WAKE TURBULENCE MITIGATION FOR DEPARTURES FROM CLOSELY SPACED PARALLEL RUNWAYS: A RESEARCH UPDATE

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OVERVIEW

The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) have embarked on a multi-phased research and development program to develop and implement wake avoidance solutions that can safely reduce separation between aircraft and improve capacity at airports in the United States National Airspace System (NAS). The mid-term phase of the research focuses on the application of wind-dependent procedures for improved departure operations from Closely Spaced Parallel Runways (CSPRs) in the U.S. These procedures are referred to collectively as Wake Turbulence Mitigation for Departures (WTMD)

This paper reports on recent findings of the joint research performed to date by members of the research team, which includes FAA, Lambert St. Louis International Airport Air Traffic Control operational staff, Massachusetts Institute of Technology (MIT) Lincoln Laboratory, MITRE Center for Aviation System Development (CAASD), NASA Langley Research Center, and the Volpe National Transportation Systems Center.

In this paper, we review the WTMD concept, including potential benefits that may be derived from its use, report on the most recent work in the development of the wind forecast algorithm, provide results of a recent simulation study of controller use of the new procedures, and conclude with a description of the initial prototype installation and validation of controller information requirements

INTRODUCTION

The current wake turbulence research and development efforts in the U.S. and Europe are being coordinated through the FAA/Eurocontrol Cooperative R&D Action Plan 14 [1]. These efforts are beginning to yield successful results, some of which will be described here, including the improvement of wind forecast algorithms, development of Air Traffic Control (ATC) systems architectures, and air traffic control procedures which may support new wake turbulence separation standards for CSPR departure operations.

Since separation standards and ATC procedures have been designed for the worst-case conditions with respect to wake behavior, there may be room for adjusting ATC procedures to provide more capacity, if wake vortex behavior can be predicted.

1. CURRENT WAKE TURBULENCE SEPARATION

Current ATC separation standards take wake vortex behavior into account, defining the distance behind wake generating aircraft at which operations can be conducted. Wake turbulence separation must be applied between successive departures from CSPRs with centerline separation less than 2500 ft, when the lead aircraft is a Heavy Jet or B757, regardless of departure runway [2]. Additionally, when thresholds are staggered (offset) by 500 ft or more, as in the case of the Lambert St. Louis International Airport (KSTL), aircraft departing from the offset threshold must be held 3 minutes after a departing Heavy or B757 on the adjacent parallel runway. This delay cannot be waived using anticipated separation. [2]

Figure 1 presents the KSTL airport layout. The three parallel runways are dual use for arrival and departures.

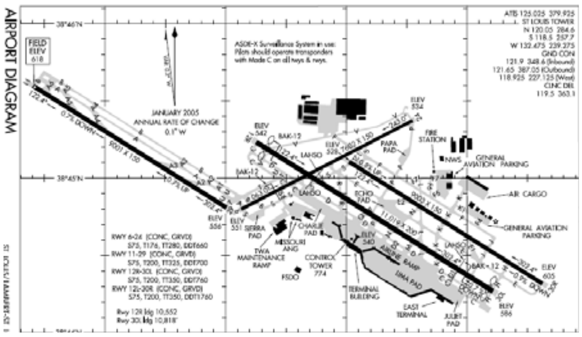

FIG 1. KSTL Airport Diagram

In East departure operations, runways 12R and 12L are used[1]. Centerline separation is 1300 ft, and the Runway 12L threshold is staggered 3100 ft to the east of the Runway 12R threshold. Paired departures using visual separation are permitted at KSTL and other CSPR airports, when weather permits, and when the lead aircraft is Large or Small because there is no wake dependency between them. However, wake separation is required when the leading aircraft is a Heavy or B757, even when it is departing from the parallel runway. The Current Ops section of Table 1 presents departure wake turbulence separation applied between two runways in today's operations, based on the wake generating status of the lead aircraft.

[1] Runway 11/29, to the west of the terminal complex, is primarily used when weather or other operational constraints do not permit arrival and departure demand to be met with the CSPRs, (12L/30R and 12R/30L), without incurring delay

TAB 1. Wake Turbulence Separation Requirements, Parallel Runway Departures

		Current Ops				WTMD Ops
		Leading Aircraft Type				
		Heavy	B757	Large	Small	All types
Trailing Aircraft Type on Parallel Rwy	Heavy	2 min or 4 NM (3 min intersection dep)	2 min or 4 NM (3 min intersection dep	Visual Separation	Visual Separation	Visual Separation
	B757	2 min or 5 NM (3 min intersection dep)	2 min or 4 NM (3 min intersection dep)	Visual Separation	Visual Separation	Visual Separation
	Large	2 min or 5 NM (3 min intersection dep)	2 min or 4 NM (3 min intersection dep)	Visual Separation	Visual Separation	Visual Separation
	Small	2 min or 5 NM (3 min intersection dep)	2 min or 5 NM (3 min intersection dep)	Visual Separation	Visual Separation	Visual Separation

2. WTMD CONCEPT

At CSPR airports such as KSTL, stable wind conditions are often observed such as those depicted in Figure 2. In these conditions wakes generated by departures on the downwind runway, may not be encountered by departures from the upwind runway. The WTMD concept seeks to recover departure capacity by identifying and predicting wind conditions under which an aircraft can safely depart behind a Heavy or B757 which has departed from the parallel downwind runway without applying wake turbulence separation.

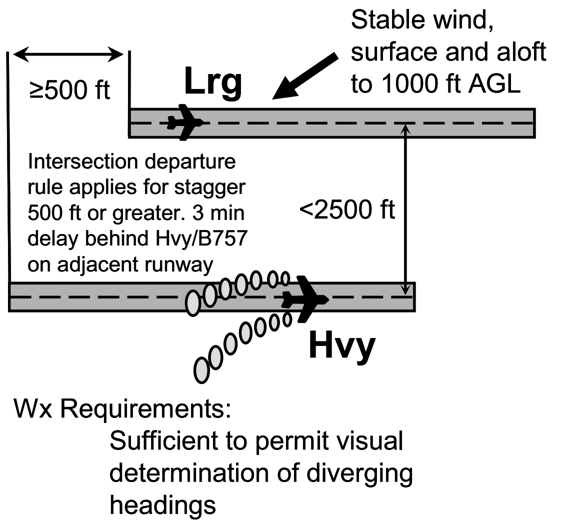

FIG 2. WTMD Wind Conditions

WTMD takes advantage of the transport of wakes generated by aircraft departing from a downwind runway, away from the path of aircraft departing from the upwind runway, enabling the waiver of the restrictions in Table 1. The WTMD Ops section of Table 1 shows that visual separation could be applied behind a leading departure from the downwind runway when WTMD is in effect. For departures from the same runway, standard departure separation would still be required, including wake turbulence requirements.

