FLIGHT SIMULATOR EVALUATION OF TAKE-OFFS CONDUCTED WITH AND WITHOUT A TAKE-OFF PERFORMANCE MONITOR (TOPM)

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Abstract

This investigation is aimed at assessing the flight crew decision making process for take-offs conducted both with and without a predictive Take-Off Performance Monitor (TOPM) display. The NLR moving base Research Flight Simulator, programmed with a Fokker 100 dynamic model was employed. An important aspect of the study was the scrutiny of crew procedures. The use of the TOPM display showed a potential safety benefit in the following conditions: a medium acceleration deficit in the presence of an engine failure; and a high acceleration deficit. In cases where performance was about normal, and a sudden failure developed at some point in the take-off, TOPM did not offer any significant safety benefits over non TOPM take-offs. It appears that the strength of a TOPM lies in identifying at an early stage of the take-off, that the performance is insufficient for a safe continued take-off.

Abbreviations and Acronyms

CRT	Cathode Ray Tube
EICAS	Engine Indicating and Crew Alerting System
EPR	Engine Pressure Ratio
FCS	Flight Control System
FO	First Officer
ND	Navigation Display
N2	RPM high pressure compressor
PF	Pilot flying
PFD	Primary Flight Display
PNF	Pilot not flying
RFS	Research Flight Simulator
RTO	Rejected take-off
SAE	Society of Automotive Engineers
TGT	Turbine Gas Temperature
TOPM	Take-Off Performance Monitor

Notation

E_{scr}	Aircraft total energy at screen height	J
h_{escr}	Relative energy screen height	m
h_{scr}	Aircraft height at runway end	m
L_{rem}	Runway length remaining after RTO (mean)	m
m	Aircraft mass	kg
V_{GO}	Earliest speed for safe continued take-off with engine failure	m/s
$V_{mc_{gnd}}$	Minimum control speed on the ground	m/s
V_R	Rotation speed	m/s
V_{scr}	Aircraft speed at runway end	m/s
V_{STOP}	Highest speed to abort take-off safely	m/s
V_1	Decision speed	m/s
V_2	Take-off safety speed	m/s

1 Introduction

Civil aircraft safety has generally improved during the last three decades for most flight phases. Some of these improvements can be attributed to the introduction of new aircraft systems such as the Ground Proximity Warning System and the Windshear Warning System. Enhanced training programmes such as the Windshear Training Aid have also been introduced in an effort to improve both pilot awareness of the problems and crew procedure accomplishment. Statistics indicate that the take-off and initial climb accident rate has not decreased[1] and such accidents accounted for around 25% of all hull losses for the period 1981-1992 (inclusive)[2]. Two of the problems causing concern include insufficient and unsafe climb-out or a runway overrun following a rejected take-off (RTO). The causes are diverse and therefore several potential solutions are currently being investigated to deal with specific problems in the accident chain, eg improved crew training[3] and ice detection sensors. Some of the take-off accidents were due to sub-standard aircraft performance and subsequent failure of the crew to recognise the abnormal situation; this prevented corrective action to be applied in a timely manner. Other than conventional cockpit instrumentation such as airspeed and engine cues, there are no other flight systems currently available to specifically aid the crew's task during the take-off manoeuvre. A Take-Off Performance Monitor (TOPM) could potentially enhance crew GO/NO-GO judgement during take-off. Several systems have been proposed over the years, but to date none has reached operational status. Various monitoring functions, algorithms and displays have been defined in these studies[4-24]. Much creditable display evaluation work has been conducted by NASA[9,11,18]. These studies involved using a (modified) Cooper-Harper rating scale for the display evaluations. The NLR investigation scrutinises not only the TOPM display, but also the associated crew procedure using both qualitative and quantitative analysis. Furthermore this study attempts to establish whether TOPM can improve crew decision making, and if so, under which particular conditions. Take-offs conducted without TOPM were used as a basis for reference. More complete details of this study are presented in Ref. 24.

1.1 Classification of Systems

The US Society of Automotive Engineers' (SAE) TOPM Aerospace Standard[1] classifies systems as follows.

Type I monitors compare the achieved airplane performance to a reference performance based on all-engines.

Type II monitors have all Type I capabilities, and in addition predict performance later in the continued take-off run.

Type III monitors have all Type II capabilities and can predict the ability of the aircraft to abort the take-off.

1.2 Background to Current Study

Two other NLR human factors studies have recently been conducted to evaluate the concepts and displays associated with each of the three monitor Types[21-23]. The goal of phase one of the study[21-22] was to establish whether TOPM, and what Type, could potentially enhance the GO/NO-GO decision making process and to identify the necessary display information. Three TOPM displays, each conforming to the SAE definitions, were developed. A *part-task* simulator facility was configured for a one-man crew. Six twin-engined aircraft pilots and seven non-pilots were subjected to a Fokker 100 simulation, whereas six multi-engined aircraft pilots were employed on a Boeing 747 simulation. Results indicate that overall, the Type III system offered the largest increase in safety (ie safe continued take-off or safe abort)[21-22]. A potential increase in safety seemed possible in two situations with the Type III system, namely:

- when a performance deficit exists large enough such that a safe climb-out is not possible; and
- when a performance deficit together with an engine failure no longer permit a safe abort or continued take-off at V_1.

Although the Type I display improved pilot detection of anomalies (relative to the no TOPM case), this did not result in safer GO/NO-GO decisions being made. Type II performance was superior to the Type I display, but inferior to the Type III display.

The second study phase[23] concentrated on the Type III system as that yielded the largest potential safety benefit in phase one. The Type III display in Ref. 21-22 presented several cues that are engine-out related. As only 25% of RTO problems are currently related to engine failure[3,20] an alternative Type III display (Type IIIB) which presents less engine-out orientated cues was thus compared to the original display (IIIA) in a follow-up study. The Type IIIA display showed a potential benefit in exactly the same two scenario groups as before. However, the Type IIIB display only showed a potential advantage in the high acceleration deficit case. The Type IIIB display, which was assumed to be more GO oriented, did not show a decrease in RTOs when compared to the Type IIIA. Ref. 23 recommended further study into the Type IIIA TOPM, and in particular stated that the very important aspects of crew interaction and crew procedures should be scrutinised in any follow-up study.

