JOURNAL OF AIRCRAFT
Vol. 44, No. 2, March–April 2007

Improved Algorithm for Takeoff Monitoring

D. Zammit-Mangion* and M. Eshelby†
Cranfield University, Bedfordshire, MK43 0AL England, United Kingdom

DOI: 10.2514/1.14989

The scope of takeoff monitoring is to provide a measure of aircraft performance during the takeoff run and to identify whether this lies within the predetermined limits of scheduled performance or otherwise. Used in conjunction with a good display, such a system, provided it is adequately reliable, will provide critical situational awareness to the crew and will thus contribute towards improving safety during takeoff. Cranfield University has developed a takeoff performance monitor based on an algorithm that determines estimates of relevant parameters from the history of the particular takeoff run, rather than relying on scheduled estimates. This, however, resulted in a delay between the start of the run and the generation of the first estimate of performance. This paper describes the improvements in performance achieved by the introduction of a modification that uses measured thrust-to-weight ratio to significantly shorten the delay and improve prediction accuracy, particularly at the start of the run.

Nomenclature

a	=	longitudinal acceleration
C_D	=	coefficient of drag
C_L	=	coefficient of lift
m	=	aircraft mass
S	=	gross wing area
T	=	thrust
V_g	=	ground speed
$V_{g\mathrm{ROT}}$	=	ground speed at rotation
V_R	=	rotation speed
V_1	=	decision speed
v_w	=	headwind speed
W	=	aircraft weight
θ	=	runway slope
ρ	=	air density
$\propto$	=	coefficient of friction

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 from 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 for the crew to ensure that the runway length available is adequate. In practice, this is done through performance scheduling where, before departure, the runway length required for the particular flight is estimated and compared with that available. The estimate has several leeways built in to ensure a sufficiently high probability of the aircraft completing the maneuver within the runway constraints.

The considerations for safety are epitomized by large transport aircraft operations, as this class of operations demands the highest levels of safety and, accordingly, introduces significant leeways and contingencies to ensure that the aircraft will clear any obstacles. A fundamental requirement in large transport aircraft operations is the need to cope with an engine failure at any point in flight. This includes the takeoff run and accordingly, allowances have been introduced in scheduled performance to allow for this contingency. For this purpose, the takeoff run has effectively been split into two phases by a decision speed V_1. If an engine failure occurs in the first phase, the crew is required to abort the run, as it would be safer to bring the aircraft to a halt than to become airborne on the remaining engine or engines. Conversely, if an engine failure occurs beyond the decision speed, the takeoff is continued. Allowances for uncertainties in the actual aircraft weight, thrust, and other operating conditions are also factored in [1]. These factors are statistically expected to reduce the probability of aircraft hitting obstacles to less than 1 in 10^7.

II. Need for Performance Monitoring

A. Nature of Performance Monitoring

Although this method of performance scheduling has been used for the last 50 years and remains the fundamental method of assuring safety in takeoff through application in the European Aviation Safety Agency (EASA) CS-25 and Federal Aviation Administration (FAA) FAR-25 regulations, there are two major issues concerning the approach. The first is that this method only provides a statistical means of protection. This is adequate from an operational risk point of view and is therefore considered acceptable by the aviation community, particularly the regulatory bodies. It does not, however, provide adequate protection on a case-by-case basis. Clearly, if an aircraft were to have a performance that is outside the limits statistically assumed to be adequate, no further protection would be provided and the aircraft would be committed to exceeding the runway distances. This may readily lead to an accident. The second issue is that scheduled performance provides protection for aircraft that will be dispatched as assumed in the pretakeoff calculations. Indeed, the probability figure of 1 in 10^7 for performance exceedance is based on expected variations in operating parameters about the assumed values. For example, allowances are made for the uncertainty involved with aircraft weight estimation. Aircraft are not weighed before departure and the dispatch weight is normally calculated by adding various estimates, including aircraft empty weight, fuel weight, and payload. The performance leeways are designed to cater for uncertainties in these values but not for other situations such as calculation errors, incorrect fuel upload, or incorrect payload declaration. Consequently, scheduled performance does not provide protection against misloading (Fig. 1). Likewise, it does not protect against the missetting of thrust. The situation is further aggravated by the fact that today, predispatch

Presented as Paper 6291 at the AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum, Chicago, Illinois, 20–22 September 2004; received 14 September 2005; revision received 23 July 2006; accepted for publication 26 July 2006.

*Lecturer, Department of Aerospace Engineering, School of Engineering. Member AIAA. Also affiliated with University of Malta, Msida MSD 06, Malta, Department of Electronic Systems Engineering, Faculty of Engineering.

†Retired. Associate Fellow AIAA.