The concept requires a wind forecast algorithm (WFA) that can provide a short-term forecast of the wind field from the surface to at least 1000 ft above ground level (AGL) integrated with a decision support tool to inform the controller when WTMD operations can be conducted and from which runways. The safety requirements for the automation are based on a simple aircraft-by-aircraft go/no-go decision. To ensure safe operations, the wind prediction has to hold only for the 2 or 3 minutes the trailing aircraft would otherwise have waited behind a Heavy or B757 departure from the parallel runway.

WTMD operations must be available for operationally useful periods; a minimum time period will be verified through discussions with controllers. This may result in some loss of potential benefit that could be obtained by applying WTMD during shorter intervals, but eliminates problems associated with controllers having to transition into and out of WTMD frequently.

The decision processes used by tower supervisors when considering operational changes that affect demand, operational complexity, and overall safety will be explored through shadow mode prototyping and evaluation efforts already underway at KSTL and planned for George Bush International Airport (KIAH). These simple elements of WTMD introduced in 2005 [1] are explored further in this paper.

3. AVAILABILITY OF WTMD BENEFITS

The utility of any particular ATC concept is dependent upon three factors: (1) how often the concept can be applied, (2) how much of an improvement in capacity the concept provides when it is used, and (3) how often this capacity improvement is available during periods of excess airport demand.

The WTMD concept has several weather-related dependencies that must be satisfied during periods when WTMD will be used; the winds must be preventing wake from reaching the parallel runway and the ceiling and visibility must be such that the Local Controller can apply visual separation between departures. Using these weather constraints, Table 2 shows that WTMD is available on one of the parallel runways at candidate airports in the United States from 20 to 51 percent of the time.

TAB 2. WTMD Availability at Selected Airports With Closely Spaced Parallel Runways

Airport	*Estimated Average WTMD Availability*
DTW	*30%*
EWR	*36%*
IAH	*20%*
PHL	*22%*
SFO	*51%*

The departure capacity increase that can result from WTMD operations is affected by the fraction of Heavy and B757 aircraft in the airport's traffic mix, as shown in Figure 3, which illustrates the result of Monte Carlo analysis of the effects of departure mix and WTMD. It also shows the additional departure capacity that may be available with WTMD procedures in effect for a given proportion of wake generating aircraft. At a 45% proportion of wake generating aircraft in the departure flow, the fast-time model estimates a 62% improvement in airport departure rate for a pair of departure runways with staggered thresholds, when the staggered threshold runway is wake independent.

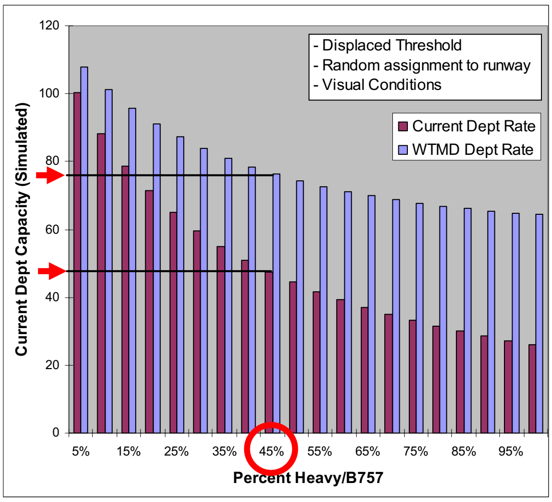

FIG 3. Departure Capacity Fast Time Analysis Results

Of course the underlying assumption in the capture of these benefits is the availability of a reliable local wind forecast, and appropriate displays and procedures to support air traffic controllers' application of this concept. The next two sections discuss the most recent modifications to the WFA and the results of a human-in-the-loop simulation of WTMD procedures during local departure operations at KSTL.

4. WIND FORECAST ALGORITHM

The WFA predicts when the runway crosswind will be suitable to ensure that the wake from the downwind aircraft will not impact the upwind aircraft. This forecast is the enabler for WTMD operations. Specifically, the algorithm must forecast when the crosswinds along the departure airspace, from the surface to the height that aircraft achieve divergent paths (nominally defined as an altitude of 1000 ft), will remain consistently strong enough to provide for wake independent operations on the upwind runway.

For purposes of this analysis the wind threshold supporting WTMD operations is defined initially as zero knots crosswind or greater (i.e., away from the runway of the trailing departure). This threshold is somewhat conservative in that some low level of negative wind may still allow for safe operation due to the transport time of the wake in reaching the other runway (depending on runway centerline separation). Additionally, the algorithm has been developed with the objective of predicting when the crosswind will remain above threshold for 20 minutes. However, from a safety perspective, a highly reliable forecast with a time horizon of only 3-4 minutes is required, composed of the current wake turbulence delay of 2-3 minutes (depending on runway stagger, see Table 1), plus an additional minute to account for the update time of the algorithm.

4.1. Algorithm Description

There are two primary components to the WFA:

- A surface crosswinds prediction derived from a regression analysis of historical wind behavior as measured by the on-airport Automated Surface Observing System (ASOS) sensor, which provides a 2-minute average wind speed every minute.
- A prediction of winds aloft (up to 1000 ft) derived from the National Oceanic and Atmospheric Administration (NOAA) Rapid Update Cycle (RUC) numerical weather prediction model. This is an additional element to the original forecast model which included only surface winds. Its role in the system is primarily to identify non-abrupt transitions from favorable to unfavorable crosswinds aloft before being detected at the surface.

For each operational runway, the WFA generates an indication of whether or not the predicted crosswinds will support WTMD procedures. The available runway ends would be made available to the controllers via a display. The predicted crosswinds must be above threshold both at the surface and aloft in order for the WFA to report a favorable ("green light") status condition (Figure 4). If the crosswind threshold is not met, the algorithm reports unfavorable ("red light") status. The runway status is updated once per minute.