2 Description of TOPM System

2.1 TOPM Display

The display, which appears on the Navigation Display (ND) of both pilot stations, presents the following information (see Fig. 1).

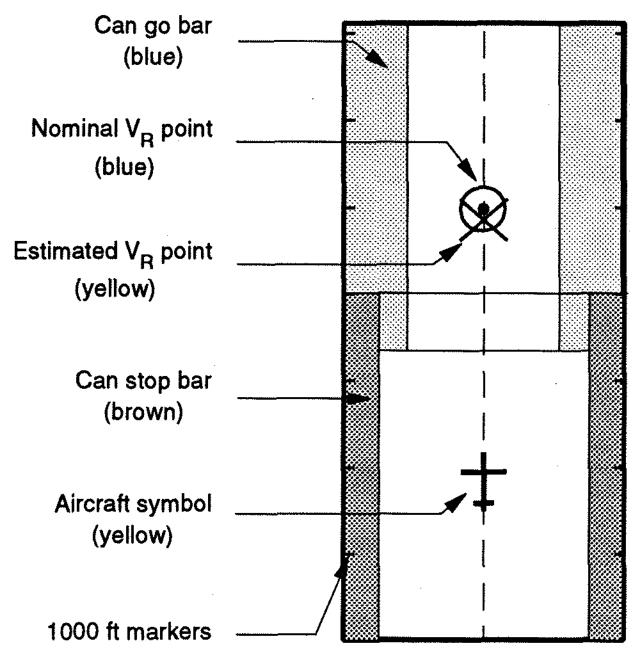


Fig. 1 Type III TOPM (not to scale)

(a) Current runway position of (yellow) aircraft (intersection of fuselage and wings indicates the position). The aircraft does not move laterally.

(b) Predicted (yellow cross) and nominal (blue circle) runway positions which the aircraft will reach when its speed becomes V_R.

(c) The runway region from where a decision to continue take-off *safely* with an engine failure is possible (blue bars). 'Safely' in this context implies the ability of the aircraft to clear the departure end of the runway by at least 35 feet (screen height) at speed V_2 (take-off safety speed). However, for wet runway operations, a reduced screen of 15 feet (permitted by existing UK regulations) is employed. The speed implied by the lower end of the blue bars is referred to as V_{GO} herein (speed not presented on display) and is limited to the minimum control speed on the ground ($V_{mc_{gnd}}$).

(d) The runway region from where it would be possible to conduct a safe stop (brown bars). V_{STOP} (speed not displayed) is the highest speed from which it should be possible to conduct a stop and is associated with the uppermost end of the STOP option bars. V_{STOP} is limited to V_R in this study.

These positions are calculated and displayed using nominally correct data before take-off. During the take-off roll, these cues are displayed on the basis of real measured data and forward computations. Note that (a) and (b) are based on Ref. 9,11. If take-off conditions change such that the aircraft can no longer achieve the required clearance of the fictitious screen at the runway end at speed V_2, then the predicted V_R marker changes colour from yellow to red. The blue bars also disappear from the display.

In the continued take-off case the TOPM display is replaced by the conventional ND after lift-off. In the event of an abort the predicted V_R position symbol and the 'can go' bars disappear, whereas the 'can stop' bars are frozen for the entire stopping manoeuvre.

For the take-off monitor evaluation, TOPM display information alone can be utilised to make the take-off decisions and thus V_1 speed data was not furnished to the pilots for these tests. In this investigation the pilot not flying (PNF) had primary responsibility for monitoring TOPM information.

2.2 TOPM Algorithm

The TOPM possesses a pre-takeoff capacity to accept input data defining the current conditions, whether ambient conditions or conditions specific to the flight. This one-time process is a combination of pilot input together with automatic data acquisition from other flight systems (eg Flight Management System)[24].

During ground roll the difference between expected and measured acceleration is established. The expected acceleration is deduced from an on-board mathematical dynamic model of the aircraft. The difference in acceleration is employed to predict the continued take-off lengths. Both zero- and first-order correction polynomials are available to predict the future accelerations. The first-order polynomial gives the best fit if the acceleration difference varies as a function of speed, eg in the presence of slush. The algorithm establishes which of the two correction polynomials is most likely to correctly predict acceleration[17]. Estimated windspeed is also incorporated in the computations. Note that the TOPM algorithm developed here and elsewhere to date, do not account for the loss of lift due to snow/icing contamination on the airframe surfaces.

The stopping prediction algorithms employ typical mean deceleration levels[24]. For the present human factors study this should suffice, but the drawbacks of this simplification for a practical system are recognised. A comprehensive TOPM stopping performance algorithm is presented in Ref. 16,19.

3 Simulation Facility

The NLR moving base (four degree-of-freedom motion system) Research Flight Simulator (RFS)[24] was used to conduct this investigation. A Fokker 100 aircraft (non-linear) dynamic model was employed. In this study wheel brake application was achieved by means of conventional brake pedals, as opposed to an autobrake system. The lift dump system was automatically deployed upon retarding of the throttles to idle when initiating the RTO. The layout of the six Cathode Ray Tube (CRT) displays (information content similar to that for a Fokker 100) is depicted in Fig.2.

Fig. 2 Research Flight Simulator (RFS) cockpit

4 Scenario Matrix Selection

The scenario matrix employed is fully defined in Ref. 21 and only a short description of important items follows.

4.1 Basic Conditions

In this study the term *basic condition* refers to *runway length* and *environment* conditions prevailing prior to brake-release. Both critical runway and non-limiting runway lengths were used. Dry and wet (reduced braking performance) conditions were employed to represent the environment variable.

4.2 Take-Off Problems

The following definitions apply. *Performance anomalies* are problems which affect airplane performance and are present throughout the entire take-off, eg incorrect engine or control setting. *Discrete events* are problems which suddenly develop during the ground roll, eg engine, tyre or Flight Control System (FCS) failures. The discrete event may be either performance or non-performance related.