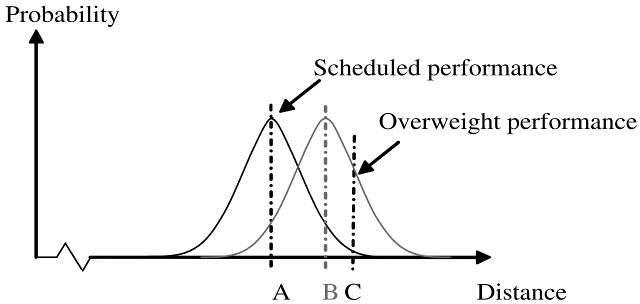

Fig. 1 Graphical representation of the effect of dispatching overweight aircraft. Scheduled gross performance at A; scheduled net performance at C. Actual overweight performance expected at B, resulting in a probability of exceeding point C being much higher than 1 in 10^7. An aircraft 10% overweight will require approximately 10% more runway to reach the same target velocity, thus increasing the probability of exceeding point C to the order of 1 in 17.

calculations can be performed several hours before departure in offices that are hundreds of kilometers away. Such calculations depend on weather forecasts and any departure from these forecasts is also not catered for by scheduled performance.

B. Consequences of Poor Performance

The said shortcomings are clearly illustrated in a number of accidents, the most well known of which is the 1982 Air Florida Boeing 737 accident in Washington, D.C. One of the major factors leading to the accident was effectively the missetting of thrust due to erroneous engine instrument indication caused by engine icing. The aircraft accelerated slowly, requiring 45 s and about 5400 ft of runway to lift off at 145 kn instead of about 30 s and 3500 ft [2]. The cockpit voice recorder (CVR) transcript clearly indicates the identification of an anomaly by at least one of the crew early in the run. The aircraft, operating in freezing conditions, was contaminated with ice or snow. It subsequently stalled and crashed shortly after becoming airborne.

More recently, on 12 March 2003, a Singapore Airlines Boeing 747 took off from Auckland, New Zealand, 100 t overweight following a human error in the transfer of the declared weight to the load sheet. The crew obtained the V speeds and set thrust for an assumed weight of 250 t instead of 350 t. This resulted in a V_R of 130 kn instead of 163 kn and reduced thrust was applied. The aircraft was overrotated, suffered a tail strike, and dragged its tail for nearly 500 m before becoming airborne in a "near stalled state." Damage of 7% was suffered from the tail strike before returning to land safely [3]. In these two accidents, both aircraft exhibited continuous underperformance during the run and yet the crews failed to abort or even increase thrust. Both flights were delayed and there are indications that the crews might have been under pressure to depart. Furthermore, it is well known that pilots tend to be "go" minded, that is, biased towards continuing a takeoff to avoid high speed rejections and consequently will not abort a run even if an engine fails several knots under V_1. The difficulties associated with aborting takeoffs on the basis of subjective perceptions that are not confirmed and consequently are dismissed or remain unanswered can be further appreciated when considering other operational and human factors.

The two accidents cited herein are clear examples of how scheduled performance fails to provide protection against situations where the actual takeoff occurs in situations that are different from those assumed in the pretakeoff calculations. This inevitably resulted in both the said flights being committed to exceeding runway allowances right from the start of the takeoff run, and the only possibility of the crew averting an accident would have been their realization of the aircraft's poor performance in time to abort the run and bring the aircraft to a halt. With present cockpit instrumentation and procedures, this can only be achieved through personal perception and is therefore subjective and not reliable. Although the CVR transcript of the Air Florida accident clearly indicates that at least one of the crew did recognize an anomaly in performance, the ultimate decision was to continue the run.

C. Ensuring Safety

The Air Florida Boeing 737 covered over 50% more runway to liftoff than expected and the Boeing 747 must have covered around 40% more runway by the time it reached 130 kn. (This estimate is based on the assumption of constant acceleration.) Both performances must therefore have been well outside scheduled limits, which allow only a 15% leeway beyond expected (average) runway requirements. Indeed, from a performance point of view, both aircraft must have become airborne only because the takeoff was not field limited, and no large obstacles that would have compromised the airworthiness of the aircraft were encountered. (The fact that the aircraft was in a near-stalled state that could have resulted in loss of control, as in the case of the Air Florida accident, is also a consequence of poor performance.) These cases are, of course, relatively extreme ones, but considering the fact that crews and operators currently have no means by which to accurately determine the actual operating conditions or measure actual field performance, it is reasonable to believe that there may be many other instances where aircraft will be performing poorly for one reason or another, with the takeoff not ending in an accident only because either runway lengths would not be limiting or the leeways allowed for contingencies that do not occur prove to be adequate. Although it can be argued that statistically these takeoffs are successful, such an approach does not fit in with current accident-prevention philosophies. Indeed, the general philosophy today focuses on ensuring the aircraft is flown within strict envelopes in order to keep the aircraft well clear of the danger of an accident. This philosophy still needs to be adopted in takeoff performance to ensure that every takeoff is completed within scheduled limits and not simply within physical runway constraints.