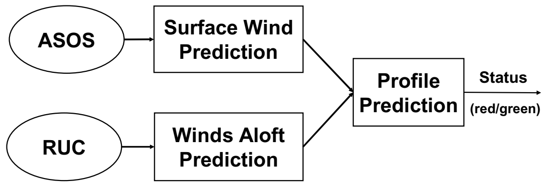

FIG 4. Block Diagram of Wind Forecast Algorithm Functional Logic

4.2. Surface Wind Prediction

The surface wind algorithm of the WFA was developed using one year (2001) of 1-minute ASOS wind data from KSTL. The derivation of the linear regression equations used for the surface wind prediction is described fully in the Appendix of [1]. The result of the analysis is a set of surface wind prediction equations corresponding to various combinations of current headwind and crosswind. Each equation provides a prediction of the expected mean crosswind speed and standard deviation (sigma) for the subsequent 20 minutes. The "lower bound" of the predicted crosswind is then defined as:

(1) Predicted_min_sfc_crosswind =
Predicted_mean_ – n* predicted_sigma

In order to qualify as suitable for WTMD operations, the predicted minimum crosswind must be at or above threshold (defined as zero knots, as previously described). Thus, the selection of the number (n) of standard deviations determines the conservatism of the algorithm.

As n increases, it decreases the likelihood of incorrectly predicting suitable wind conditions for WTMD procedures (referred to as a Type 1 Error), but also increases the likelihood of incorrectly predicting unsuitable crosswinds (Type 2 Error). [1] Thus, choosing the value of n permits assessment of the tradeoff between safety and benefits. A range of values was tested during the development process, taking into account the importance of maintaining an extremely low probability of a Type 1 error.

4.3. Stability of Prediction

To address controller operational concerns about potentially frequent status changes, the algorithm is structured to minimize the occurrence of a "flickering" status output, i.e. short alternating periods of favorable and unfavorable conditions when the minimum predicted crosswind is near the threshold value. This is done by allowing the value of n to vary based on the current alert status. A very conservative requirement (higher n) is chosen in order to transition from a red condition to a green condition; once this requirement is met, a more relaxed requirement (lower n) is imposed for transition back to red condition. Two additional requirements are imposed in order to further reduce flickering and to ensure reliability. First, the direction of the measured wind must be no more than 60 degrees offset from normal to the runway. Second, the wind speed must not be below 3 knots.

4.4. Winds Aloft Prediction

The most recent versions of the WFA add predictions of crosswinds for altitudes up to 1000 ft, the point during departure at which divergent headings are expected to obviate wake separation concerns. The vertical wind profiles are derived from the NOAA RUC model, which is run hourly by the National Center for Environmental Prediction (NCEP), at spatial resolutions of 40, 20, and 13 km. It provides hourly forecasts out to 6 hours, and 3-hourly forecasts out to 24 hours, at 6 height levels between 0 and 350 meters (1148 ft).

Two versions of the vertical wind aloft prediction algorithm have been developed. In the first version, the wind profiles used for the initial application of RUC data to the WFA were generated by interpolation of wind values from the four 20 km RUC grid points nearest to KSTL, interpolated to a single vertical profile at the airport position. This version was used in the validation process described below. A revised version uses the four 13 km grid points nearest the airport, and is described later.

As with the surface wind prediction algorithm, the winds aloft algorithm estimates the lowest crosswind expected and compares it to the acceptable threshold (zero knots). It examines the wind at each model height up to 1000 ft. It uses as its minimum expected crosswind the lowest model crosswind component at any of these height levels, minus 1 knot (as an additional conservative buffer).

4.5. Algorithm Evaluation and Validation

The algorithm was applied to data from 2004 to generate surface crosswind predictions for the evaluation dataset. The surface winds were combined with hourly RUC crosswind profiles (four nearest 20 km resolution points), interpolated to KSTL, to yield a WTMD status (i.e. red or green condition) using the zero knot crosswind threshold. Forecasts were generated for both orientations of the parallel runways at KSTL (12R/30L and 12L/30R). The algorithm evaluation results presented here are based on the combination of these two orientations.

4.6. WTMD Availability

Before verifying the algorithm's performance, a general characterization of the availability of WTMD was developed. A forecast favorable for running WTMD was issued for 25% of the individual minutes in the evaluation data set. These were grouped into nearly 450 continuous events, with a mean event length of 4.5 hours and a median length of 2.25 hours. 54% of the days during 2004 had at least one favorable wind forecast event.

4.7. Validation

The validation data set ("truth") consisted of the same 1-min ASOS crosswinds mentioned above, along with aloft crosswinds extracted from a dedicated on-site Laser Imaging Detection and Ranging (LIDAR) system. Eleven months of LIDAR data were available (February through December 2004). The LIDAR's scanning strategy allowed for orthogonal scanning every 5 seconds over the runways for approximately 15 out of every 75 minutes. Crosswinds were extracted roughly every 5 m in the vertical from just below 15 m to a height of nearly 300 m. Subsequent processing interpolated these to a fixed 5-m profile, and then applied a 2-min median time filter to yield profiles for each minute, consistent with the ASOS observations. The non-uniform nature of the LIDAR coverage, along with other sporadic outages, resulted in 14% time coverage (roughly 70,000 minutes) of validation data.

The evaluation distinguishes between two types of errors. "Type 1" errors occur when the wind forecast algorithm indicates favorable WTMD conditions, but at least one truth crosswind point (either surface or aloft, from the forecast minute out to 3 minutes) violates the 0-knot threshold. "Type 2" errors occur when an unfavorable WTMD wind forecast is followed by a period of entirely favorable actual crosswinds, both surface and aloft.

The observed error rates of the two types are shown in Table 3. The very low Type 1 error rate is attributable to a total of only five erroneous forecast minutes. A cumulative distribution of these errors by forecast lead time is shown in Table 4. Of the five instances for which the crosswind threshold was violated within 3-minutes of the forecast, there were two times that the violation occurred within 2-minutes of the forecast time, and no instances in which the threshold was violated in the first minute after the forecast. Furthermore, these five minutes of error occurred during three separate, rapid wind shift events, occurring on three days in August. Through analysis of surface and radar data, all three were found to be associated with clearly identifiable synoptic and mesoscale phenomena. Two events were due to cold-frontal passages and the other was caused by nearby thunderstorm activity.

TAB 3. Evaluation Summary for KSTL Data From Feb-Dec 2004 Expressed as Error Rates

Evaluation Type	**Type 1 Error Rate**	**Type 2 Error Rate**
Full Profile	4.83×10^{-4}	0.71
Surface Only	4.59×10^{-4}	0.75
Aloft Only	0.11	0.39

TAB 4. Cumulative Distribution of Forecast Horizons at Which Type 1 Errors Occur

Forecast Horizon (min)	0	1	2	3
Errors	0	1	3	6

To illustrate, the verification profiles for the thunderstorm convection event of 25 August 2004 and the associated KSTL Next Generation Radar Data (NEXRAD) vertically integrated liquid (VIL) plot are shown in Figures 5 and 6. Clearly the 1-

minute change in crosswind profiles is due to outflow from the line of strong convection approaching KSTL seen in Figure 6.