4.2.1 Performance Anomalies

4.2.1.1 Inertial Related Performance Anomalies For inertial performance anomalies airplane acceleration differs from the nominal value expected for the reported conditions and recommended engine setting - the difference is referred to as the *performance deficit/surplus* level. In the presence of most performance deficits/surplus the acceleration difference either remains constant or varies (ie increases/decreases) as a function of speed during the ground roll[4-5,16-20], ie

(a) Constant performance deficit/surplus: These are called *static* anomalies, eg caused by incorrect throttle setting.
(b) Increasing performance deficit/surplus: These are termed *dynamic*, eg due to slush drag (*V-squared* effect).

The response of the TOPM display elements to the individual factors within a given performance anomaly group is very similar. Thus it is not necessary to subject pilots to all conceivable problems. Instead the simulation considers changes in acceleration which are in accordance with the definitions of static and dynamic anomalies[21].

4.2.1.2 Wind Related Performance Anomalies
Dynamic wind anomalies (windshears) were considered and variations in the headwind were introduced to effect aircraft performance.

4.2.1.3 Magnitude of Anomalies Three performance anomaly magnitudes, namely LOW, MED(IUM) AND HIGH (in order of increasing intensity) were considered. Superscripts '+' and '-' are used to denote surplus and deficit conditions respectively.

(a) LOW$^-$ This deficit results in V_1/V_R being achieved at a point further along the runway, but it is always possible to either safely abort or safely continue the take-off in the event of an engine failure.
(b) MED$^-$ The performance level falls such that a time interval exists during which the aircraft has neither the ability to continue take-off safely with engine failure nor the ability to stop within the critical runway length.
(c) HIGH$^-$ This deficit gives rise to an unsafe (continued) take-off, even in the absence of a discrete event. On a critical runway V_R is achieved at a point such that safe clearance to the screen is not possible.

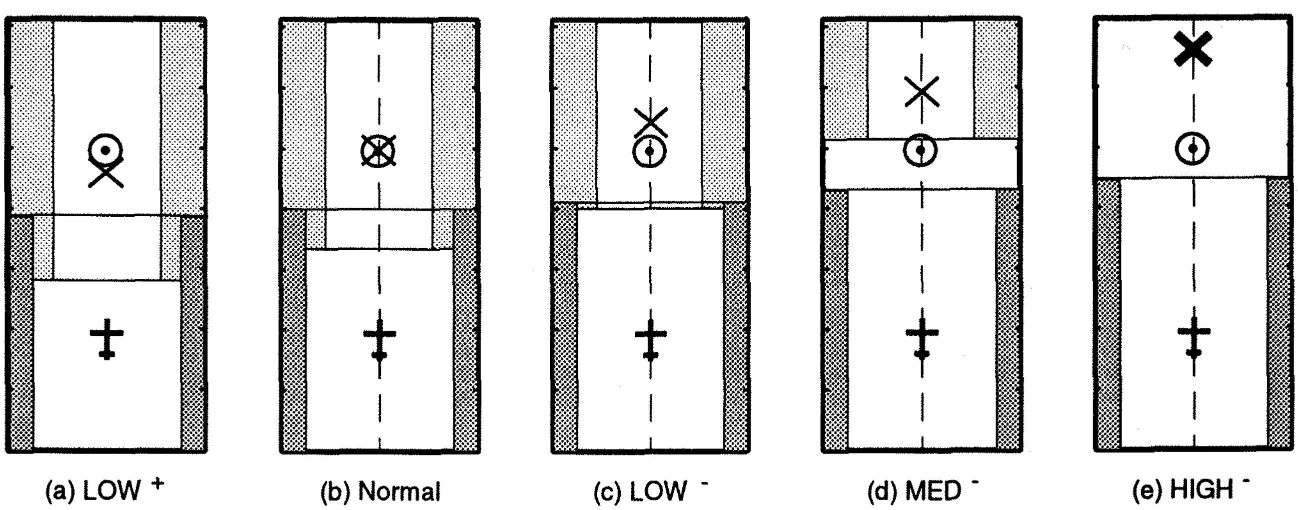
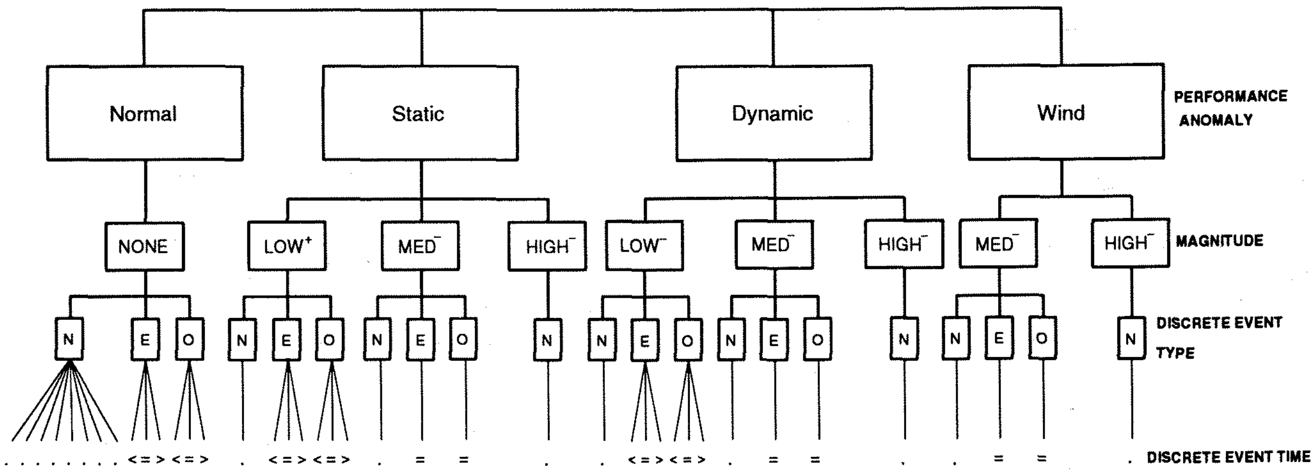


Fig. 3 Appearance of TOPM for five performance levels



N None < Before V_1
E Engine = Close to V_1
O Tyre or FCS > After V_1

Fig. 4 Reduced scenario tree

Fig. 3 shows the TOPM display for the five performance levels considered herein. Note the migration of the predicted V_R position (cross) as performance decreases and the appearance of a gap between 'can stop' and 'can go' bars in the MED$^-$ case (Fig. 3d). In the HIGH$^-$ case the 'can go' bars disappear (Fig. 3e).