D. Takeoff Monitoring to Date

Concern about the inadequacy of scheduled performance has been voiced as early as the procedure's adoption and this has led to the belief that a takeoff performance monitor was needed to complement current procedure. This instrument would provide an indication of the actual performance of the aircraft during the run, thus providing crucial situational awareness supporting the crew's decision to continue or abort before V_1. Several attempts to develop a takeoff monitor were made in the late 1950s and 1960s. In the 1950s, the British air registration board (ARB) suggested that a 2% standard deviation in the prediction estimates would be desirable [4]. The technology of the time effectively restricted most designs to be electromechanical in nature and this did not adequately support the development of acceptable performance monitors. Consequently none was introduced in operation and enthusiasm gradually disappeared by the 1970s. Interest was again raised following the Air Florida accident, with the National Transportation Safety Board (NTSB) organizing a public hearing addressing takeoff monitoring in May of the same year [2]. Indeed, the Society of Automotive Engineers set up a takeoff performance monitoring ad hoc committee in 1984 and released a minimum performance standard, AS-8044, in 1987 [5]. This standard recommends that "the probability that TOPM system tolerances will, of themselves, cause an error greater than $\pm 5\%$ in the apparent all-engine operating take-off distance to rotation speed shall be 0.01 or less." This requirement is statistically equivalent to the earlier ARB recommendation.

With the introduction of digital computing technology and, more recently, powerful computer and computational capabilities, the task of takeoff performance monitoring has become more realistic, but new difficulties were discovered, such as that involving an acceptable presentation format on digital displays. Although there have been several other designs proposed since, once again none have yet been introduced to operational service.

III. Cranfield Performance Monitor

A. The Concept

The basic scope of the Cranfield work was to develop a system that would be of high value in the flight deck. This effectively laid down the requirements of high accuracy and ease of integration with the current procedure.

The Cranfield work considers that reliability, in this context, should be assessed in terms of how well the system facilitates the crew's correct decision to continue or reject a run and their capability of completing the maneuver successfully. This clearly renders critical the ergonomic design of the display, but from an algorithm point of view, it necessitates accurate estimates of performance. Furthermore, it also has significant implications on the monitoring methodology. Indeed, the requirement implies the need for timely indication of performance as the risks associated with aborting a run increase rapidly as the run progresses. This has resulted in the determination of aircraft performance being based on forward predicting, in real time, the distance that the aircraft will actually cover by V_1 (which, in the limiting case, is V_R). This estimate is then compared with that which would be allowed for by scheduled performance. The prediction is only made up to V_1 because predictions of distances covered after V_1 are unreliable. This is mainly due to the uncertainties associated with a piloting technique. Nevertheless, comparisons of performance up to V_1 are expected to give a conservative representation of the leeways estimated to be available with respect to the scheduled values of takeoff distance required (TODR), takeoff run required (TORR), and accelerate-stop distance required (ASDR). This concept has been presented in a prior publication by the authors [6].

The consideration of the intended instrument's integration with the current procedure has resulted in the identification that the highest value of the instrument would be achieved if it complemented the current procedure by protecting against those scenarios that are currently most vulnerable to a high risk of accident. As a result, the instrument was designed primarily to identify continuous and, in particular, subtle underperformance. Crews are well trained to respond to discrete anomalies but, as yet, have no reliable means with which to counter subtle situations. Continuous underperformance can be very subtle and consequently can go unnoticed or unchecked as indeed has happened in the accidents referred to in this text.

B. Takeoff Run Modeling and System Integration Issues

The classical method of modeling an aircraft during the ground run is derived from the equation of acceleration:

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

The prediction of the distance that the aircraft will cover by the time it reaches V_1 is essentially derived from this equation. The estimate requires the determination of a number of parameters, including total thrust, aircraft weight, ambient temperature and pressure, wind velocity, aircraft airspeed and position, runway profile, rolling drag and the coefficients of lift and drag. It is relevant to emphasize that, since it is the actual, rather than the scheduled, distance that is being predicted, the actual values of the relevant parameters need to be used in the solution of the equations. This may involve complex computation depending on other measured parameters (as in the case of thrust estimation), on standard values (such as values for C_L and C_D), or inputs by the operator (aircraft weight and V speeds).

Such requirements can readily render the algorithm too complex or may compromise the capability of integration with existing avionic architectures. The architectures of most existing glass-cockpit large transport aircraft is based on the ARINC-429 databus, which is a unidirectional, point-to-point bus. This implies that each data flow path between line replaceable units (LRUs) physically requires an independent ARINC-429 cable and connection. This and other considerations such as bus standard update rates may render impossible the installation of complex performance monitoring algorithms requiring a large data set for computation. Consequently, the dependence of the algorithm on a minimal data set was considered fundamental. This requirement has led Cranfield to develop a novel design that determines most of the parameters required from the profile of the run history as it develops. Indeed, the algorithm only requires inertial reference system (IRS) ground speed and calibrated airspeed as continuous inputs and V_1, scheduled distance to V_1, ambient temperature and pressure as one-time inputs at the start of the run. As the algorithm needs to detect the start of the takeoff, so other parameters such as the takeoff/go-around (TOGA) button or thrust lever position need to be monitored before the start of the run. These parameters constitute a minimal data set that supports the operation of the algorithm but other data such as longitudinal acceleration, runway profile, and aircraft position would further facilitate computation. All the information required is usually available within the flight management system (FMS) and inertial navigation system (INS) or attitude and heading reference system (AHRS) thus simplifying the installation on the aircraft for which the instrument is intended.