The bottom two rows of Table 3 show the error rates if each of the two components of the wind forecast algorithm are considered in isolation. The errors of the surface component are very similar to those of the final forecast and show that this component is the primary driver of the total algorithm. In the absence of upper-level verification, an evaluation based on the surface component alone provides a fairly good approximation of the complete algorithm performance for KSTL. The RUC-based upper level component on its own is much more aggressive in identifying favorable crosswind conditions (see the much lower Type 2 error rate), but also exhibits a clearly unacceptable Type 1 error rate. Its role in the system is primarily to catch cases where a non-abrupt transition from favorable to unfavorable crosswinds manifests itself aloft before being detected at the surface. This also provides protection against unexpected wake transport after departure and prior to reaching 1000 ft.

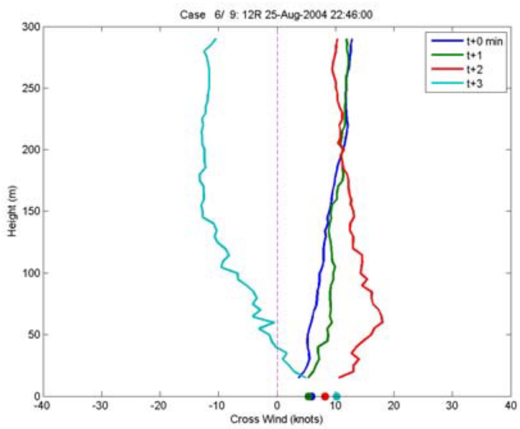

FIG 5. Profile Verification for KSTL Runway 12R/30L on 25 Aug 2004

In Figure 5 above, positive crosswind values are favorable for WTMD operations. The colored dots at 0 m height represent ASOS observations. The four profiles correspond to the forecast initiation time (t + 0, 22:46 GMT) plus the three subsequent minutes. At initiation, the wind forecast algorithm indicated a favorable crosswind, however, at t+3 min (left profile) the initial forecast failed as indicated by the negative crosswind prediction in the vertical profile.

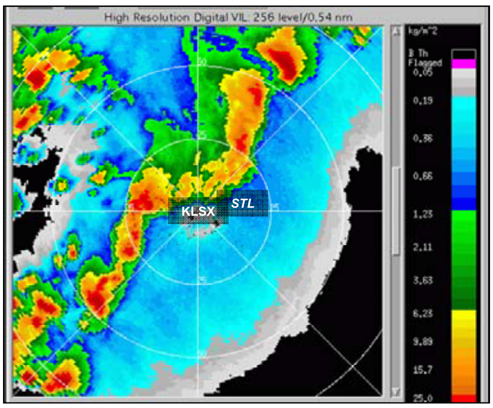

FIG 6. Vertically Integrated Liquid (VIL) From the KLSX NEXRAD at 22:48 on 25 Aug 2004

4.8. Continuing Test and Evaluation

The performance evaluation indicates that Type 1 errors are very rare and were attributable to sharp wind shifts associated with features that could be identified through automated analysis or weather assessment conducted by supervisory controllers. In converging on an end state system, continuing testing and modification of the WFA is aimed at increasing system benefits while maintaining these errors at a sufficiently low rate to ensure safe operations.

A modification of the winds aloft prediction methodology is being tested in the current real time operational demonstration and is expected to result in a further reduction of the Type 1 error rate, as compared to the offline analysis results presented here. Instead of using a single interpolated profile, the WFA examines the model winds from multiple neighboring grid points extracted from the highest resolution (13km) operational RUC model. The algorithm examines the forecast winds for the two hourly forecast validation times that bound the current time. An additional requirement is that the forecast validation time in advance of the current time must be at least 20 minutes into the future; this sometimes requires a third set of forecast profiles to be examined. The WFA examines the winds at each validation time, each neighboring grid point, and each level up 1000 ft AGL. The minimum value (minus 1 knot) is used as the minimum predicted wind to be compared to threshold. Using individual grid points increases the likelihood of a timely detection of an advancing wind shift.

In addition, an automated analysis of radar data to detect nearby convection that could potentially induce wind shifts is under investigation. A simple approach is to monitor radar reflectivity in the area surrounding the airport for appearance of nearby weather, such as that shown in Figure 6. More advanced approaches would take advantage of existing sophisticated wind shift detection and tracking algorithms, such as the Machine Intelligent Gust Front Algorithm (MIGFA) used in the Terminal Doppler Weather Radar (TDWR) system [5]. This automated analysis would become a component of the WFA that would override the issuance of a green light condition derived from the surface and aloft wind prediction sub-algorithms. In practice, the opportunity for a tower supervisor to manually override the WFA status condition already exists within the proposed WTMD concept of operations, which further reduces the risk of exposure to a Type 1 error.

There are other parameters within the algorithm structure that would allow an increase in system benefits without imposing unacceptable safety risk. For example, the evaluation presented here reflects the use of a zero-knot crosswind threshold. Ongoing observational analysis of actual wake transport behavior being conducted by the Volpe Transportation Center may justify a lower (i.e. slightly negative) threshold which would yield higher system benefits. Also built into the algorithm is the flexibility to change the number (n) of standard deviations from the mean predicted wind used to determine the minimum crosswind prediction.

The error reduction approaches described above may allow a relaxation of the value of n used in green status conditions. A sensitivity analysis indicates that system benefits may be increased by as much as one-third while still maintaining a sufficiently low probability of Type 1 error.

It is important to note that a comprehensive safety evaluation of the WTMD procedures will be based on a layered approach to mitigating identified safety concerns, of which the WFA is only one component. The layers of WTMD design which contribute to overall safety include: reduced separation procedures used by the controllers, the procedures used by the supervisor to turn on and off WTMD, the safety net defined by the conservative crosswind criteria used to trigger WTMD, and the automation functions which enable and disable WTMD.

