Tactical Separation and Safety Alerting System for Terminal Airspace

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Provision of tactical alerts to aid air traffic controllers in providing separation assurance in terminal airspace is hindered by the complexity of the airspace, its operations, and flight procedures. A prototype automation system is studied that provides controllers with both separation and safety alerts based on or derived from the separation standard for terminal airspace. The system models flight trajectories heuristically, with use of merged intent information from readily available sources: area navigation departure procedures, flight-plan routes, and arrival nominal interior routes used in terminal automation systems. Flight vertical intent is modeled according to standard procedural restrictions except when superseded by controller-issued altitude clearances. Importantly, flight trajectories are modeled for all aircraft, including those conducting visual approaches. New safety-alert thresholds for aircraft conducting visual approaches are studied. Performance of the system is evaluated through fast-time playback of recorded air traffic data from high-fidelity Human-In-The-Loop simulations and real-world operations in two Terminal Radar Approach Control facilities. The prototype system is found to produce a false-alert rate of 8% for separation alerts. The number and validity of safety alerts are studied by comparing with the current Conflict Alert system, showing that the false alerts of Conflict Alert are at 85% and they are avoided in the prototype system.

I. Introduction

First priority in air traffic control is separating aircraft and issuing safety alerts [1]. Lack of issuance of safety alerts where required was first in the top-five highest-risk safety issues of Federal Aviation Administration

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(FAA) in 2018 and 2019[2]. Increasing operational errors has also become a safety concern [2]. Both the Common Automated Radar Terminal System (CARTS) [3] and the newer Standard Terminal Automation Replacement System (STARS) [4] have a conflict-alert functionality, commonly referred to as Conflict Alert (CA). CA has been in operation for more than 35 years and is the current state-of-the-art system that assists controllers in their separation task. CA provides safety alerts based on alert thresholds [3, 4] that represent the unsafe proximity to an aircraft and are much smaller than the standard separation minima [1]. Analysis of the effects of CA safety alerts showed [5] that 80% of those in terminal area may be nuisance alerts, not providing useful information beyond what the controllers already know and not being necessary to maintain safety. Thus, CA has not been able to mitigate either FAA's top safety issue of lack of issuance of safety alerts or the concern of increasing *operational errors*, defined as controller-caused losses of the standard separation. Minimizing operational errors could be achieved with separation alerts based on the standard separation minima.

The inherent complexities of terminal operations pose a number of challenges to the development of automated tools that provide the controller with separation and safety alerts. Routine large-angle turns before final approach require proper handling to prevent a proliferation of nuisance alerts. Spacing aircraft near standard separation minima to maximize arrival and departure throughput increases the difficulty of predicting separation conflicts without causing too many false alerts, which are potential losses of separation that do not materialize when there is no intervention by the controllers or pilots [6].The difficulty also stems from the dynamic and complex nature of the separation standard itself, which depends on relative course heading, aircraft weight class, distance to the runway, and other factors [1]. Further challenges come from the complexity involving aircraft conducting approaches to multiple parallel runways: with some conducting instrument and others conducting simultaneously visual approaches.

The FAA safety issue can be reduced with a system that provides controllers with both separation and safety alerts with good alert lead time and small false-alert rate when operating in a real-world setting. A real-world setting is advocated for testing because it involves realistic yet complex, uncertain, and off-nominal situations. Little research on conflict detection in the literature takes on the challenges in terminal airspace allowing all possible air traffic in a real-world setting. A prototype alerting system, called the Terminal TSAFE (Tactical Separation Assured Flight Environment) or T-TSAFE in short, has been developed in this direction [6]. T-TSAFE has been shown to provide an

[2] Private communication. Sarasina Tuchen, Electronics Engineer at U.S. Department of Transportation, Volpe National Transportation Systems Center, Sept, 2019

average alert lead time of 40 seconds to first loss of separation with small false-alert rate [6, 7]. This paper enhances T-TSAFE with inclusion of aircraft conducting visual approaches and the recent altitude-restriction method [7] of obtaining level-altitude flight-intent information. Updates and enhancement to previous conference papers [8, 9] are provided. The main contributions of this work are (1) propose safety-alert thresholds for aircraft conducting various visual approaches and validate that they can be a good starting point for practical applications with real-world traffic; (2) measure the false-alert rate of separation alerts of T-TSAFE with better statistics; (3) directly compare for the first time T-TSAFE and CA alerts, based on the same sets of full-day real-world traffic data from two different Terminal Radar Approach Control (TRACON) facilities, showing that the current STARS CA system still has large false-alert rate and that T-TSAFE avoids those false alerts.

The rest of this paper is organized as follows. Section II provides background information on relevant studies on separation assurance at different time horizons. Section III reviews briefly T-TSAFE trajectory and conflict detection mechanism, elaborates on safety-alert thresholds involving aircraft conducting visual approaches, and provides an overview of the system. Section IV describes the approaches to evaluate T-TSAFE performance. Section V presents the results with discussion. Section VI concludes the work.

II. Background

A number of approaches to conflict detection and resolution (CDR) in air traffic management were reviewed in Ref. [10]. Since then there has been considerable research on CDR for both en route and terminal airspace. A three-layer structure of separation assurance was advocated in the Advanced Airspace Concept (AAC) [11, 12]. The strategic layer addresses conflicts from two to 20 minutes into the future. The tactical layer addresses conflicts in a time horizon of two minutes or less. A third layer of safety is provided by an independent airborne collision avoidance system such as TCAS (Traffic Alert and Collision Avoidance System) [13], which addresses possible collisions in a time horizon of less than 45 seconds. Strategic CDR for the scheduling process in terminal airspace was studied in Refs. [14, 15]. The strategic en route AAC Autoresolver [16] was improved with arrival management and weather avoidance in [17] and extended to terminal airspace in Ref. [18]. False and missed alerts due to trajectory prediction errors were addressed through increased separation criteria in [19], adaptive algorithms for improving trajectory accuracy in [20], and use of probabilistic conflict detection in Ref. [21]. NASA has developed an advanced arrival management function for terminal controllers known as terminal sequencing and spacing (TSAS) [22], which performs strategic CDR for the scheduling process that enables use of performance-based navigation (PBN) arrival procedures. The tactical layer of protection in the AAC is known as TSAFE. It can be envisioned initially as an independent CDR system [23] to aid controllers before transitioning to a fully autonomous system, which could take decades [17]. The design and performance of en route TSAFE have been described in Refs. [23-25]. TCAS is mandated worldwide on large transport aircraft to reduce the risk of mid-air collision. A new approach for designing safer TCAS is described in Ref. [26].