Another feature of the Cranfield design is that the algorithm does not require the use of extensive databases which are often used to map thrust functions and runway profiles. This is possible due to the philosophy of keeping the pilot in the loop (through the adoption of an appropriate display) and the prediction method used in the algorithm. The algorithm instead uses a number of coefficients that are aircraft type specific, thus reducing the memory requirements of the hardware on which the algorithm can run.

C. Algorithm Performance Requirements

In principle, the determination of the relevant parameters in real time supports a much more reliable prediction of accuracy than if scheduled parameters were to be used. This approach, however, introduces one challenge, namely, the fact that the algorithm cannot provide an output in the initial part of the run while it is generating the first estimate of the parameters. Consequently, the presence of a "data capture" window at the start of the run, during which the algorithm is not capable of providing an output, is an integral characteristic of this design.

In essence, the data capture process involves the estimation of the relevant parameters from the actual performance observed. This clearly requires the algorithm to be capable of handling sensor errors and the various perturbations that will be experienced during the run. The Cranfield algorithm uses best fit techniques to provide an optimal estimate, resulting in an increase in confidence of the estimate as the data capture window is lengthened. This, however, is not desirable, as it compromises the monitor's capability of providing an early indication of performance. There exists, therefore, a tradeoff between initial estimate integrity and size of the capture window, which results in a delay in algorithm output.

Although AS-8044 [5] specifies the basic accuracy and requires instruments to not provide information that can be hazardously misleading, the authors are of the opinion that this does not adequately address the accuracy requirements. This is because, as the run progresses towards V_1, the risk associated with aborting (or continuing the run if performance is inadequate) increases. Consequently, the crew needs to be increasingly more confident in their decision as V_1 is approached. This, in turn, leads to the need for the performance monitor to be more reliable as V_1 is approached. The algorithm accuracy, therefore, will need to improve along the run and this is not reflected in either AS-8044 or the ARB recommendation. As a result, Cranfield has developed an internal standard to reflect such requirements [7]. This standard effectively splits the run up to V_1 in three segments as shown in Fig. 2. In the first segment, speeds will be low, typically below 70 kn ($\frac{1}{2}V_1$), and the risks of overrun or damaging the aircraft if the run is aborted in this segment are low. Indeed, crews often elect to abort runs if any system malfunction occurs in this segment. Segment 2 involves the middle part of the run and speeds up to about 100 kn or 120 kn, and the last segment involves the final run to V_1. It is evident that the third segment

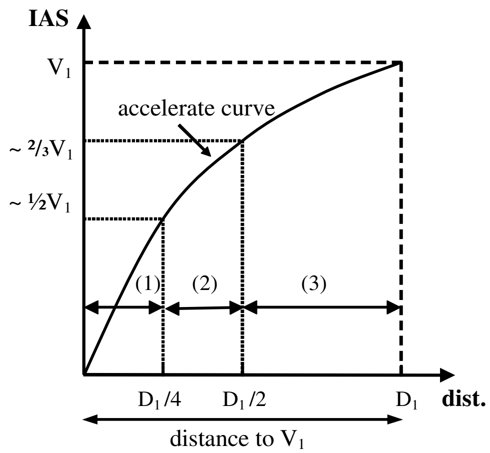

Fig. 2 Ground run segmentation for the purpose of quantifying prediction accuracy requirements.

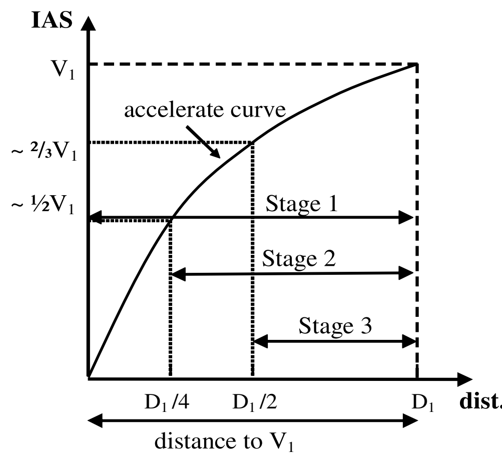

Fig. 3 Ground run segmentation for the purpose of quantifying algorithm performance.

requires high system integrity to ensure that the probability of the performance monitor providing an indication that will mislead the crew will be acceptably low. Rejection in stage 3 is usually considered to constitute high risk as it involves high-energy braking, which can result in operational delays, aircraft unserviceability, or even overrun. Rejections are accordingly avoided in this segment unless the airworthiness of the aircraft is considered to be compromised. The Cranfield performance standard was designed to reflect such considerations and accordingly requires higher accuracies in the later stages of the run up to V_1. These requirements have been established as a compromise between acceptable levels of accuracy and what, in practice, was considered to be achievable and are as follows: segment 1: basic indication; segment 2: 6% accuracy; segment 3: 3% accuracy; and V_1: 1.5% accuracy. All levels are at 99% confidence [7].