Benefit is driven by opportunity, and the Type 2 error describing the occurrence of lost benefit is a reasonable stand-in. Safety is ultimately defined by the risk of a wake encounter. This risk may occur when a sudden wind shift (whether detected or undetected by WTMD) occurs while reduced separation is in use. The size and duration of an unacceptable wind shift will ultimately be determined through wake and a/c departure track analyses and these analyses are yet to be completed. Although some of these shifts would be detected by WTMD, they are all worthy of analysis because they will lead to design of mitigations including supervisor procedures for enabling and disabling WTMD, possible requirements for a real-time vertical wind profile sensor as a part of the system, and automated disabling of WTMD triggered by causes for the shifts (convective weather, gust fronts, etc.). .). Ultimately it is the analysis of the size of the wind transitions in type 1 errors and other transitions from 'green' to 'red' that will provide requirements for WTMD. An acceptable level of overall risk will be reached when today's risk for wake encounters is maintained or reduced.

5. HUMAN IN THE LOOP SIMULATION OF DEPARTURE PROCEDURES

5.1. Research Issues

A human in the loop (HITL) simulation was used to explore controller usability of WTMD procedures and the adequacy of information provided by a prototype decision support tool and associated displays. The availability of the previously described WFA is assumed to be providing the information on available runways. A secondary goal was to generate real-time, human-in-the-loop departure rate data, which could be used to estimate benefits from using the WTMD procedures, and validate the fast time simulation results.

The controller assessment used a combination of objective data collection, questionnaire methods and semi-structured interview techniques to solicit controller opinion on the utility and effectiveness of different aspects of WTMD procedures. Effects on controller workload, coordination between controllers in the execution of the procedures, and the effectiveness of a prototype WTMD display were also evaluated. The full research report is available in [3]. The research questions addressed in the study are:

- Can the WTMD procedures be used effectively by controllers during departure operations from closely spaced, parallel runways?
- How will controllers respond to an unplanned termination of WTMD or other non-normal events?
- Is the information available in the prototype display of WTMD status sufficient to support WTMD operations?
- What is the effect of arrival traffic on the usability of WTMD procedures?
- Is there an adverse effect on perceived workload when using WTMD procedures?
- What is the effect of WTMD procedures on achieved departure rates?

5.2. Method

A part-task simulation of WTMD operations was conducted using the Control Tower Simulation Facility (TSF) at the MITRE Air Traffic Management (ATM) Laboratory. Operations were modeled at KSTL. A subset of the controllers' normal workload was simulated, including sequencing departure and arrival traffic, communicating with aircraft, coordinating with other controllers, managing flight strips and, for this study, transitioning into and out of WTMD operations. Traffic in all scenarios was set to provide continuous departure demand on each of the two parallel runways.

The tower simulation includes a visual system for simulation of tower viewpoint, communications to support two or more controller positions, pseudo-pilot control of simulated arrival and departure traffic, and communications and subsidiary displays including the X-band Airport Surface Detection Equipment (ASDE-X), Digital Bright Radar Indicator Tower Equipment (DBRITE), and ASOS Controller Equipment Integrated Display System (ACE-IDS) which was used to display WTMD status information. Figure 7 depicts the TSF in the configuration used in this study. The ACE-IDS display is in the lower center between the local control positions.

FIG 7. MITRE ATM Lab Tower Simulation Facility

One supervisor position and two local control positions were emulated. The supervisor could monitor the communications of either local control position.

5.3. WTMD Displays and Information Requirements

Previous work [3] has developed preliminary requirements for information displays for local controllers and supervisors to support WTMD operations. One of the requirements expressed by KSTL staff was to adapt an existing display to host the WTMD status information, rather than add another display to a crowded tower cab. Prototype display designs were proposed [4], which implement the requirements; two of those prototypes were adapted for evaluation in this study. The adaptation was based on controller input specifically with regard to planning and expected supervisory interaction with the display functionality. Additional task analysis and information requirements verification is being completed by the NASA Langley Research Center and briefly described later in this paper.

The primary display device in this simulation was the existing ACE-IDS. All supervisor interactions with displays were with the ACE-IDS prototype interface. This information display system is the controllers primary surface wind reference.

However, it should be noted that this system is not fitted at each airport for which WTMD may provide benefit. The specific display modality actually installed in an operational system must still be determined.

A secondary, simultaneous display of WTMD runway status was created on the simulated ASDE-X display. An additional field was added, which simply indicated the current WTMD runway status. No interface to this display was provided, and when required, status changes were made by lab staff.

5.4. ACE-IDS Display and WTMD Operations

Figure 8 shows an overview of the ACE-IDS display with the WTMD status field. Separate ACE-IDS displays were available at the local control position (seen in the lower center of Figure 7) and at the supervisor position (not shown).

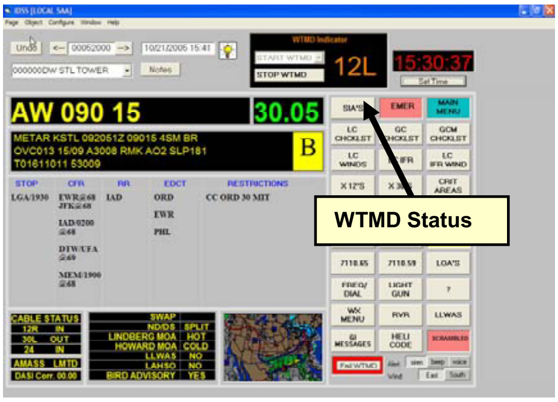

FIG 8. Overview of ACE-IDS Display With WTMD Status Field

Figure 9 shows the implementation of the WTMD field and other controls that would be used at the supervisor position to start and stop the WTMD procedure. The WTMD field incorporates a runway selection pull-down list, which would be populated with available runway ends as determined by the WFA.

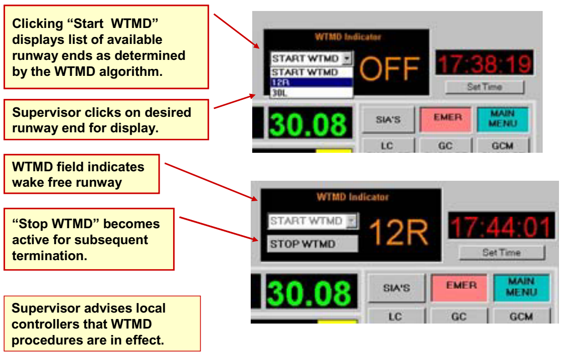

FIG 9. WTMD Display Supervisor Controls

The supervisor implements WTMD by selecting an eligible WTMD runway for display and verbally advising the local controllers that WTMD operation was now in effect. If a change in wind conditions is anticipated (e.g. convection approaching the airport), the supervisor would advise the local controllers to suspend WTMD operations, then click on the STOP WTMD button on the supervisor's display. "OFF" would be displayed in the WTMD field, and no further departures would be released under WTMD wake separation criteria

Any unexpected change in wind conditions or an undetected system failure would automatically terminate WTMD. A tower cab area aural alert would be broadcast (for this simulation the term "WTMD OFF" was used) until silenced by a supervisor. The supervisor would verbally verify that all controllers are aware WTMD procedures were terminated.