4.2.2 Discrete Event Selection The scenario matrix adopted incorporates the following, namely engine failure/fire, tyre bursts, hydraulics failure of the horizontal stabiliser (control force was approximately five times higher than normal) and no failure. The discrete events were categorised in three speed regimes, namely well before V_1, close to V_1 and well after V_1 (includes failures after V_R).

4.3 Scenario Reduction

The performance anomaly, discrete event and basic condition combinations are numerous. A sample consisting of a reasonable cross section was selected[21]. The reduced scenario matrix consists of 40 scenarios summarised in Fig. 4. The results presented herein are those for the Captain as pilot flying (PF), both with and without TOPM. Results for the First Officer as PF are given in Ref. 24.

5 Crew Flight Procedures

Prior to each take-off a simple pre-takeoff checklist was required to be conducted so that the aircraft was properly configured for take-off. A crew briefing was required to be given by the PF before take-off[24].

5.1 Crew Co-Ordination for Conventional Take-Offs

An operational procedure representative of current airline practice was employed[24] and this included the usual PNF "V_1" and "ROTATE" call-outs. The PF was required to release the thrust levers at V_1.

The procedures outlined in Table 1 were adopted for the failure cases. The word STOP was used to initiate an RTO. When used by the First Officer (as PNF) it was to be regarded as an advice (as opposed to a command).

5.2 Crew Co-Ordination for TOPM Aided Take-Offs

This procedure was identical to the non TOPM take-off crew co-ordination with the following exceptions. The PF was required to release thrust levers when the PNF called "CAN FLY" as the aircraft entered the 'can go' bar area. The choice of this procedure was based on the premise that once the aircraft is within the 'can go' area, initiation of an RTO should only be expected in extreme emergency situations, eg explosions or an extensive fuselage fire. The aircraft should have the ability to continue take-off, even with failure of the critical engine, and clear the screen at V_2 once it is within the 'can go' area. As the aircraft left the 'can stop' bars (but within the 'can go' bars area assuming overlap - see Fig. 3b) the PNF called "GO" indicating that the STOP option was no longer available, ie only continued take-off possible. The call "ROTATE" followed at V_R.

5.2.1 Failures During Take-Off The rules presented in Table 1 were adopted. The advisory nature of the First Officer STOP call to initiate an RTO was identical to that for non TOPM take-offs. In the overlap area of 'can go' and 'can stop' bars both options are available, and

No TOPM	TOPM*	Action
Up to 80 kt	Up to 80 kt	RTO for all observed failures or exceedences
Above 80 kt to V_1	Above 80 kt to V_{GO}	Rejected take-off only for ● LEVEL 3 ALERTS ● Conditions, which render the aircraft unflyable, eg jammed controls, fire, explosions.
	V_{GO}-V_{STOP}	Captain must decide action to take in case of failure/anomaly. RTO for conditions which render the aircraft unflyable, eg jammed controls, fire, explosions, etc.
Above V_1	Above V_{STOP}	Continue take-off

* Last three TOPM options assumes overlap of 'can go' and 'can stop' bars

Table 1 Procedure for failures during take-off

thus the ultimate decision was left to the Captain who could ascertain the best course of action to take for the conditions prevailing.

5.2.2 Procedure for TOPM Indicated Dangers If the aircraft was within the brown 'can stop' bar area, and the 'can go' and 'can stop' bars migrated such that a region on the runway appeared where neither GO nor STOP options is available, then the PNF called STOP - GAP (NB a gap appears between brown and blue bars - see Fig. 3d).

If the aircraft was within the 'can stop' area and the updated V_R position cross changed colour to red, indicating an unsafe continued take-off, then the PNF called STOP - RED CROSS (Fig. 3e).

6 Data Collection

The *qualitative* evaluation involved the use of post-test display rating questionnaires for both TOPM and non TOPM take-offs. This questionnaire considered aspects such as use of colour, display dynamics, ease of interpretation, level of mental workload, degree of situation awareness and crew procedure issues. A 'comparative questionnaire' (comparing TOPM and no TOPM) was also administered after all tests had been conducted. The *quantitative* data collection involved automatic recording (frequency of 10 Hz) of 64 selected parameters for each take-off run. In addition, at the termination of each run crew members were asked (by an inflight observer) whether performance was normal, better- or worse-than-normal.

7 Evaluation Procedure

The evaluation programme was tailored such that each subject attended the NLR facility for two full days.

7.1 Test Subjects

Six experienced airline flight crews were obtained to conduct this experiment. The subjects were all rated on twin-engined, glass cockpit, jet aircraft. The average subject age was 39. Average Captain flight experience was 8600 hours (minimum and maximum values being 3800 and 17000 hours respectively). Average First Officer flight experience was 4100 hours (minimum and maximum values being 1200 and 12000 hours respectively).

7.2 Subject Briefing

Each subject was furnished with a written briefing guide prior to arrival in Amsterdam. A pre-test briefing consisted of a verbal explanation of all items described in the briefing guide (eg evaluation tasks, flight simulator facility, cockpit displays, take-off procedures both with and without TOPM).

7.3 Evaluation Sequence

The training session employed to familiarise subjects with the flight simulator facility, the handling qualities of the simulated aircraft, the flight displays and warning systems, crew flight procedures and the evaluation tasks required approximately half a day. The subjects were provided with a range of flight scenarios that included normal, degraded and better-than-expected performance. The objective was to minimise the influence of learning effects.

Following the training session, a quantitative evaluation was performed for both TOPM and non TOPM take-offs. The order of the scenarios was randomly selected for a particular evaluation. The interface (ie TOPM or no TOPM) sequence was also random. During the evaluation the six crews flew a total 480 scenarios (with Captain as PF) - 240 for each interface.

8 Results and Discussion

8.1 Qualitative Analysis

The post-test questionnaires were in a *tick-the-box* format and comprised five statements with opposite viewpoints at the two extreme ends of the scale; the middle rating always indicated a *neutral* position. *All First Officers answered these questionnaires as PNF, whereas the Captains responded as PF.* Non-parametric statistical methods have been used to analyse the questionnaire data[24]. The Sign Test was used to test for significant differences across related samples, whereas the Mann-Whitney U Test was used for independent samples. The probabilities reported are one-tailed and the significance level, α, is set at 0.05.