D. Performance Results

The Cranfield algorithm was evaluated on a number of categories of aircraft, including a commuter-sized twin turboprop and large 4-engined jet transports. The evaluations were carried out using real flight data recordings of normal takeoffs. The algorithm was consequently exposed to different operating conditions, typical disturbances, and signal errors. The prediction accuracy of the algorithm was measured throughout each run and results indicate that the algorithm is capable of achieving the accuracies required by both the in-house standard and AS-8044. A limitation of the original design, however, was that the algorithm was not provided with any initial estimates. This resulted in a relatively long data capture time (up to 10 s) to ensure a reliable estimate of actual performance. Furthermore, the start of the time window naturally has to be delayed until steady conditions are achieved. This compromised the effectiveness of the instrument, particularly considering that extended rolling starts, where final thrust setting is only achieved at speeds of 50 kn or more, are not uncommon. As a result, it was not considered feasible to provide a reliable indication of performance with the prediction algorithm in the first stage of the run. To counter this limitation, an alternative method that monitors instantaneous achieved performance (instead of predicting performance up to V_1) was integrated with the algorithm until the prediction accuracy was considered to confidently lie within performance targets. The Cranfield system therefore relied on acceleration monitoring in the lower airspeeds with a gradual transition to predictive monitoring as the end of the first segment is approached. Although the authors do not consider acceleration monitoring alone to provide an adequately reliable means of performance monitoring, it provides the basic indication that is considered acceptable in the first segment. Performance monitoring based on vehicle acceleration has, over the years, been studied in detail by different organizations and this approach is now mature. Consequently, the validation work carried out was focused on demonstrating the integrity of the predictive algorithm.

One of the evaluation programs involved analyzing 40 runs using data recordings from real flights of Boeing 747 aircraft. The recordings were arbitrarily selected, covering a reasonable range of operational conditions, including various combinations of thrust and weight (Table 1). The takeoffs also had varying degrees of rolling start, thus providing a reasonable representation of actual operating conditions. The algorithm was executed on these 40 runs and prediction was compared with the actual distance that was calculated to have been covered. The maximum prediction errors observed in stages 2 and 3 (which cover segments 2 and 3 and segment 3 only, respectively, Fig. 3) were then calculated. The results are presented in Table 2, where the maximum absolute error is presented in meters and as a percentage of the distance covered up to V_1. A normal distribution of the maximum error was assumed to facilitate the calculation of the standard deviations and 99% confidence limits of the expected maximum errors.

IV. Improved Algorithm

A. The Modification

Although the results of the validation program were satisfactory, it was evident that the full potential of the algorithm were not yet exploited and the fusion of the acceleration monitoring, although acceptable, increased the complexity of the algorithm. Consequently, further development was carried out in an attempt to significantly reduce the data capture window.

The two parameters that have the most effect on aircraft performance are thrust and aircraft weight. Referring to the expression for acceleration [Eq. (1)], thrust T is the dominant component in the numerator, particularly for low airspeeds where the aerodynamic drag is low, while the denominator comprises the

Table 1 Summary of the salient performance parameters of the recorded B747-400 takeoffs

	Weight/lbs	$V_{g\mathrm{ROT}}$/kn	Run time to V_R/s	Dist. to V_R/m
Minimum	462,720	114	20	660
Average	724,130	144	37	1518
Maximum	874,240	173	53	2352

Table 2 Estimated maximum prediction error of the original algorithm using the B747-400 data recordings

Max. error	Stage 2	Stage 3
Average	2.86%	1.15%
Std. dev.	1.15%	0.61%
99% conf.	5.54%	2.57%

aircraft mass. The operating ranges of these parameters are large. Indeed, the range of takeoff weights observed in the 40 runs (Table 1) provides a good illustration of this. Thrust can be reasonably expected to have a likewise large operating range, not only because of variations in ambient conditions, but also because of reduced-thrust takeoff procedures that are usually adopted when field lengths are not limiting. Consequently, the early estimation of the effects of these two parameters was considered fundamental to supporting a quicker first estimate of performance.

Referring to Eq. (1), it is evident that the explicit calculation or estimation of thrust and weight is not necessary as the thrust-to-mass ratio is, in essence, what affects performance. Conveniently, the thrust-to-weight ratio can be readily identified by measuring initial (peak) acceleration. This measurement is, however, slightly complicated in rolling start takeoffs, due to the presence of aerodynamic drag and the dynamic nature of the start. The equivalent peak acceleration can nevertheless be estimated by taking into account the airspeed at the moment at which thrust will have stabilized following the setting of the thrust levers.