Consideration of a real-world setting in terminal airspace with allowance of all flight types of different separation requirements has been lacking in previous research. It is common in terminal airspace to have encounters among the Instrument Flight Rules (IFR) flights and other special ones: flights of Visual Flight Rules (VFR), flights unassociated with flight plans called Mode-C Intruders (MCIs), and flights conducting visual approaches. Conflicts with the special flights may affect the schedule as they may require the IFR departure and arrival flights to deviate from their planned routes. In fact, close encounters between IFR and VFR aircraft ranked the first in the FAA's 2017 highest-risk safety issues [27]. The current operational Conflict Alert system does address all possible real-world encounters, however its large nuisance rate [5] and negative alert lead time to losses of separation [6] make it less useful.

The prototype T-TSAFE system proposed in Ref. [6] exhibited good average alert lead time and a low false-alert rate when a single deterministic flight-intent based trajectory is used for conflict detection. The STARS was shown to provide minimal flight-intent information required for T-TSAFE [8]. A limitation was that terminal controllers must make manual entries of all altitude clearances for the system to acquired level-intent information to avoid many false alerts. This limitation was resolved in Ref. [7] as the controllers may only need to enter those altitude clearances that are not attributable to altitude restrictions on waypoints or in the runway descent profiles. An initial study of safety alerts on aircraft conducting visual approaches was reported in Ref. [9]. Human-In-The-Loop (HITL) simulation experiments focusing on user interfaces for T-TSAFE were conducted with positive feedback from controller participants in Ref. [28].

This paper provides an update on the safety-alert thresholds for aircraft conducting various visual approaches and validate them with real-world traffic data. The performance of this prototype system with both separation and safety alerts and the recent altitude-restriction method of acquiring flight-intent information [7] is assessed while its safety alerts are compared with those of the operational CA system. In particular, this paper addresses whether the safety alerts proliferate and whether the false-alert pairs of CA can be avoided in the prototype system. The false-alert rate of separation alerts including its statistical uncertainty for the T-TSAFE prototype is also determined with recorded high-fidelity HITL air traffic data, which provides more data points and includes recorded intervention actions of the controllers and pilots.

III. T-TSAFE System

This section starts with a review of the conflict detection mechanism for the T-TSAFE system. Safety-alert thresholds for aircraft conducting visual approaches are then elaborated upon as this topic is neither adequately addressed in the initial prototype system nor in Conflict Alert. A functional overview of the system then follows.

A. Conflict Detection

T-TSAFE trajectory prediction relies on aircraft current state and flight intent information to generate an analytic, deterministic kinematic trajectory, consisting of a horizontal track, a speed profile, and an altitude profile. Flight-intent information currently includes Nominal Interior Routes (NIRs), Area Navigation (RNAV) Departure Procedures (DPs), flight-plan information, and altitude clearances. The filed flight plans generally do not contain departure procedures so the RNAV DPs are needed to project fine-detailed departure trajectories. Similarly the NIRs are needed to project fine-detailed arrival trajectories. Altitude clearances are needed for accurate prediction of trajectory changes. Many altitude clearances are attributable to altitude restrictions; the nonattributable ones are expected to be entered into the system by controllers [7].

The horizontal track of a flight is first constructed analytically with segments of straight lines and circular arcs following heuristic rules [6, 7], depending on whether the aircraft is in conformance (on track) with its intent route: a route defined as the merge of the NIR, RNAV DP, and flight plan. Although other special rules may apply to aircraft near different segments of the NIR, two basic heuristic rules are the following:

1) If an aircraft is on track, it captures the next waypoint in its intent route
2) If it is off track, it starts with a straight line along its current course and then joins its intent route with circular-arc segments upon interception; it continues along a straight line if there is no interception.

Speed and altitude profiles are then constructed based on speed and altitude restrcitions. Currently only simple speed upper bounds for departure flights and speed lower bounds near the final approach and runway threshold fixes are imposed. Level altitudes are based on well-known altitude restrictions at certain waypoints on a TRACON route (NIR or RNAV DP) or in the descent profile for a particular arrival runway [7]. When TSAS capability is implemented, well-defined speed and altitude restrictions will become available in the efficient PBN procedures of RNAV and required navigational performance terminal routes [22].

Conflict detection is based on the single definitive trajectory so constructed. Uncertainty is reflected in that a new trajectory is predicted every update cycle. For example, the predicted position of an aircraft at some future time may be different for different trajectory predictions at different radar updates. This single-trajectory approach to conflict prediction introduces minimal aircraft state prediction uncertainty and reduces false predictions, at the expense of slightly shorter alert lead time to a potential conflict. In this context, the concept of missed alert is not appropriate because the true trajectories are never known for real-world air traffic data.

A conflict is defined as a violation of the separation or safety requirements per the standard in FAA Order JO 7110.65Y [1]. The older version of 7110.65V [29] is used for our analysis in accordance with our traffic data. Given aircraft state information at each radar update and trajectory intent for each aircraft, computed trajectories are compared for each aircraft pair to detect instances where the applicable separation requirements are violated. Rules of "*m* of *n*" cycles, *m* predictions of violation of the alert thresholds out of *n* radar update cycles, for specifying alert conditions are used to filter alerts [7].

As mentioned, we distinguish between a separation alert that results from a potential violation of the required separation minima and a safety alert that results from a potential violation of safety alert thresholds. A separation alert is between two IFR flights and a safety alert is between an IFR and either a VFR, a visual-approach, or a MCI flight.

B. General Safety-Alert Threshold for Visual Approach

A large portion of daily terminal operations involve aircraft conducting visual approaches. A visual approach (VA) is an air traffic control authorization for an aircraft on an IFR flight plan to proceed visually to the airport or runway. At all times the pilot must have either the airport or the preceding aircraft in sight. Reported weather at the airport must be ceiling at or above 1,000 ft and of visibility of 3 statute miles or greater [1].

Visual approaches serve to increase arrival capacity under visual meteorological conditions by reducing inter-arrival spacing below that of the standard separation minima in effect under IFR. Before giving a visual-approach clearance, the controller must ensure that the aircraft is not about to lose separation with another aircraft. After the visual-approach clearance, the pilot becomes responsible for maintaining visual separation with (and only with) the preceding aircraft on the same or adjacent parallel runway. The controller is still responsible for providing safety alerts or traffic advisories to the pilot when the aircraft on visual approach is in unsafe proximity to the preceding aircraft, and for maintaining the standard separation minima with other visual- or instrument-approach aircraft. Thus, an automation system needs to determine automatically if separation or safety alerts are required and detect conflicts between any pair of aircraft involved, providing the controller with separation alerts for potential loss of the standard separation minima and safety alerts for potentially unsafe situations involving aircraft on visual approaches.