5.5. Communications, Aircraft Control and Traffic

Controllers communicated with pseudo-pilots using conventional push-to-talk communications methods to provide the normal instructions associated with local control of departure and arrival operations. Ground control operations were simulated by a confederate who executed ground movement commands for all surface traffic until the aircraft were established in a departure queue for Rwy 12L or Rwy 12R.

There was continuous departure demand on both runways. A mix of wake turbulence category aircraft was developed with the proportion of Heavy and B-757 aircraft ("wake generators") set nominally to 50%. The actual proportion of wake generators on a particular runway varied from 38–50%.

5.6. Subjects

Three controller teams participated in the study, but this paper will focus on the controller team from KSTL, who were most familiar with local operating procedures and CSPR wake turbulence separation. Their operations and procedures were considered to be representative of those used by other fully qualified controllers at their facility, and most likely yielded the most representative results. These controllers were highly experienced and a summary of their qualifications is presented in Table 5.

TAB 5. KSTL Controller Experience

Mean Experience, Years, KSTL Controllers				
	Total All	Total Tower	Total Sup or CiC	Total CSPR
Mean	20	18	14	14
Range	15 - 27	13 - 23	9 - 17	9 -18

Each designated local controller experienced 3 departure scenarios as local controller and 1 as supervisor. The designated supervisory controller experienced 3 departure scenarios as supervisor and 1 as local controller.

5.7. Scenarios and Scenario Variables

Four departure scenarios were developed to expose controllers to a variety of conditions. The airport was configured in a southeast operation with runways 12L and 12R as the active runways. Each scenario included a transition to or from WTMD operations occurring such that 25 minutes of each scenario were conducted using WTMD operations, and 15 minutes with standard operations

Scenario variables were adjusted to provide a variety of conditions under which to conduct WTMD operations, including non-normal events. The variables included:

- Initial WTMD Condition (ON or OFF)
- Transition type (Planned, Unplanned)

- WTMD Runway (12L or 12R)
- Departure Condition (departures only or mixed arrivals with departures).

5.8. Non-normal Events

Two types of non-normal events were included in each scenario: unplanned transitions out of WTMD operations resulting from assumed system failure or wind shift, and, for the mixed operation, a “refusal event” in which a pilot refused takeoff clearance after taxiing into position on the wake-free runway.

5.9. Data Collection

The ATM Lab provides automatic recording of many simulation system state parameters which was post-processed to provide departure and arrival data for each scenario. Tower cab area communication was captured by an omni-directional microphone and digital voice recorder. The recordings were reviewed manually and a count of the coordination events was made. At the end of each scenario, each controller completed a Bedford Workload Assessment form [6] which was adapted for use by controllers in this simulation. The Bedford instrument asks controllers to assess their overall level of spare capacity during the scenario, while performing their primary task, in this case applying appropriate separation rules while controlling arrival and departure traffic. Controllers then completed a final 25-item questionnaire at the end of the simulation. covering understanding of the WTMD concept, procedures, displays, and simulation fidelity. They indicated the extent of their agreement with each statement by selecting one of five choices ranging from Strongly Disagree to Strongly Agree.

At the conclusion of each scenario a semi-structured debriefing on WTMD procedures and displays was conducted. Comments from the debriefings were used to supplement the data from the final written questionnaire.

5.10. Results and Discussion

The results of the completion questionnaire, the semi-structured procedures debriefing, and the Bedford workload form suggest that, overall, controllers found the WTMD procedures to be easy to learn and easy to apply, and that they did not increase their overall workload above what is normally experienced. Figure 10 shows mean scores for the KSTL controllers by question category.

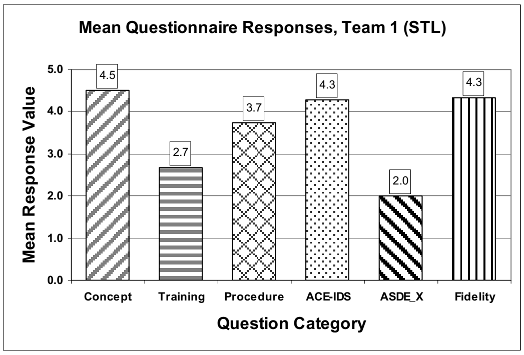

FIG 10. Mean Questionnaire Responses, KSTL Controllers

Controllers expressed confidence in their understanding of the concept (mean 4.5), and execution of the WTMD procedures (3.7). They positively evaluated the ACE-IDS display (4.3), and indicated that simultaneous display of WTMD runway status on the ASDE-X added little value (2.0).

The designated supervisor recorded that, as he observed controller coordination during WTMD operations, it appeared to be more difficult than with standard procedures. He also agreed with the statement that asserted that significant additional training would be necessary for controllers to understand the procedure, and disagreed that it was easy to apply WTMD procedures during the mixed arrival-departure condition. Local controller questionnaire responses and debriefing feedback did not express similar concerns. Given the small number of controllers in this study, any individual response should be interpreted carefully, but the opinion of an experienced supervisor with intimate knowledge of the KSTL operation should also be carefully considered.

5.10.1. WTMD Displays Assessment

In the Displays category, questions focused on information content and usability of the ACE-IDS and utility of the WTMD status information on the ASDE-X display Summary scores for the KSTL team are shown in Figure 11.