Results for the TOPM show favourable ratings for choice, size and colour of symbology, display dynamics, ease of interpretation, amount of information presented and situational awareness[24]. For example, Fig. 5 suggests that ratings for TOPM indicate a higher degree of situational awareness ($p = 0.039$). Significant differences were not revealed across PF and PNF groups for either no TOPM or TOPM ($p = 0.298$ and 0.689 respectively).

A one-tailed test showed that the overall display ratings for TOPM (Fig. 6) were higher than those for non TOPM take-offs ($p = 0.039$). The mode for TOPM was good, whereas it was fair for no TOPM. An across subject group analysis for non TOPM take-offs indicated that PNF ratings were higher ($p = 0.037$). A similar analysis for TOPM did not indicate a significant difference ($p = 0.423$).

As an example of the results from the final 'comparative questionnaire', Fig. 7 presents ratings for the relative time taken to detect anomalies. Data indicated that there was no difference between PF and PNF groups ($p = 1$) and that the TOPM system was considered to enable faster detection of anomalies.

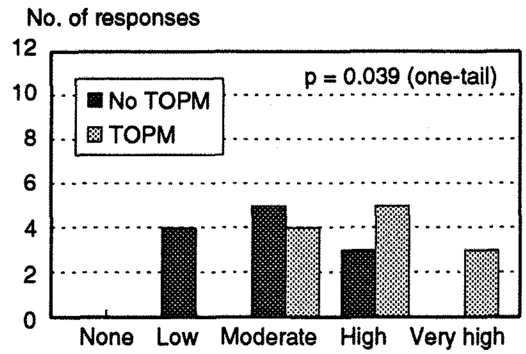


Fig. 5 Degree of situational awareness provided

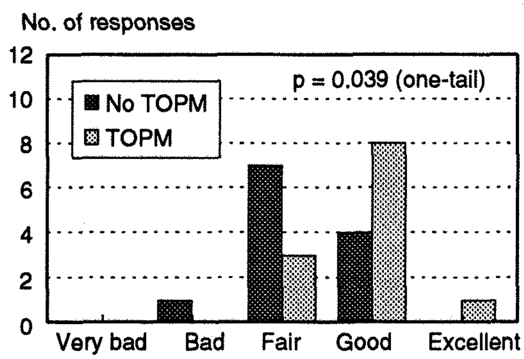


Fig. 6 Overall rating for display

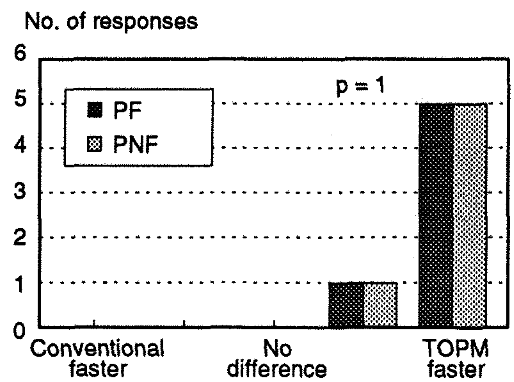


Fig. 7 Speed of detecting anomalies

8.1.1 Subject Comments A summary of the most frequent comments is presented below.

(a) Subjects stated that aircraft acceleration/performance was difficult to gauge for non TOPM take-offs. It was also commonly voiced that TOPM generally improved situational awareness and that anomalies were detected easier and earlier.

(b) Numerous pilots stated specifically that they appreciated very much the CAN FLY call. It gave them a certain degree of confidence about the aircraft take-off ability.

(c) Some subjects stated that the GO call associated with exit from the 'can stop' bars could perhaps be misinterpreted after a failure, and it may potentially lead to an inadvertent early rotation. Alternative suggestions for the GO call were V_1, MUST FLY and CONTINUE.

(d) A number of First Officer (PNF) subjects indicated that workload increased when using TOPM. However, analysis of the subjective workload ratings[24] did not show a significant difference between TOPM and non TOPM take-offs ($p = 0.288$).

(e) Several subjects stated that the TOPM and speed tape integration needed improvement, ie either incorporate TOPM on the Primary Flight Display (PFD) or provide a speed tape on the TOPM. This was related to improving the pilot instrument scan pattern. Several pilots also suggested that automatic audio call-outs for the V_{GO} and other important speeds could prove to be beneficial.

(f) Pilots suggested that perhaps the "gap" condition (Fig. 3d) should draw greater crew attention. One PF suggested "if a gap appears and <u>remains</u> for more than say two seconds (actual limit to be determined by trials and due software restrictions), or if a red cross appears, this should trigger a class 3 alert on EICAS, as this situation is an emergency that requires an RTO."

(g) There was no general consensus on crew procedure issues such as advisory and commanding nature of First Officer call-outs, crew member responsible for throttle control during take-off/RTO, and delegation of PF and PNF duties. This concerns both TOPM and non TOPM take-offs. It was clear from a pre-test questionnaire that the take-off/RTO procedure used by every crew in their respective airline operations were all dissimilar. Subjective ratings, however, did show that the PNF should be responsible for monitoring TOPM information.

8.2 Quantitative Results

8.2.1 Post-Run Question At the termination of each run, pilots were asked whether the performance was normal, better- or worse-than-normal. Fig. 8 presents the responses. For a given interface there is very little difference between PF and PNF responses. However, when the results across interfaces are compared, there were 27% more correct responses when using TOPM. The results would tend to suggest that TOPM enabled superior detection of anomalies.