The standard for unsafe proximity of an aircraft for safety alerts has not been established, so proper safety-alert thresholds are studied here, especially for aircraft in various complex visual-approach scenarios. For Conflict Alert, the safety-alert thresholds depend on specific airspace region within the terminal area: type I for the area near the runway, type II for the area where an aircraft makes an approach to a runway, and type III for the remainder of the general terminal area; the horizontal and vertical thresholds for the type I, II, and III airspace regions are 0.5 n miles and 275 ft, 0.75 n miles and 275 ft, and 1.2 n miles and 375 ft [3, 4], respectively. The present work incorporates flight-intent information, the trajectories can be determined more accurately, thus larger alert thresholds can be used, leading to earlier alerts with no alert proliferation and fewer false alerts. The critical alert thresholds can be adjusted based on observations. We propose to measure unsafe proximity and safety-alert thresholds for visual-approach flights based on the severity of violation of the standard separation minima that would be in effect under IFR. The severity of the conflict is measured in terms of a conformance separation metric and the time to the predicted conflict.

The concept of conformance separation has been used to classify the severity of operational errors [30]. In terms of the horizontal and vertical standard separation minima, $r_{\min}$ and $h_{\min}$ respectively, the conformance separation is defined as $s = \sqrt{V_r^2 + H_r^2}$ where $H_{\mathrm{r}} = r/r_{\min}$ and $V_{\mathrm{r}} = h/h_{\min}$ with r being the horizontal and h being the vertical separations of the aircraft pair at some instant. The ranges for nonwake conformance separation of operational errors of class A and class B are, respectively, $s \leq 0.34$ and $0.34 < s \leq 0.75$; that of class C is $s > 0.75$ and $V_{\mathrm{r}} \leq 0.90$ and $H_{\mathrm{r}} \leq 0.90$; and that of class proximity event is either $V_{\mathrm{r}} > 0.90$ or $H_{\mathrm{r}} > 0.90$. For wake separations, only the horizontal separation is considered and only classes A, B, and C are used; their corresponding ranges are $H_{\mathrm{r}} \leq 0.70$, $0.70 < H_{\mathrm{r}} \leq 0.85$, and $H_{\mathrm{r}} > 0.85$, respectively.

A good starting point for the values of safety-alert thresholds can be obtained from consultation with Subject Matter Experts (SMEs) and observations from real-world traffic data. From communications with SMEs during the HITL experiments [28], controllers typically keep aircraft pairs on visual approaches with a separation of 2.2 n miles when the standard IFR separation is 3 n miles. They also suggest that, for TRACON operations, an adequate time scale for a controller to respond to potential conflicts is 40 seconds. Thus, for aircraft not involving wake turbulence, we propose to use the class-B conformance separation of 0.75 as the safety-alert thresholds when the standard nonwake separation minima would be in effect if the aircraft were to maintain IFR separations. To minimize false alerts, we also propose the following constraint: when it is predicted that a visual-approach pair is going to violate the safety alert thresholds, no safety alert will be annunciated unless and until the first predicted violation of the safety alert thresholds is less than 40 seconds away. For aircraft involving wake turbulence, our observations show that real-world data are more supportive of using the class-A conformance separation of 0.70 (see Sec. V.C.3). This general safety-alert threshold may need modification for aircraft conducting simultaneous approaches to parallel runways as discussed in the following.

C. Safety-Alert Thresholds for Specific Visual Approaches

1. Four Types of Visual Approaches

Four different types [1] of visual approaches are considered. They are visual approaches to the airport or runway and to parallel runways of three different ranges of runway centerline separation: less than 2500 ft, between 2500 ft and 3400 ft, and larger than 3400 ft.

If there is no potential loss of separation with any other aircraft when the pilot reports the airport or runway in sight, the aircraft can be cleared for a visual approach to the airport or runway. If the pilot reports sighting a preceding aircraft, no matter if the airport or runway is in sight or not, the aircraft may be cleared for visual approach to the runway following the preceding aircraft (not of a super weight class).

When the pilot reports the preceding aircraft in sight, an aircraft may be cleared for visual approach to a runway following, and maintaining visual separation with, a preceding aircraft that approaches an adjacent parallel runway less than 2500 ft apart. The preceding aircraft may be on a visual or instrument approach. An aircraft may also be cleared for an Instrument Landing System (ILS) approach maintaining visual separation with the preceding aircraft on an adjacent runway within 2500 feet. The ILS-approaching aircraft is said to be on VV: the scratch-pad notation for this approach at Los Angles Internal Airport (LAX).

Once it is assured that there is no potential loss of separation, visual approaches may be conducted simultaneously to parallel runways separated by 2500 to 4300 feet or by more than 4300 feet. Aircraft approaching parallel runways separated by more than 4300 ft are considered to be in independent complexes. An aircraft may be cleared for ILS approach to a landing runway while maintaining visual separation with a preceding aircraft conducting a visual or instrument approach on a parallel runway in an adjacent complex. The ILS-approaching aircraft is said to be on VS: the scratch-pad notation for this approach at LAX.

Figure 1 illustrates notionally these different visual approaches using parallel runways 24L, 24R, 25L, and 25R at LAX. The centerline separation is 670 ft between 24L and 24R, 850 ft between 25L and 25R, and 4000 ft between 25R and 24L. So runways 24L and 24R are in one complex while 25L and 25R are in a different complex. The arrival runways mostly used at LAX are 24R and 25L, which are separated by 5520 ft. Thus, the two complexes are usually called adjacent complexes. Aircraft A1 is cleared for visual approach to runway 24R, denoted by V24R; such shorthand notation is often used for controllers to keep track of the aircraft status. Aircraft A2 is also denoted by V24R but it is cleared for visual approach to runway 24R following and maintaining visual separation from A1. Aircraft A3 is V24L; it is cleared for visual approach following the preceding aircraft A2 that approaches the adjacent parallel runway less than 2500 ft apart. Aircraft A4 is I24R and A5 is I25R so they are cleared for ILS approach to runways 24R and 25R, respectively. Aircraft A6 is denoted by VV since it is on ILS approach to runway 25L but maintaining visual separation with the preceding aircraft A5 on the adjacent parallel runway less than 2500 ft apart. Aircraft A7 is on VS since it is on ILS approach to runway 25L but maintaining visual separation with the preceding aircraft A4 on the parallel runway in an adjacent complex.