The original algorithm was therefore modified to incorporate the measurement of peak acceleration and the estimate of the thrust-to-weight ratio at the start of the run. This estimate was then used to provide an initial condition to the predictive algorithm, thus reducing the uncertainties in parameter estimation and concurrently allowing the significant reduction of the data capture window.

B. The Evaluation

The revised algorithm was evaluated on the same set of data that was used to evaluate the original algorithm. This allowed the direct comparison of the merits of the improvements introduced. The results of the new evaluation are presented in Figs. 4–9 and Table 3.

It is evident from Table 1 that the 40 runs cover a wide range of operating conditions. Indeed, various degrees of rolling start were observed. As was done in the evaluation of the original algorithm, the start of the takeoff was considered to be the instant at which the thrust

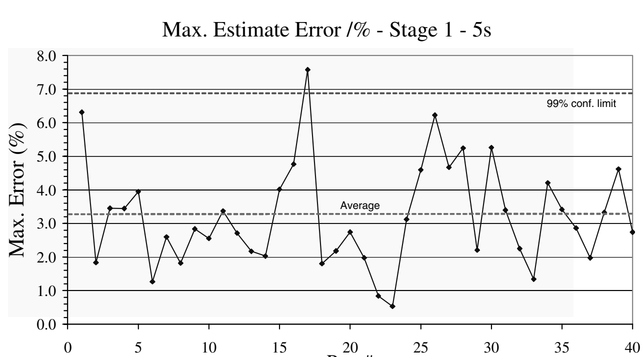

Fig. 4 Maximum algorithm prediction error after 5 s into stage 1. Presented in absolute terms as a percentage of the actual distance covered.

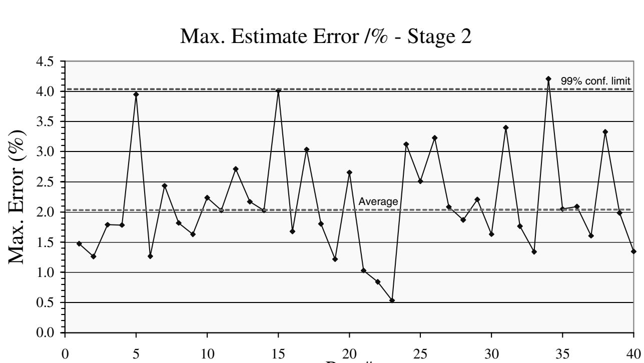

Fig. 5 Maximum algorithm prediction error in stage 2. Presented in absolute terms as a percentage of the actual distance covered.

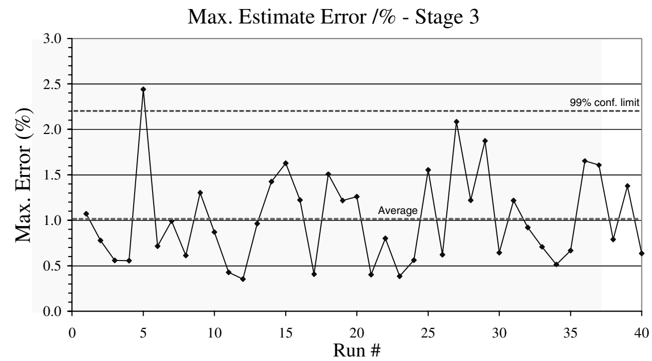

Fig. 6 Maximum algorithm prediction error in stage 3. Presented in absolute terms as a percentage of the actual distance covered.

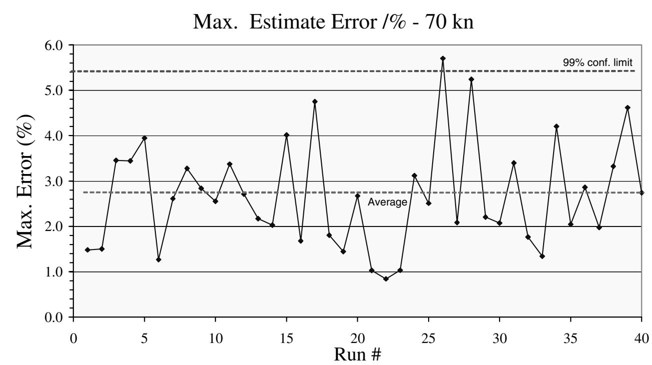

Fig. 7 Maximum algorithm prediction error past 70 kn. Presented in absolute terms as a percentage of the actual distance covered.

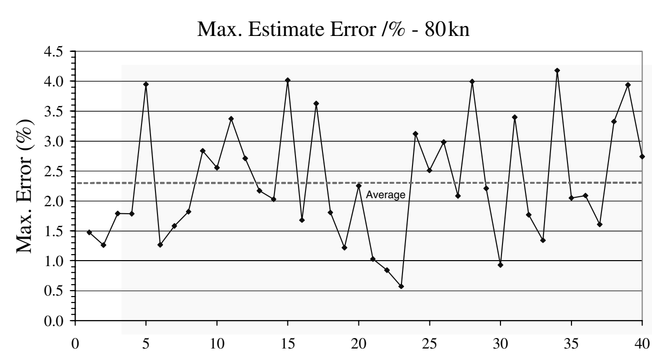

Fig. 8 Maximum algorithm prediction error past 80 kn. Presented in absolute terms as a percentage of the actual distance covered.