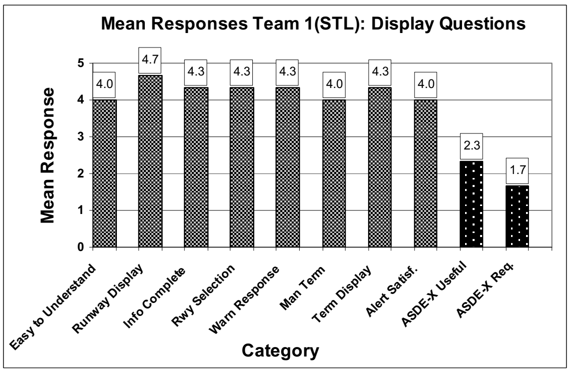

FIG 11. Mean Questionnaire Responses, Displays ACE-IDS Display

The KSTL team gave an overall positive evaluation to the ACE-IDS display on the statements related to understanding the display information (mean 4.0), identifying the WTMD runway (4.7), seeing that WTMD had been terminated (4.3), ease of configuring the display when starting (4.3) and stopping (4.3) the procedure, and the suitability of the aural alerts (mean 4.0). During the debriefing, display usability improvements were identified. More than one controller suggested that an indication that WTMD procedures are “available” should be a display feature. In the prototype for this study, the supervisor was required to activate the “start WTMD” pull-down list to determine whether runway ends were available. One controller expressed that the location of the WTMD status field should be adjacent to the airport surface wind field, since winds are routinely scanned at each departure clearance.

Most importantly, a controller noted that the ACE-IDS display is not currently certified as a “safety critical” display. Use of ACE-IDS for WTMD status may depend on whether it can be qualified as a safety critical system.

The current KSTL controllers judged the display WTMD information on the ASDE-X display to be unnecessary, as long as the information was available on the ACE-IDS display.

5.10.2. Tower Cab Coordination Analysis

Table 6 presents the observed coordination communication event rate with WTMD ON and WTMD OFF. Coordination communication rate was reduced by nearly 40%. With regard to overall workload, the reduction in coordination demand may have been offset by the increase in departure communications resulting from the improved departure throughput.

TAB 6. Coordination Communication Rates

Tower Coordination Events, Three Departure Scenarios			
	Time, Minutes	Event Count	Event Rate
WTMD Off	27	59	2.19
WTMD On	75	99	1.32
Rate Reduction			39.60%

5.10.3. Bedford Workload

The Bedford workload results indicate that no significant workload effects were experienced by the controllers when using WTMD procedures. Controllers confirmed during debriefing that the WTMD procedures would not be a workload issue, Figure 12 shows the mean workload reported by the KSTL controllers for the 4 departure scenarios. Overall mean Bedford score for the KSTL controllers during the departure scenarios was 2.33, with a score of 1 indicating low workload and 10 indicating high workload.

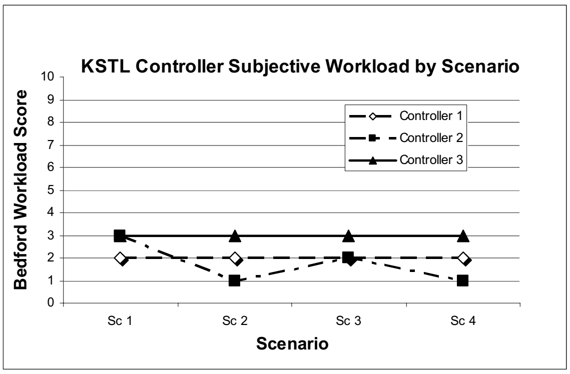

FIG 12. KSTL Controller Bedford Workload Ratings

5.10.4. Non-Normal Events

Regarding unplanned termination, controllers indicated essentially that there was no effect other than the requirement to re-apply standard wake separation rules. Recovery from an unplanned termination may have been more complex if surface re-routing of departures to a more advantageous runway would improve efficiency.

5.10.5. Departure Rates

The summary of the achieved departure rate in each scenario is presented in Table 7.

TAB 7. Mean Departure Rates (Per Hour), KSTL Controllers

KSTL Controller Departure Rate Summary			
	12ROff	12ROn	% Chng
Deps Only	35	37	5.7%
Mixed Ops	22	25	13.6%
	12LOff	12L On	% Chng
Deps Only	23	42	82.6%
Mixed Ops	23	35	52.2%

There was an overall increase in departure rates on each runway when WTMD procedures were in effect. The rate increase was larger when WTMD operations were in effect on Rwy 12L than for Rwy 12R. This is attributable to the substantial benefit of eliminating the non-waivable 3 minute intersection departure delay on Rwy 12L (in this case due to staggered threshold). Table 8 compares the findings of the fast time analysis results reported earlier with the total airport departure rate during the HITL simulation; the HITL simulation showed a departure rate increase of 36%. The Monte Carlo simulation results showed an improvement of 62%. It should be noted, however, that the KSTL controllers exceeded the WTMD Off Monte Carlo prediction by 10 dep/hr and essentially matched the WTMD On prediction.

TAB 8. Comparison of HITL and Monte Carlo Airport Departure Rates, Dep/Hr

	WTMD Off	WTMD On	% Incr
Monte Carlo Dep Rate	48	78	62.5%
HILT Dep Rate	58	79	36.2%

5.10.6. HITL Conclusions

Controllers found the WTMD procedures to be useable. Overall, the procedures were judged easy to understand and implement and the transitions to and from WTMD operations were performed without difficulty. They noted that each facility will have unique requirements that will require facility-specific standard operating procedures for the conduct of WTMD operations to be developed. Requirements for controller training were addressed only briefly in this study and controller opinion was mixed with regard to whether significant additional training would be required.

Responding to unplanned termination and pilot refusal events posed no significant operational problems that would be more serious than similar events that occur when normal wake separation procedures are in effect.

Mixed arrival and departure operations were easily accommodated on each runway, and no adverse workload or other operational effects were noted.

The WTMD preliminary display information requirements were validated using the prototype display. Controllers indicated that the ACE-IDS platform would be a suitable candidate for hosting WTMD information, assuming that safety and reliability of the system for that purpose can be established. Supervisors found the interaction with the prototype display to be straightforward. Controllers expressed a preference for a voice message to annunciate an automatic termination of WTMD procedures rather than alert tones.

There were no adverse effects on controller workload reported by controllers. In addition, there was evidence of reduced coordination required among KSTL controllers when WTMD operations were in effect. The highest workload scores reported by the KSTL controllers were still within the normally expected range.

Increased departure rates for Rwy 12L were consistently observed when WTMD procedures were in effect, primarily related to the elimination of the 3-minute staggered threshold delay required behind wake generators on the adjacent runway. A smaller improvement in departure rates was observed on Rwy 12R. Observed results compared favorably with the fast time analysis results. Assignment of Heavy Jet and B-757s to the non-wake-free runway may maximize total departure throughput at airports where threshold staggering is not present. Other local procedures related to departure routes and gates may have to be modified, if this approach is adopted.