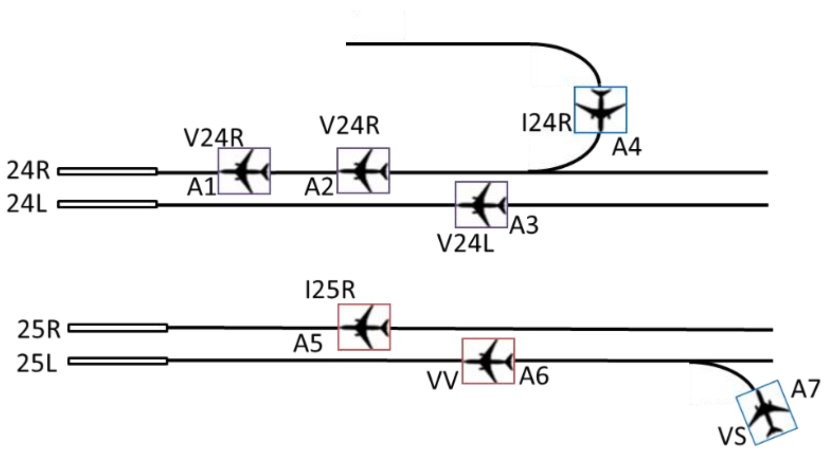

Fig. 1 An illustration of various visual and instrument simultaneous approaches to parallel runways.

2. *Safety-Alert Thresholds*

Safety-alert thresholds for the four types of visual approaches may be different. VA aircraft pairs approaching the same runway successively must maintain large enough visual separation to allow safe landing. This can be assured by the general safety-alert thresholds: a minimum conformance nonwake separation of 0.75 or wake separation of 0.70

with a time to first predicted conflict within 40 seconds. Closer separation should be attended to by the controller to decide if a traffic advisory to the pilot is warranted.

For VA aircraft pairs approaching parallel runways less than 2500 ft apart, once the aircraft are established on their localizers, they are not confined by the radar minima, though a super or heavy may not overtake another aircraft and a B757 or large aircraft may not overtake a small aircraft [1].

An aircraft is considered to be established on its localizer if it is within an angular course extending from the localizer transmitter (1000 ft from the far end of the approach runway) along the runway centerline with a full-scale course width of 700 ft at the runway threshold [31]. The actual length of the arrival runway is used in T-TSAFE to determine the angular width. Additionally, T-TSAFE requires the course heading of the aircraft to be within 10 degrees of the final approach course – a value determined so that some losses of separation due to operational errors were reproduced [7]. To take into account noisy radar signals, between the runway threshold and the final approach fix, T-TSAFE further allows the localizer width to increase by 10% and the aircraft course heading to be within 45° of the extended runway centerline. When aircraft make parallel approaches, T-TSAFE consider that a blunder occurs if it is predicted that one aircraft will be off the localizer, fall between the extended runway centerlines of the parallel runways, and head toward the other runway.

Because runways less than 2500 ft apart are treated as a single runway for ILS approaches, when at least one of the aircraft in a VA pair has not established on its localizer in a simultaneous approach to parallel runways separated by less than 2500 ft, the general safety-alert thresholds should again be applicable. Once the aircraft are established, alerts are generated only when a blunder is predicted to occur. We suggest the following runway-separation safety-alert threshold for VA pairs in a blunder: a conformance alert threshold of value d/r_{min}, where d is the separation between the runway centerlines and $r_{\min}$ = 3 n miles, which would be the required minimum if the aircraft were performing ILS approach during the blunder. A super or heavy aircraft overtaking another aircraft, or a B757 or large aircraft overtaking a small one, would trigger wake turbulence alerts. However if the succeeding aircraft then slows down so that the two aircraft travel nearly side by side, no alerts are triggered based on the $d/r_{\min}$ value. Should a blunder occurs while they are abreast of each other, the situation may *not* be safe. Thus, it might be better to use just the single runway safety thresholds even after the aircraft are established.

For aircraft conducting simultaneous visual approaches to parallel runways separated by 2500 to 4300 feet, the controller must provide the standard separation until the aircraft are established on a course heading that will intercept the extended centerline of the runway at an angle not greater than 30 degrees [1]. Thereafter, the aircraft are as if they are making independent approaches with no alerts unless a blunder occurs. Each runway localizer may have a stream of aircraft conducting visual approaches. Before both aircraft intercept their localizers with course headings within 30 degrees of the extended centerlines of the runways, the general safety-alert threshold should apply. Thereafter the runway-separation safety-alert threshold should apply if one or both aircraft drift off their localizers.

For aircraft conducting simultaneous visual approaches to parallel runways separated by more than 4300 feet, the requirement is merely that each aircraft must be assigned a heading that will allow the aircraft to intercept the extended centerline of the runway at an angle not greater than 30 degrees [1]. It is not necessary to apply any other type of separation with aircraft on the adjacent final approach course. In contrast to the case when runway separation is less than 4300 ft, there is no longer separation requirements during turning onto the localizers starting from any angles; the parallel runways are operated independently in different complexes if the aircraft turn onto the localizers from opposite sides of the runways such that their routes will not cross each other.

Aircraft streams in different complexes typically join the localizers from opposite sides of the runways at LAX. Two ILS-approach aircraft must maintain a minimum separation of 3 n miles horizontally or 1000 ft vertically before being established on the localizers. However, a VA aircraft pair does not subject to such a requirement, not even that of the general conformance separation of 0.75. Thus, no alerts should be generated during turn-on to the localizer unless a blunder is detected to occur. SMEs and observations suggest that this rule applies not only to the VA aircraft pair but to any VA aircraft in one complex and other VA or ILS-approach aircraft in an adjacent complex as the controllers do not want to see any such alerts. Without this rule, the number of alerts as reported in Sec. V.C.3 would be proliferated.