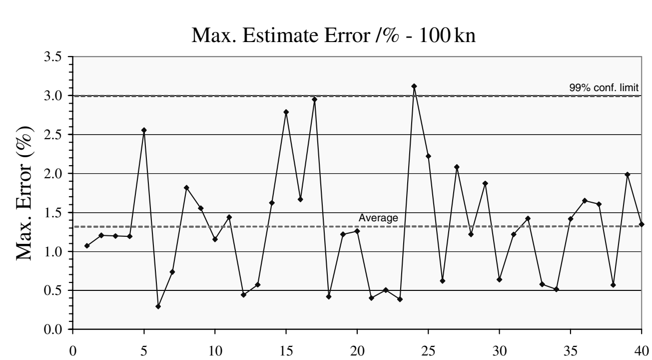

Fig. 9 Maximum algorithm prediction error past 100 kn. Presented in absolute terms as a percentage of the actual distance covered.

Table 3 Estimated maximum prediction error of the modified algorithm using the B747-400 data recordings

Max. error (%)	Stage 1 (after 5 s)	Stage 2	Stage 3	Past 70 kn	Past 80 kn	Past 100 kn
Average	3.2	2.1	1.0	2.7	2.3	1.3
Std. dev.	1.5	0.9	0.5	1.2	1.0	0.7
99% conf.	6.8	4.1	2.2	5.4	4.6	3.0

levers were advanced beyond the intermediate position after the crew would have completed the engine checks. As the actual value of V_1 on any particular run was not available, the predictions were extended to the point of rotation. This is acceptable, as, in general, V_R is the regulated upper limit of V_1 [8].

V. Discussion

The results presented in Table 3 indicate that the performance of the modified algorithm is superior to that of the original version. Indeed, the prediction accuracy is observed to have improved slightly in stage 3 and quite substantially in stage 2. This characteristic was expected, because the improvements were introduced in the algorithm to improve the prediction accuracy in the earlier parts of the run. Improvements are observed in both the average (expected) maximum error and the standard deviation, resulting in a 14% improvement in accuracy at the 99% confidence level in stage 3 and a 26% improvement in accuracy in stage 2.

The modification also allowed a significant reduction of the data capture window. Indeed, with a window of 5 s, the maximum prediction error throughout the run was observed to be within 7% and, on average, 3.2%. As in the case of the original algorithm, the maximum error could be further reduced with the adoption of a longer window, but this would defeat the purpose of the modification. The authors are of the opinion that a 5 s window is a good compromise. This would result in the performance monitor not indicating in the first 5 s after target thrust is achieved, but this is not considered as a major drawback. In fact, even the airspeed indicator, which is a fundamental instrument for takeoff, does not indicate in the first seconds of the run due to the low airspeeds involved and this is not of any concern.

The maximum prediction error after transiting the 70, 80, and 100 kn cutoff points was also observed. Depending on aircraft type and company procedures, one of these three salient speeds is often chosen as the airspeed below which the run will be aborted if any system failure is detected. Past 100 kn, a system failure will normally have to affect safety for the run to be aborted. It is relevant, therefore, to present the algorithm accuracy with respect to these cutoff points. Although the performance past 80 and 100 kn is within AS-8044 specifications, the error expected between 70 and 80 kn is slightly outside this limit. It must be emphasized, however, that the instantaneous error in prediction is dynamic in nature, with a trend reducing to zero as V_1 is approached (there is no prediction at V_1). Consequently, in the 2 or 3 s past 70 kn, as the aircraft accelerates to 80 kn, the maximum error limit (99% confidence level) drops to well within AS-8044 requirements. This ties in well with the 80 kn callout on the flight deck. This effect is clearly demonstrated in Fig. 11.

The prediction accuracy in the early parts of the run is dependent on the accuracy of the thrust-to-weight ratio estimate and this clearly depends on the accurate estimation of peak acceleration. The acceleration data on the 40 runs was taken from an accelerometer sampled at 4 Hz. A typical recording is presented in Fig. 10. The noise content in the signal has a component at the niquest frequency, suggesting the presence of aliasing. This, together with the slow sampling rate of 4 Hz, has significantly compromised the effect of filtering. Although these features most certainly do not compromise the purpose for which the installation on the aircraft is intended, the source does not prove ideal for the purpose of this work. Nevertheless, the performance is considered acceptable, suggesting that the algorithm is robust enough to cater for such installation. The accuracy of the algorithm is expected to improve with installations that are more conducive to the accurate estimation of thrust-to-weight ratio.