6. WTMD PROTOTYPE IMPLEMENTATION: WORK IN PROGRESS

The next steps in the implementation of the WTMD procedures are already underway. This work includes installation of prototype systems at KSTL, and planned for George Bush Houston Intercontinental Airport at Houston, Texas, USA (KIAH). The prototypes will be operated in shadow mode for the purpose of evaluating the real time performance of the algorithm and to introduce additional tower staff to the WTMD concept. The WFA parameters will be assessed to help determine the optimum balance between control of Type I error and the availability of the procedure as previously described.

The second goal of the prototype assessment will be to perform a final validation of information requirements for the decision support tool. While a preliminary assessment of requirements was completed to support the HITL simulations, a more comprehensive review in conjunction with a task analysis, particularly for the supervisory controllers has been undertaken by the NASA Langley Research Center. Initial steps and preliminary findings of this work are described in the next section.

6.1. Information Requirements Analysis: Role of Supervisory Air Traffic Controller in WTMD Operations

Subjective data was collected from supervisory controllers at the (KSTL) Air Traffic Control Tower for the purpose of verifying their information requirements for operation of the WTMD prototype, specifically the information that is required for authorization of the procedure.

It is assumed that Supervisors would have to comply with certain administrative requirements as a result of authorizing the procedure, e.g., facility log entry, updated ATIS, and coordination with other facilities. One question of interest was whether this administrative overhead would affect a decision to use the procedure under conditions of low departure demand and/or impending convective weather.

Data collection was conducted in the office space which houses the prototype WTMD display. Participants were briefed on the WTMD concept, given a brief demonstration of the prototype, and then presented with three air traffic scenarios using storyboards. The storyboards included the WTMD runway status, airport configuration, traffic loading and weather information (current and forecast). A generic, prototype interface was available for reference, but there was no direct interaction with the interface as part of the study. Following the storyboard discussions participants completed a written questionnaire.

Five participants provided data; two current supervisors, and three staff members, one of whom was a former supervisor and two who have worked as controller-in-charge. They averaged 22.6 years of ATC experience including both Tower and TRACON qualifications. Mean experience was 15 years at KSTL. Participants provided comments concerning how they envisioned using the procedure, as well as thoughts regarding a potential interface.

The controllers universally reported that there was clear value for the WTMD Procedure at KSTL even with the reduced traffic volume experienced in recent years. They stated that they would authorize use of the procedure even if it were of benefit to only one or two aircraft, regardless of the administrative overhead required. They reported that the information provided regarding traffic demand (current and projected), weather and traffic flow management information (including flow restrictions) was adequate with respect to the authorizing and terminating of the procedure. There was consistency among the participants regarding the type of information that was accessed for day-to-day operations (weather, traffic loading, flow restrictions, etc.), and the priority of accessing that information, and information that would be accessed during use of the procedure.

Unsolicited comments indicated that controllers would actively assign wake generating aircraft to runways to maximize benefits from use of the procedure. (Note that the initial implementation of the WTMD concept does not require or expect wake related runway assignment of aircraft to maximize departure throughput. This approach minimizes the change from current operations until operational experience is gained. There was also general consensus that the WTMD procedure would provide additional latitude in conducting operations in several common situations.

A specific WTMD application was cited by 3 participants as being particularly beneficial. If WTMD allows wake independent operations on an arrival/departure runway adjacent to Heavy and B-757 operations on the downwind runway, the upwind runway may be able to support two departures between arrivals, instead of the more typical single departure. Additional data collection on information requirements from controllers at KIAH will be completed, with a full report to be issued at a later date.

7. SUMMARY

Substantial progress has been realized in the development and implementation of the WTMD procedures. A mature operating concept has resulted from close cooperation among stakeholder groups. Substantial benefits have been predicted by analysis, and partially validated through a small scale HITL simulation. The underlying wind forecast algorithm has been tested against historical and, to a limited extent, real time wind conditions. The testing and validation has indicated a relatively low (and desirable) Type 1 error rate. Residual errors appeared to be identified with mesoscale or convection events, which might be detectable by additional automation or through supervisory controller oversight to provide an additional layer of safety to the operation.

Prototype system architectures have been developed and installed at two airports which will provide further validation of the end-to-end system. The systems installed at KSTL and KIAH will provide additional wind data, with forecast validation available through the real time wake sensor array at KSTL. Controllers have indicated during the HITL simulation that the procedures are both workable and beneficial to their management of departure traffic, and that the information elements to be included in a decision support tool are sufficient for their use. The final form of that display must still be determined.

8. KEYWORDS

Wake turbulence, closely spaced parallel runways, wind forecast algorithm, wake behavior, human-in-the-loop, simulation, air traffic control

9. REFERENCES

[1] Lang, S., J. A. Tittsworth, C. R. Lunsford, W. W. Cooper, L. Audenaerd, J. Sherry, and R. E. Cole, 2005, An Analysis of Potential Capacity Enhancements Through Wind Dependent Wake Turbulence Procedures, 6th USA/Europe ATM Research & Development Seminar, Barcelona.

[2] Federal Aviation Administration, 2006, Air Traffic Control, FAA Order 7110.65R, Federal Aviation Administration, Washington, D.C.

[3] Moertl, Dr. Peter M., Clark R. Lunsford, Jeffrey A. Tittsworth, and Alain Oswald, 2005, Concept and Display Alternatives for Wake Mitigation for Departures, The MITRE Corporation, McLean, Virginia.

[4] Troxel, S., and R. L. Delanoy, 1994, Machine Intelligent Approach to Automated Gust Front Detection for Doppler Weather Radars, SPIE Proceedings – Sensing, Imaging, and Vision for Control and Guidance of Aerospace Vehicles, Vol. 2220, 182–192, Orlando, FL.

[5] Domino, David A., Clark R. Lunsford, Dr. Peter M. Moertl, Alain Oswald, 2006, Controller Assessment of Procedures for Wake Turbulence Mitigation for Departures (WTMD) from Closely Spaced Parallel Runways, MP 06W0000102, The MITRE Corporation, McLean, Virginia.

[6] Lunsford, Clark. R., Dr. Peter M. Moertl, Jeffrey A. Tittsworth, 2005, Initial Concept of Use for Closely Spaced Parallel Runways (CSPR) Wind-Dependent Departures, MP 05W0000285, The MITRE Corporation, McLean, Virginia.

[7] Roscoe, A. H., and G. A. Ellis, 1990, A Subjective Rating Scale for Assessing Workload in Flight. A Decade of Use, Technical Report TR90019, Royal Aerospace Establishment, Farnborough, U.K.

10. AUTHOR BIOGRAPHIES

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