While most VA aircraft pairs approach parallel runways in different complexes at LAX from opposite sides of the localizers, in general they may approach from either the same side or different sides simultaneously with or without their tracks crossing. Once the aircraft are established on their localizers, no safety alerts will be generated unless a blunder is to occur. However, before they are established, if they turn onto their localizers from the same side of the runways (say, both from the right of the centerline of runway 24R in Fig. 1), or if their flight routes cross each other while they turn onto the localizers from different sides of the runways, their proximity may necessitate safety alerts. Real-world examples of these situations can be found in Sec. V. In these situations, we propose the following safety-alert threshold: a conformance threshold equal to $\min\{d/r_{\min}, 0.75\}$, where d is again the runway separation and

r_{min}= 3 n miles. For example, if the runway separation is 9000 ft (1.5 n miles), the conformance alert threshold would be 0.5. This threshold applies when one or both of the aircraft blunder after being established on the final or during the aircraft's turn-on to their localizers. If the runway separation is too large, a conformance separation of 0.75 results. Note that, if the aircraft turn onto their localizers from different sides of the runways and their flight routes do not cross, the safety threshold will never be triggered unless one aircraft is to overshoot the localizer. In practice, it appears that controllers may ensure a 1000-ft vertical separation during the localizer turn-on when the tracks will cross. (It is possible that this observation corresponds to the aircraft not being cleared for the final approach yet.) Note that for those aircraft within their own complex, alerts could still be generated. In summary, the rule for aircraft conducting visual approach to parallel runways separated by more than 4300 ft is the following: no alerts between VA and VA, or VA and ILS, aircraft in different complexes unless it is detected that a blunder is to occur or when the tracks cross, in which case a conformance threshold equal to $\min\{d/r_{\mathrm{min}}, 0.75\}$ is used, where d is the runway separation and r_{min}= 3 n miles.

As seen in the case of the four-runway, two-complex simultaneous approaches at LAX in Fig. 1, multiple-runway visual approaches with a mix of visual and ILS approaches can be complicated. The alert problem is simplified by grouping the runways in different complexes that act as independent airports as described above. Our proposed safety-alert thresholds are much larger than those of Conflict Alert, which uses thresholds correspond to a conformance threshold value of d/r_{min} with d being 0.7 times the runways' centerline separation for parallel-runway approaches irrespective of the runway centerline separation. For single runway approaches, CA alert thresholds for type I, II, and III terminal areas correspond to conformance thresholds between 0.17 and 0.40, much smaller than our general safety-alert threshold values of 0.75 (nonwake) and 0.70 (wake).

D. System Overview

A functional diagram for the process of conflict prediction and declaration in the T-TSAFE prototype system is shown in Fig. 2. First, the incoming input data, which include the aircraft radar-track and flight-plan information, are used by the Aircraft Manager and Mediator (AMM) to update the states of aircraft. The aircraft states and intent information are then passed to the Conformance Monitor so the aircraft conformance status is updated and returned to the AMM. The aircraft are then passed to the Trajectory Predictor to generate new trajectories of the aircraft. The aircraft with updated trajectories are then passed to the Conflict Detector, which updates the aircraft with prediction and declaration of potential conflicts. The AMM finally sends the updated aircraft conformance and conflict information, as well as aircraft sequences to different runways, as events to the Observer Components that have registered for events with the AMM. An example observer component is a default observer that outputs the results as extended markup language files. Another one can be an observer for graphic user interface. The user interface for T-TSAFE is described in Ref. [28].

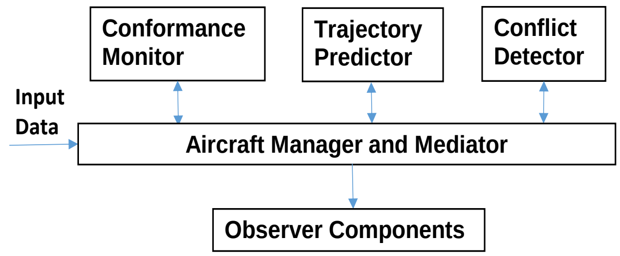

Fig. 2 A functional diagram of T-TSAFE conflict detection.

IV. Methods of Performance Evaluation

The main objective of this work is to evaluate the performance of the current updated T-TSAFE prototype system, which supports both separation and safety alerts with level altitudes obtained from published altitude restrictions. The performance of separation alerts is based on alert lead time and false-alert rate. These metrics for safety alerts are not readily measurable from our real-world air traffic data. Nevertheless the safety-alert thresholds for aircraft conducting visual approaches in Sec. III.C can be assessed and the number and quality of T-TSAFE safety alerts can be compared to those of the Conflict Alert system for the same real-world traffic data sets.

A. Performance Analysis with HITL Data

Alert lead time for the T-TSAFE prototype has been measured previously to be 43 seconds with operational error cases [6, 7]. As mentioned in Sec. III.B, SMEs suggest that a 40-second alert lead time before first loss of separation (LOS) is generally sufficient for the controllers and pilots to avoid the LOS, as they are already being in voice contact. Since the operational-error cases were only from Dallas/Fort Worth (DFW) TRACON (known as D10), it is interesting to see if the same can be concluded with HITL data from another TRACON. Furthermore, false-alert analysis in Ref. [6] relies on examining aircraft tracks to look for possible actions of controller or pilot intervention since such information was not available in real-world air traffic data. Statistical uncertainties of the estimation was not determined either. Using air traffic data from the HITL experiment simulating Southern California TRACON (SCT), both the alert lead time and false-alert rate can be measured. The experiment setup was described in Ref. [28].

In contrast to real-world data, actions of controller or pilot intervention were recorded in the HITL experiment. The air traffic data were recorded from 12 HITL simulation runs; each run lasted 40 minutes and involved high-fidelity flight operations of ILS approaches to LAX directed by controllers who were recently retired from SCT. The aircraft were piloted by human confederates with flight trajectories governed by the underlying Multi-Aircraft Control System (MACS) [32]: a powerful research tool that provides high-fidelity air traffic simulation.

The outputs of conflict information from playback of the recorded HITL air traffic data were analyzed. The alerts were mostly separation alerts with some safety alerts involving VFR flights. The safety minima of 1.5 n miles horizontally and 500 ft vertically applied when VFR flights involved. The alerts were classified in a classification scheme [6] suitable for real-world traffic data in terms of loss-of-separation (LOS), valid non-LOS (VNLOS), and false alerts. A LOS alert is followed by an actual loss of separation. A VNLOS alert refers to a conflict declaration that is *not* followed by an actual LOS, but there are one or more controller or pilot intervention actions during a time window between 20 seconds before the initial time of conflict detection and 10 seconds after the time of last detection. The trajectories for a non-LOS alert were examined to determine if the alert was valid based on whether a loss of separation was averted because a controller action occurs within the time window. Otherwise the alert would be a false alert. The look-ahead time for conflict detection was 120 seconds. Note that false and nuisance alerts are different conceptually. While all false alerts are nuisance, some of the LOS and VNLOS could also be nuisance (e.g. when the duration is too short). Nuisance alerts are defined based on the effectiveness and necessity of the alerts to the controllers [5]. Because the definition of a nuisance alert is somewhat subjective, we focus our analysis on false alerts.