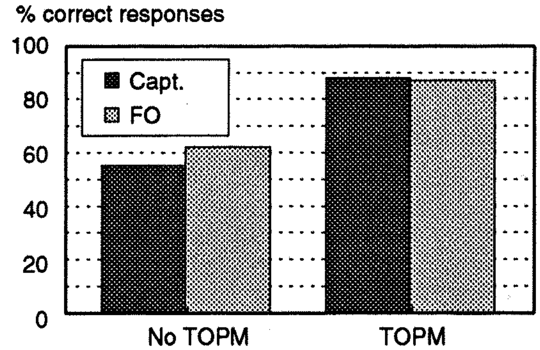


Fig. 8 Correct detection of sub-standard performance

8.2.2 Actions In some take-offs the required screen height clearance or V_2 were not ultimately achieved at the runway end. However, the aircraft did manage to climb-out and achieve sufficient airspeed and height without a crash in those cases. In fact the PF used the total energy of the aircraft to either prioritise speed or altitude to effect safe outcome. In some take-offs emergency thrust was employed by the crew in the later stages of the take-off roll or initial climb. Thus the total energy the aircraft attained at the runway end is used to determine whether the take-off was safe. If it is assumed that the aircraft attains an airspeed equal to V_2 at the runway end, a relative energy height can be calculated by

$$E_{scr} = m\, g\, h_{scr} + \tfrac{1}{2}\, m\, V_{scr}^2 \qquad (1)$$

$$h_{escr} = \frac{E_{scr} - \tfrac{1}{2}\, m\, V_2^2}{m\, g} \qquad (2)$$

where

V_{scr} aircraft speed at the runway end
h_{scr} aircraft height at the runway end
h_{escr} relative energy screen height
E_{scr} aircraft total energy at screen height.

The value of h_{escr} therefore is a measure of the height which can be attained at the runway end using the total available energy. If h_{escr} is greater than the minimum clearance (35 ft or 15 ft for dry and wet runway conditions respectively), the take-off is considered safe. Those continued take-offs where the aircraft failed to become airborne before the runway end are classified as being unsafe, regardless of the speed achieved.

The five possible outcomes and colour codings in the figures presented overleaf are as follows.

Black	Unsafe RTO; the airplane did not stop before the runway end.
Dark Grey	Safe RTO; the airplane stopped on the runway.
Light Grey	Safe continued take-off; relative energy screen height larger than 15/35 ft for wet/dry runway respectively.
White	Unsafe continued take-off for aircraft airborne at runway end; relative energy screen height lower than 15/35 ft for wet/dry runway respectively.
Cross hatch	Unsafe continued take-off as aircraft not airborne at runway end.

In order to identify under which particular conditions a TOPM may be beneficial, results analysed in Ref. 24 were considered in the categories listed below, namely

(a) all scenarios combined,
(b) sub-sets of scenarios consisting of various performance anomaly and discrete event combinations,
(c) three sub-sets focused on malfunction timing,
(d) three sub-sets scrutinising the performance anomaly classes.

For the purpose of this paper only a selection of the results is presented.

<u>8.2.2.1 Nominal, LOW$^+$ and LOW$^-$ Performance With Discrete Events</u> In most of the LOW performance anomaly class cases, crew actions were similar to the nominal take-off group and results are thus presented collectively herein. Data indicated that in these situations TOPM was not able to offer any significant safety benefits over non TOPM take-offs; crew performance was similar in both cases[24]. Fig. 9 shows the percentage of continued take-offs in response to the three discrete events considered herein. Without TOPM about 50% of the take-offs were continued. As 50% of the failures occurred before V_1 this result is not surprising. For the TOPM aided take-offs the results are dissimilar. In the event of a FCS failure around 45% of the take-offs were continued. Around 60% of take-offs were continued in the engine failure cases and 20% more in the advent of a tyre failure. The fact that a greater number of take-offs were continued with TOPM is probably attributable to the crew procedure used in the current study (Table 1). This required the PF to remove his hands from the throttle once the aircraft entered the 'can go' area. Entrance into 'can go' area effectively demanded a more go-minded attitude.

The reaction time is that measured from time of failure to the initiation of the abort. The results presented in Fig. 10 indicate that the average reaction time for an engine failure was approximately 1 s. The difference across interface appears to be minor. Average reaction times in response FCS failures were slightly longer at 1.2 s. Reaction times in response to tyre failures for take-offs without TOPM guidance were on average about 1.6 s. This increase can be attributed to the fact that the tyre burst is a less obvious failure than either the engine or FCS failure (appropriate EICAS warnings appear in these two latter cases); therefore the tyre failure detection time can be longer (the only cues available were associated physical vibration and noise). With TOPM the mean reaction time for tyre failure increased to approximately 3 s. Results in Ref. 24, however, indicate that in these cases the average runway distance remaining after RTO (L_{rem}) increased (relative to no TOPM) and the total number of RTOs decreased for TOPM aided take-offs (Fig. 9). It appears that only those take-offs which were not critical with respect to the RTO manoeuvre were aborted, and this allowed a longer decision time. When the tyre failure occurred at low speed, crews generally hesitated prior to making a decision in order to ascertain the possible outcome.

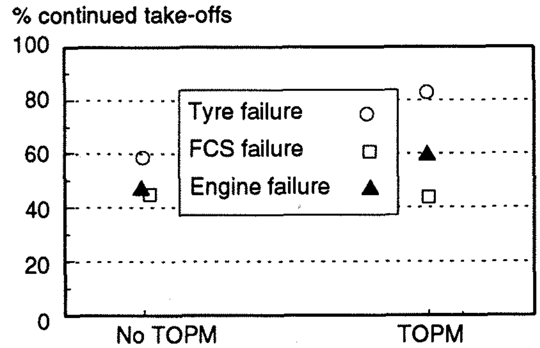


Fig. 9 Nominal, LOW$^+$ and LOW$^-$ performance: reactions after failures

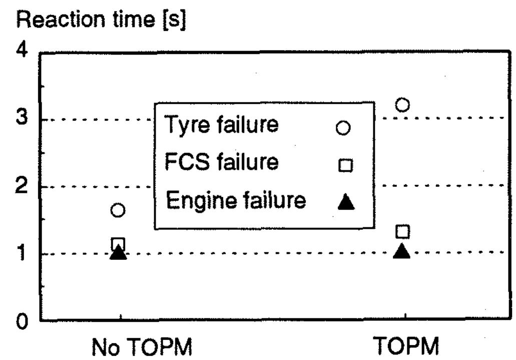


Fig. 10 Average reaction time: from failure to abort initiation

<u>8.2.2.2 MED Performance Deficit With Engine Failure</u> Without TOPM most take-offs were continued (76%) as Fig. 11 shows. Most of these continued take-offs were unsafe and 60% of all take-offs did not manage to even become airborne before the runway end; this could well have resulted in a high speed crash in real operations. All take-offs were safely aborted when TOPM was used (Fig. 11b) at an average speed lower than the no TOPM cases - even before the engine failure occurred. In this case a gap occurred between 'can go' and 'can stop' bars (see Fig. 3d) and the TOPM crew procedure required initiation of a RTO.

