical phase of the takeoff run up to the decision speed, after which the aircraft is committed to the takeoff. The display has been developed to reduce the measure of performance to a single parameter that objectively determines whether or not the aircraft is operating within the acceptable margins permitted by performance scheduling.

The second solution is the design of a display that is intuitive in operation and does not increase pilot workload. By eliminating all superfluous information, and presenting the measure of performance in relative terms, the indicator presents a quasi-steady indication that can be immediately assimilated. By positioning the display close to the ASI, it is in the standard scan of the flight instruments and does not require any modification to the standard takeoff procedure.

The takeoff monitor described herein has the capability to detect anomalous performance early in the takeoff run, well before the decision speed has been reached, and to alert the crew in a nonexecutive manner. This enables the crew to respond to an anomalous performance indication and reject a takeoff from a safe speed.

Preliminary pilot assessment and feedback suggests that the display should be acceptable in the flight deck and that its introduction should contribute toward greater safety during takeoff.

References

[1] Illingworth, J. K. B, and Hopkin, H. R., "A Note on the Design of Take-Off Monitors," Royal Aircraft Establishment TM IAP 697 (Aero 657), 1960.

[2] Anon., "Takeoff Performance Monitor (TOPM), System, Airplane, Minimum Performance Standard for," Society of Automotive Engineers Inc., Aerospace Standard AS-8044, 1987.

[3] Ojha, S. K., *Flight Performance of Aircraft*, AIAA Education Series, AIAA, Washington, D.C., 1995, Chap. 16.

[4] Zammit-Mangion, D., and Eshelby, M., "An Ergonomic Concept for Take-Off Performance Monitor Design," *SAE World Aviation Congress*, Society of Automotive Engineers Inc., Paper 2001-01-2981, 2001.

[5] Klass, P. J., "Monitor Designed to Aid Jet Takeoffs," *Aviation Week and Space Technology*, June 23, 1958, pp. 65–71.

[6] Anon., "Takeoff Monitors Compete for Market," *Aviation Week and Space Technology*, July 28, 1958, pp. 77–79.

[7] Fusca, J. A., "Takeoff Monitor Computes Runway Roll," *Aviation Week and Space Technology*, Vol. 69, No. 15, 1958, pp. 99–105.

[8] Morris, G. J., and Lina, L. J., "Description and Preliminary Flight Investigation of an Instrument for Detecting Subnormal Acceleration During Take-Off," NACA TN-3252, 1954.

[9] Grover, J. H. H., "Safe Take-Off Indicators," U.S. Patent No. 4,130,015, 1978.

[10] Hosford, N. F., "Aircraft Take-Off Monitoring," U.S. Patent No. 3,128,445, 1964.

[11] Anon., Minutes of Meeting No. 1 of the Take-Off Performance Monitoring Ad Hoc Committee of the Aircraft Division of the Aerospace Council, Society of Automotive Engineers Inc., 1984.

[12] Middleton, D. B., Srivatsan, R., and Person, L. H., Jr., "Takeoff Performance Monitoring System Display Options," *AIAA/AHS Flight Simulation Technologies Conference*, AIAA, Washington, D.C., 1992, pp. 57–67.

[13] Cleary, P. J., Kelman, L. S., and Horn, L., "Aircraft Performance Margin Indicator," U.S. Patent No. 4,638,437, 1987.

[14] Verspay, J. J. L. H., and Khatwa, R., "A Comparative Evaluation of Three Take-Off Performance Monitor Display Types," *AIAA Flight Simulation Technologies Conference*, AIAA, Washington, D.C., 1993, pp. 147–155.

[15] Middleton, D. B., Srivatsan, R., and Person, L. H., Jr., "Simulator Evaluation of Displays for a Revised Takeoff Performance Monitoring System," NASA, TP-3270, 1992.

[16] Zammit-Mangion, D., and Eshelby, M., "A Simplified Algorithm to Model Aircraft Acceleration During Take-Off," AIAA Paper 2005-6016, 2005.

[17] Zammit-Mangion, D., and Eshelby, M., "An Improved Algorithm for Take-Off Monitoring," AIAA Paper 2004-6291, 2004.

[18] Purry, J., "A Human Factors Evaluation of a Take-Off Performance Monitor System," M.Sc. Dissertation, School of Engineering, Cranfield University, Bedfordshire, England, U.K., 2003.