The HITL traffic data produced more conflicts than typical real-world data as there were many off-nominal encounters besides the nominal ones. The off-nominal encounters were either due to artifacts in the localizer-capture logic of MACS or by design so as to increase the difficulty in the aircraft separation task [28]. This artificial increase in conflicts put T-TSAFE in a test beyond real-world operations. The large number of LOS alerts allows a measure of the average alert lead time in a way similar to Refs. [6, 7]. Multiple experimental runs with recorded intervention actions of controllers and pilots allow more reliable determination of the false-alert rate. To better understand the resulting large number of alerts, the alert classification scheme is further refined as follows.

LOS alerts are divided further into three categories: Operational Error (OE), Pilot Deviation (PD), and VFR. Note that we consider LOS as a conflict that includes loss of not only the standard separation but also the safety thresholds. A LOS alert is OE if it is due to controller errors (e.g., clearances, or lack thereof, leading to a LOS), PD if it results from an error attributable to the pilot, and VFR if it is a safety alert involving a VFR flight. A typical OE LOS alert would be one resulting from the operational error of inadequate management of spacing after the aircraft have passed the final approach fix. In the HITL simulation experiment, each "pseudopilot" confederate controlled about 10 aircraft. In addition, MACS made an aircraft join the localizer by turning it to or at a waypoint instead of simply enforcing the standard 30º intercept of the localizer. This resulted in simulation artifacts such as the so-called dogleg approach in which the aircraft intercepted the localizer with an unrealistically long approach leg, or in the opposite extreme the aircraft made a sharp, near 90º turn onto the localizer. Instead of no separation requirement for aircraft established on parallel localizers, aircraft on dogleg approaches would still require the standard separation of 3 n miles. A loss of separation is classified as a PD when it is due to such simulation artifacts. Also classified as PD alerts are those LOS alerts that are created intentionally by the experiment personnel by forcing an aircraft to unexpectedly bust an altitude clearance, make a turn, or reduce speed dramatically [28]. VFR LOS alerts are themselves in a category because of their large number, being created by flying intentionally VFR flights head-on toward IFR flights.

VNLOS alerts are also further refined as Normal Maneuver (NM), Abnormal Maneuver (AM), and VFR alerts. A NM VNLOS alert is one for which the potential conflict was avoided through a normal speed, heading, or altitude maneuver of the aircraft. An AM VNLOS alert is one for which the potential conflict happened to be resolved due to simulation artifacts or other MACS-specific behaviors not from the controller. A VFR VNLOS alert is one involving a VFR flight; it can be resolved from normal or abnormal maneuvers. When it cannot be accounted clearly that an alert is followed by a loss of separation, the alert would be counted conservatively as a false (non-LOS) alert.

Figure 3 shows the ground tracks and altitude profiles of aircraft S481 and S945 involved in a false alert. Aircraft S945 and S481 were conducting simultaneous approaches to parallel runways 25L and 24R, respectively, at LAX. The runway centerline separation was 5520 ft. The thick circles indicate the predicted first loss of separation based on the thick solid lines of the predicted trajectories. The thin circles indicate closest points of approach (CPA). The circles have diameters of 3 n miles. The successive stars are one minute apart. The squares are waypoints and the arrows indicate the direction of flight. The predictions for the horizontal tracks and altitude profiles are good with proper turn-on intercept of the localizers. The altitude profile predicts S481 to level first at 3600 ft, which is the at-or-above altitude restriction at the waypoint named HUNDA, and then to descend as soon as it passes HUNDA. This prediction of descent resulted in a potential violation of the vertical separation requirement of 1000 ft. The prediction continued and an alert was generated that lasted 45 seconds. However, the aircraft initiated the descent 20 seconds later than the prediction, which was sufficient for the aircraft to capture the localizer and become established on the final approach, whereupon no separation requirement applied anymore. The descent of S945 from 2500 ft to 2200 ft might help the clearance of the alert as well. In general, we expect the controller to enter a level altitude if an aircraft is to remain at that altitude restriction while it is no longer restricted. In the current situation, the delay is short or on the borderline and so the alert was counted as false.

As mentioned in Sec. III.A, the concept of missed alert in a real world setup is ambiguous in a real-world system since real trajectories are not available for comparison. We distinguish between missed prediction and missed detection of an actual LOS. A missed detection of a LOS refers to an instance in which a LOS actually occurred but the system cannot detect it even at the moment of LOS. In our approach, no missed detection is likely because when an actual LOS occurs, it will be reported if the aircraft states are reported accurately. Instead we can define a missed prediction of a LOS as a failure to predict the LOS before some minimum lead-time threshold below which the controller does not have sufficient time to respond. Thus, the traditional sense of large number of missed alerts amounts to a large reduction in the average alert lead time in a real-world system.

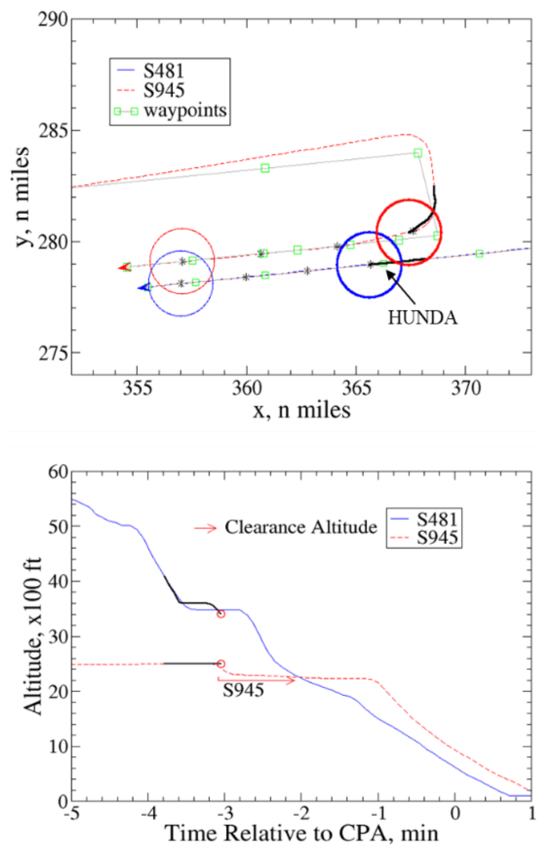

Fig. 3 Ground tracks and altitude profiles for aircraft involved in a FA alert.