<u>8.2.2.3. Static Performance Deficit</u> Only the MED and HIGH performance deficit scenarios are considered in this and the next section. Half of these scenarios also incorporate a discrete event. A static performance deficit involves a constant loss in along-track acceleration. This was simulated by an erroneous engine setting; the Engine Pressure Ratio (EPR) value shown on the engine display

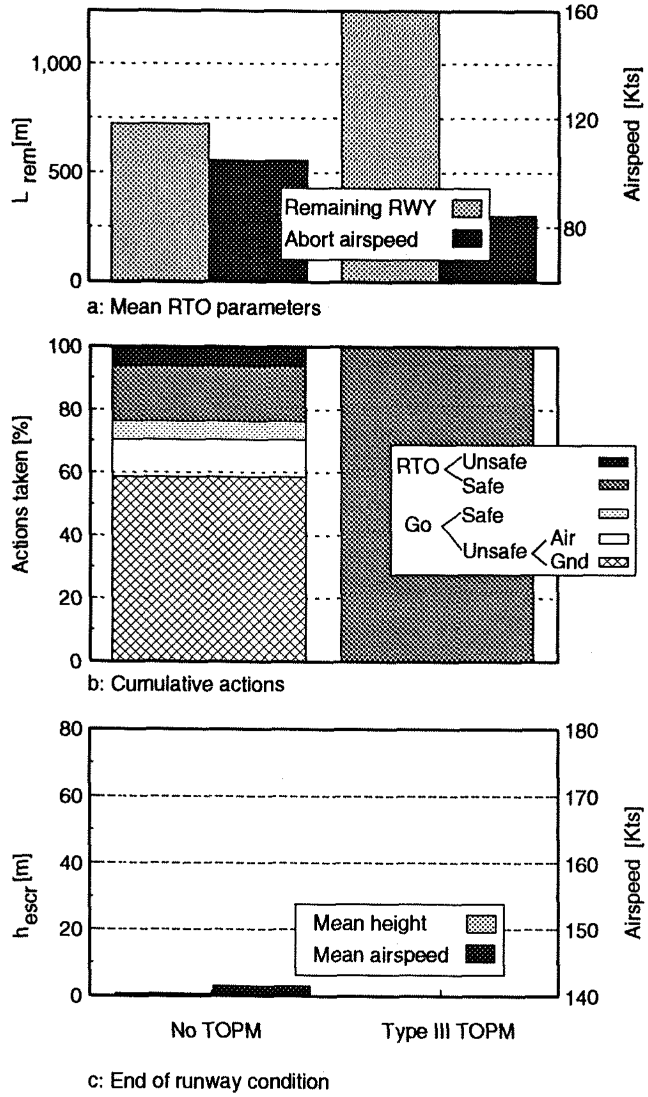


Fig. 11 MED⁻ Performance with engine failure

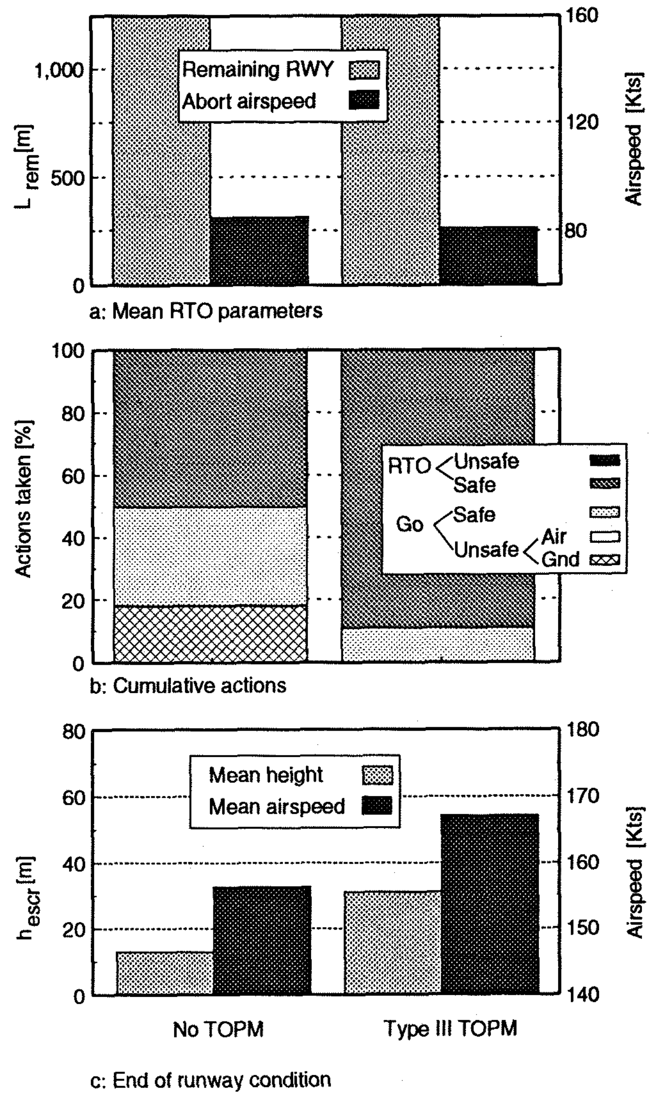


Fig. 12 Static performance deficit

was not the true value. The other engine parameters N2 and TGT were correctly displayed, and showed a value lower than normal for the EPR value displayed. This failure bears some resemblance to the Air Florida Boeing 737 accident at Washington National Airport in 1982[1,19-20]. Only one of six crews detected this anomaly from engine instrument readings alone. The average runway distance remaining after the RTOs was considerable in both no TOPM and TOPM cases as Fig. 12a indicates. Fig. 12b shows that a higher percentage of take-offs were rejected (all safely) when TOPM was available. For the non TOPM take-offs there were a significant number of unsafe continued take-offs. Fig. 12c shows that on average the screen height conditions were superior for the TOPM aided take-offs.