The robustness of the algorithm in terms of its capability of forward-predicting performance based on the *actual* performance of the aircraft during the run and its independence from scheduled data indicate that the instrument would have identified the under-performance in both the accidents referred to in the introduction. Indeed, considering that the two aircraft covered in excess of 40% of the expected distance, this would certainly have been picked up by the instrument and the situation made aware to the crew sufficiently early in the run to render rejection a relatively low risk maneuver, even in the freezing and contaminated runway conditions under which the Air Florida aircraft was operating.

The analysis performed on the 40 runs provides a clear indication of the expected accuracy of the system in operation. However, a greater number of runs covering a wider range of combinations of operating conditions (configuration, weight, altitude, temperature,

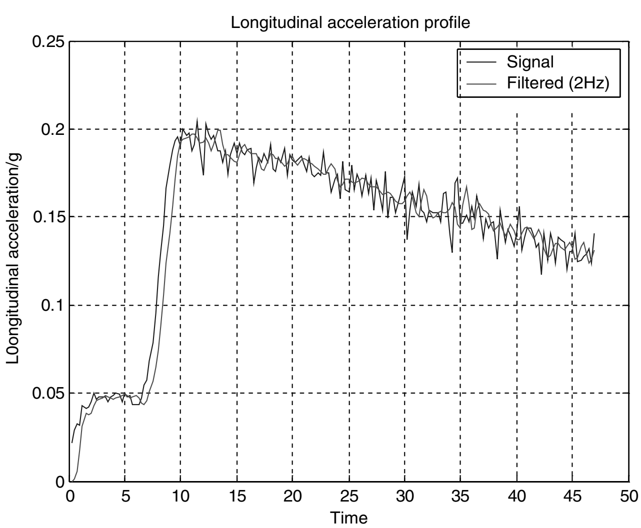

Fig. 10 Acceleration profile of run 26.

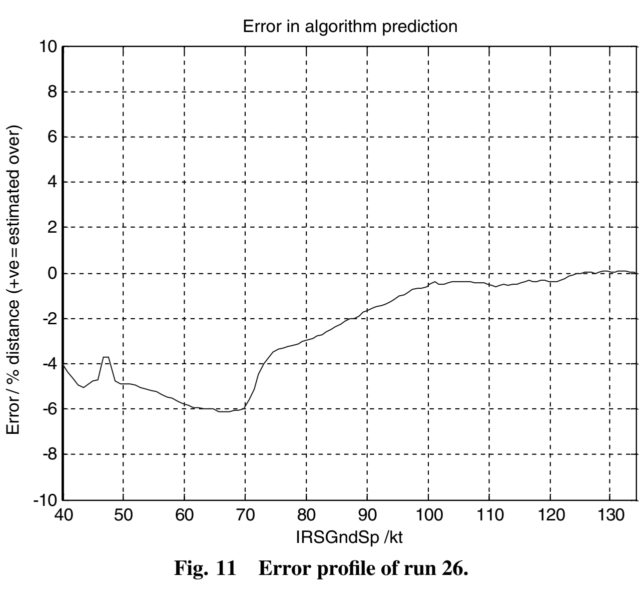

Fig. 11 Error profile of run 26.

thrust setting, etc.) would further increase the confidence in the results obtained.

VI. Conclusion

The evaluation has demonstrated that the improved algorithm is capable of greater prediction accuracy than the original design, particularly at the initial stages of the run. This renders the possible elimination of acceleration monitoring and fusion in the early stages, thus supporting the implementation of a simpler and conceptually more reliable system. The overall accuracy and early indication capabilities of the improved algorithm indicate that the system can provide high value information in the flight deck. Integrated with an appropriate ergonomic display, the algorithm can certainly contribute to enhanced safety by allowing operators to monitor takeoff performance in real time and thus avoid unknowingly operating closely to or beyond the limits of scheduled performance.

Acknowledgment

The authors would like to thank British Airways and, in particular, Mike Nebylowitsch for their support of this work.

References

[1] Zammit-Mangion, D., and Eshelby, M., "Evaluation of A Take-Off Performance Monitoring Algorithm in Large Jet Transport Operations," AIAA Paper 2003-5616, Aug. 2003.

[2] "Aircraft Accident Report—Air Florida Inc. Boeing 737-222, N62AF. Collision with 14th Street Bridge, near Washington International Airport, Washington, D.C., January 13, 1982," NTSB Report No. NTSB-AAR-82-08, 1982.

[3] "World Aircraft Accident Summary—CAA CAP479," Airclaims, 2004, Sheet A03:9.

[4] 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.

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

[6] Zammit-Mangion, D., and Eshelby, M., "An Ergonomic Concept for Take-Off Performance Monitor Design," Society of Automotive Engineers Inc. Paper 2001-01-2981, Sept. 2001.

[7] Zammit-Mangion, D., and Eshelby, M., "A Proposal for a Revised Performance Standard for Take-Off Performance Monitor Design," Society of Automotive Engineers Inc., Paper 2000-01-2126, Sept. 2001.

[8] "Joint Aviation Requirements, JAR-25—Large Aeroplanes," Civil Aviation Authority JAR-25-107(e)(1), 1994.