B. Safety-Alert Analysis with Real-World Data

To assess the number and validity of safety alerts for T-TSAFE, we perform fast-time playback of real-world air traffic data in T-TSAFE. Two real-world data sets were used, one was SCT traffic data recorded on February 24, 2012 where CARTS was used, and the other was traffic data recorded on July 26, 2014 from D10 where STARS was used. The SCT data corresponds to mixed operations of aircraft conducting visual and instrument approaches, while the D10 data corresponds mostly to visual approaches. This is based on the weather conditions and observations of aircraft trajectories leading to the final approaches. Visual approaches usually involve shorter final approach courses than instrument approaches.

Air traffic data recorded at NASA included radar tracks and flight-plan information of associated aircraft but not tracks unassociated with flight plans. FAA's CARTS or STARS CDR (Continuous Data Recording) data contains CA conflicts, associated and unassociated tracks, but no flight-plan information. Thus, unassociated tracks are extracted from the CDR data and inserted into the NASA-recorded data so that Mode-C Intruder alerts can be generated and studied as well. The look-ahead time was set to 90 seconds, which is still large compared to 40 seconds used in CA, so the effect of noisy radar tracks is reduced.

With the current data it was not possible to identify at runtime if an aircraft was conducting a visual approach, so all IFR arrivals were assumed to be on visual approaches for both data sets. This assumption amounts to subjecting all arrival flights to the safety-alert thresholds, similar to their being subjected to the smaller safety-alert thresholds of CA. As a result, the number of separation alerts would decrease while the number of safety alerts may increase. But it is then possible to directly compare between the safety alerts generated by T-TSAFE and those actually reported by CA in the field for the same traffic data. Because of the assumption of visual approaches for all arrival flights and the uncertainty in the actions of controller and pilot intervention, alert lead time and false-alert rates for the safety alerts may not reflect the performance of T-TSAFE. However we can still classify and validate the alerts by examining the trajectories to assess the effectiveness of the safety-alert thresholds. In particular we can see why T-TSAFE avoids the false alerts of CA and furthermore determine the false-alert rate of CA.

We executed T-TSAFE in two modes: altitude restriction (ALR) and dead reckoning (DR). ALR mode is the normal mode in which aircraft trajectories are modeled using all available flight-intent information, including published altitude restrictions when aircraft conduct instrument or visual approaches. In the DR mode, aircraft trajectories are modeled using dead-reckoned trajectories based on current states without flight-intent information.

However, both modes use the same safety or separation alert thresholds determined dynamically, based on flight-intent information such as the nominal interior routes, which help determine the arrival runways and localizers. We expect that more CA alert pairs coincide with those of T-TSAFE in the DR mode than those in the ALR mode since CA relies on DR trajectories. We also note that alerts appearing in the DR mode but not in the ALR mode must be false, as verified by comparing the predicted and actual aircraft trajectories and the flight-intent information. The percentage of CA alerts in this category provides the false-alert rate of the safety alerts of CA.

V. Results and Discussion

The utility and efficacy of an alerting system are affected by such attributes as false-alert rate, alert lead time, and the number and quality of alerts. T-TSAFE results for these attributes by the methods of Sec. IV are presented and discussed in this section with comparison of safety alerts to those of CA.

A. Alert Lead Time

The average alert lead time was measured to be 45 seconds with a standard error of the mean of 3 seconds based on 173 LOS separation alerts, involving IFR flights on arrival to LAX during the twelve HITL experiment runs. This corresponds to a 95% confidence interval of (39, 51) seconds. This result is consistent with the result measured based on a series of operational error cases in D10 TRACON [6, 7].

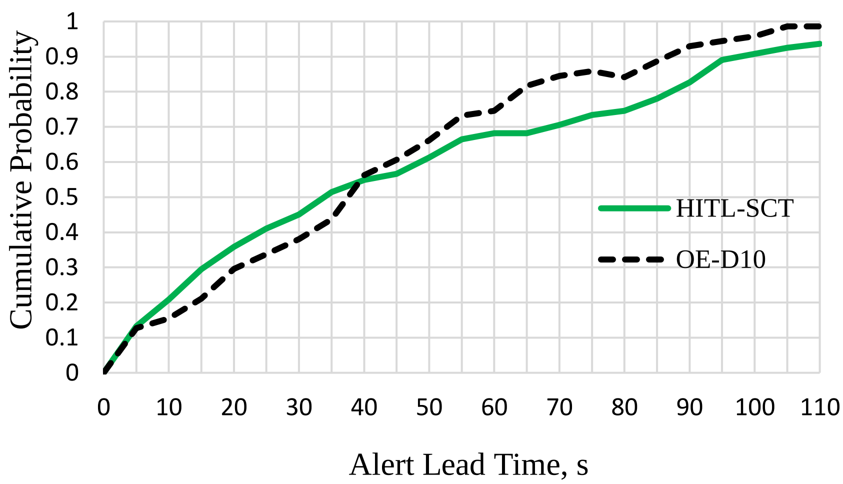

Fig. 4 CDF of alert lead time for LOS alerts from HITL and operational error (OE) data.

The cumulative distribution function (CDF) $F_T(t) = P(T \leq t)$ of the alert lead time T, which is the cumulative probability of alerting *within* time t (> 0) to the first loss of separation, is shown in Fig. 4. As a comparison, the alert CDF plot as in Ref. [7] for the alerts from a set of D10 operational errors is also shown. The cumulative probability for alert lead time, *t*, measures the percentage of the total LOS alerts having an alert lead time less than *t*, so $1 - F_T(t)$ is the probability of having alert lead time greater than t. As can be seen, the two plots generally agree even though the data were from two different TRACONs. If we define missed predictions as those with a lead time less than 10 seconds, the HITL data shows a 20% probability of missing while the operational-error data shows a 15%. Apart from the unpredictable errors resolvable by trial planning as in the case of operational errors [7], the HITL data have simulation artifacts as explained earlier that cause the missed predictions. For example, a sudden descent of a leading aircraft established on its final approach course could cause a LOS with a succeeding aircraft making a dogleg simultaneous approach to a parallel runway, which would not be a LOS if the succeeding aircraft is established. The cumulative probability for the HITL data appears bigger (less) than that for the operational-error case for alert lead time below (above) 40 seconds.