8.2.2.4 Windshear Once again, there were far more continued take-offs when TOPM was not available; a large proportion of these being unsafe as Fig. 13 shows. All RTOs and continued take-offs conducted with the aid of a TOPM were safe. On average the aborts were initiated at a lower speed when compared to non TOPM take-offs. Fig. 13c shows that the end of runway conditions were superior when TOPM was used.

9 Conclusions

(a) The results indicate that a potential increase in take-off safety seems possible in two classes of scenarios with a Type III TOPM, namely:

- when a performance deficit together with an engine failure no longer permit a safe abort or continued take-off at V_1; and
- when a performance deficit exists large enough such that safe climb-out is not possible.

Such performance anomalies could arise as a result of severe windshear, sub-standard thrust and excess

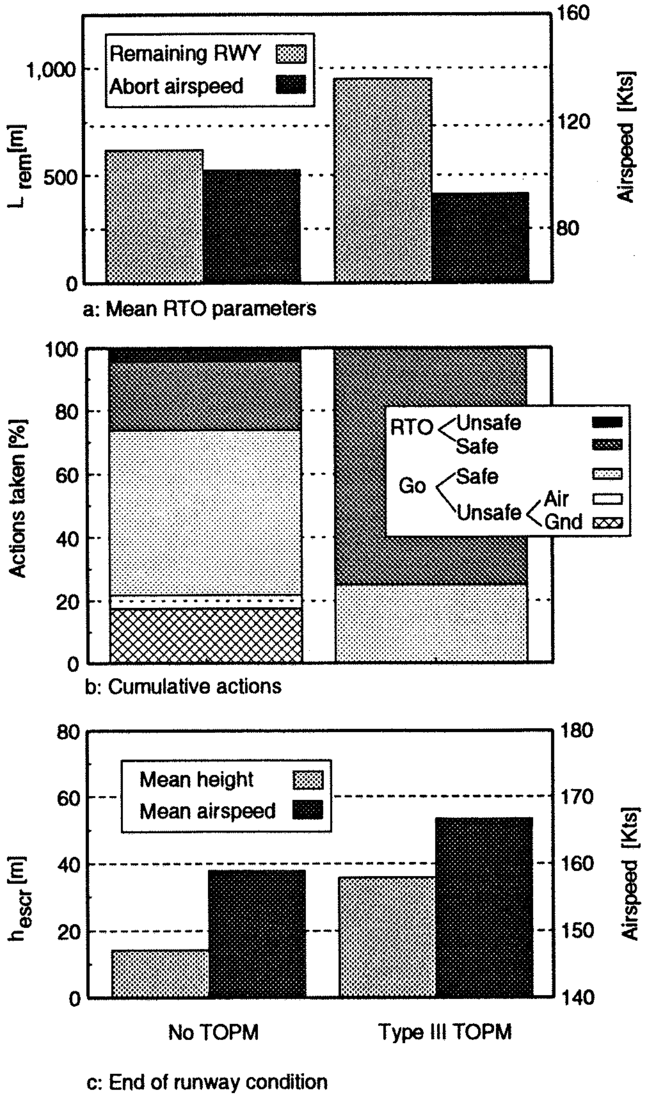


Fig. 13 Windshears

slush on the runway surface. In cases where performance was about normal, and a sudden failure developed at some point in the take-off, TOPM did not offer any significant safety benefits. These findings agree fully with previous results[21-23]

(b) Detection of performance anomalies improved with TOPM.

(c) Crew response to a tyre failure may take longer than for more obvious failures such as engine failures. Average reaction time in the later case was about 1 second.

(d) Most subjects agreed that TOPM provided useful performance information during the take-offs. Subjective ratings imply that situational awareness, the ability to detect anomalies, and overall display rating were significantly (statistical) higher for TOPM aided take-offs.

(e) TOPM symbology rating associated with size, choice, colour, ease of interpretation and benefit were favourable.

(f) The STOP - RED CROSS and STOP - GAP calls were generally considered as emergency situations, similar to other Level 3 alerts.

(g) Integrating TOPM on a PFD speed tape or providing a speed tape on the TOPM were suggestions to facilitate easier scanning. Implementing TOPM on a Head-Up-Display was also a common remark.

(h) Subjective comments indicated the workload increased for TOPM aided take-offs. This could be analysed in any future study using appropriate workload estimation techniques.

(i) The "CAN FLY" call appears to instill a go-minded attitude and was very much appreciated by the crews. It appeared to provide some confidence in the continued take-off ability of the aircraft.

10 Recommendations for Further Study

The potential benefits of a system incorporating only a discrete warning to the crew, instead of a comprehensive display, could be investigated further. Such a TOPM system could incorporate the predictive Type III algorithm which detects the situation when an overlap between the 'can go' and 'can stop' bar area disappears. (By definition this would also initiate a warning in the HIGH performance deficit case). In the event that unsafe performance is identified, a warning would be generated, which should trigger the crew to abort the take-off. The warning could be audio and/or visual, but further work is required to define this. The potential advantages of this system are:

- the current V_1 speed is used as the decision criterium for take-off decisions. This implies minimum distraction from current practice;
- the TOPM warning logic can be inhibited above a predefined speed, eg 100 Kts, which will prevent the system from giving potentially dangerous false warnings at very high speed;
- crew workload will not necessarily increase because additional information is not presented when the take-off is normal (dark cockpit concept). Crew reaction to a warning could be similar to that for any other Level 3 alert;
- costs are likely to be lower if a display is not required;
- additional instrumentation will not be required in current generation aircraft to feed the TOPM algorithm;
- it may be possible that certification will become less daunting.

Clearly further work is required to fully validate (or invalidate) the ideas presented above. To that end, further efforts are encouraged.

11 Closure

The overall conclusion of this and the previous NLR related studies is that a TOPM may have the potential to improve safety when a significant performance deficit is present. This improvement in safety arose because detection of the performance anomaly normally occurred at low speed, usually before 100 Kts, when considerably less than half the runway had been used. The crew is then able to take appropriate action, usually a safe RTO. In cases where performance was about normal, and a sudden failure developed at some point in the take-off, TOPM did not offer any significant safety benefits. It would therefore appear that the strength of the Type III TOPM investigated herein lies in identifying at an early stage of the take-off, that the performance is not sufficient for a safe continued take-off.

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