B. False-Alert Rate

The false-alert rate is measured as the percentage of false alerts among the total number of alerts for each HITL experiment run. The mean value over 12 runs, each lasting 40 minutes, was 7.7% with a standard error of the mean of 1.4%. This corresponds to a 95% confidence interval of (4.5%, 11%). The data distribution for the false-alert rates in different runs is approximately normal since they are symmetrical about the mean with only one mild outlier false-alert rate of 19%. This outlier run has four false alerts, all of which have encounters similar to Fig. 3 involving different aircraft pairs, for which the horizontal predicted trajectories intercepting the localizer were inaccurate when compared to the actual long dogleg approaches.

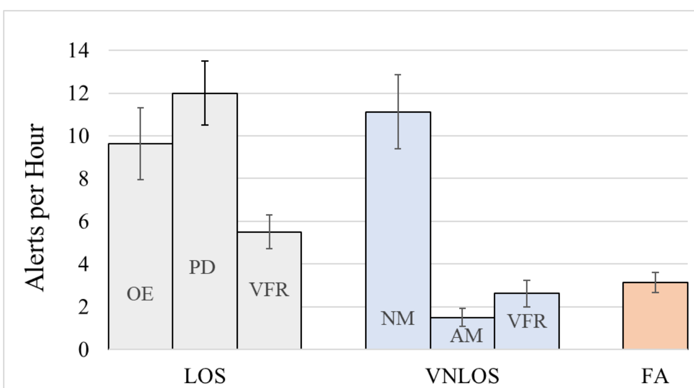

Fig. 5 Alert rates for different types of alerts from the HITL data.

Based on the classification of alerts in Sec. IV.A, Fig. 5 shows the mean alert rates and standard errors in alerts per hour, grouped into LOS, VNLOS, and false alert (FA) and they are averaged over all data from the runs. Each group is subdivided into the refined alert types indicated. During the data-collection runs, a prior version of T-TSAFE was operated with controllers having the option to make keyboard entries of altitude clearances. The results shown here are from playing back of the recorded HITL traffic data with the current improved T-TSAFE system. As can be seen, the total number of LOS alerts is large, consisting of 20% VFR, 44% PD, and 36% OE alerts. The number of VNLOS alerts are correspondingly large. As explained earlier, the reason behind the large number is the simulation artifacts and intentional creation of conflicts. The VNLOS alerts were mainly (73%) resolved with normal speed, altitude, and heading maneuvers, with 10% cleared by unexpected abnormal maneuvers due to MACS instead of the controllers and 17% being (VFR) safety alerts cleared by the controllers using normal maneuvers on the IFR flights involved. The false alerts were conservatively determined similar to the one in Fig. 3.

C. Safety Alerts

T-TSAFE safety alerts can be better understood in relation to the safety alerts from the operational Conflict Alert system for the same real-world traffic data. Classifying CA alerts, as explained in Sec. IV.B, in terms of T-TSAFE alerts in the ALR and DR modes shows the reason why T-TSAFE avoids most of CA's false alerts.

1. Classification of CA's Alerts

Conflict alerts and Mode-C Intruder alerts from the Conflict Alert system (CA–CA and MCI–CA) were extracted from FAA's CDR data on July 26, 2014 for STARS at D10 and on February 24, 2012 for CARTS at SCT. A CA–CA is an alert between two IFR and/or VFR flights while a MCI–CA is between an IFR or VFR and an unassociated flight. These alerts are compared with those generated from playing back recorded traffic data from the same days with T-TSAFE in the ALR and DR modes.

Table 1 Classification of STARS CA alerts at D10 in terms of T-TSAFE alerts in the ALR and DR modes

	Major CA–CA	Nonmajor CA–CA	Major MCI–CA	Nonmajor MCI–CA
CA-only	5	7	5	11
CA–DR-only	26	0	0	1
CA–ALR-only	1	0	0	0
CA–DR–ALR	5	3	0	11
Outside-Class-BC	2	16	3	124
Total	39	26	8	147

Table 1 shows the results of the comparison for D10. The alerts are categorized into major and nonmajor ones. An alert is major if it involves departures and arrivals from the major airports of DFW and Dallas Love Field, otherwise it is nonmajor. Outside-Class-BC alerts refer to alerts for which either both aircraft involved are VFR flights outside class B and C airspace or, in the case of a MCI alert between a VFR and an unassociated flight, the VFR flight is outside class B and C airspace. Outside-Class-BC alerts are nuisance alerts for sector controllers of class B and C airspace [5]. Other alerts are divided into CA-only, CA–DR-only, CA–ALR-only, and CA–DR–ALR alerts. A CA-only alert means that T-TSAFE did not issue an alert for that aircraft pair. A CA–DR-only alert was alerted by T-TSAFE in the DR mode, but not in the ALR mode. A CA–ALR-only alert was alerted by T-TSAFE in the ALR mode, but not in the DR mode. A CA–DR–ALR alert was alerted by T-TSAFE in both the DR and ALR modes. As seen in Table 1, 84% (31 out of 37) of major CA–CA alert pairs that were not Outside-Class-BC were alerted as well in the DR mode of T-TSAFE; 62% (16 out of 26) of the nonmajor CA–CA alerts and 82% (127 out of 155) of the CA–MCI alerts were Outside-Class-BC.

Table 2 shows similar alert classification for SCT. Here only LAX is considered a major airport and there were alerts from flights involving 30 different small airports. The number of major CA and MCI alerts is unexpectedly small, which could result from some CA alert suppression options being turned on at LAX. Thirty-eight percent of nonmajor CA–CA alerts and 71% of the MCI–CA alerts were Outside-Class-BC. As expected, the differences between T-TSAFE in the DR and ALR modes for the nonmajor alerts are insignificant, as the flight-intent information is lacking for the small airports.

Table 2 Classification of CARTS CA alerts at SCT in terms of T-TSAFE alerts in the ALR and DR modes

	Major CA–CA	Nonmajor CA–CA	Major MCI–CA	Nonmajor MCI–CA
CA only	1	27	2	43
CA–DR-only	6	1	0	2
CA–ALR-only	0	0	0	0
CA–DR–ALR	2	52	0	54
Outside-Class-BC	0	50	0	246
Total	9	130	2	345

2. CA's False Alerts

The aircraft trajectories for major CA–CA alerts for the D10 traffic data were examined to identify false alerts. Two such alerts are presented here with the predictions of T-TSAFE in the DR mode included.

Figure 6 illustrates a case in which T-TSAFE would project the aircraft to fly across the localizers if dead reckoning were used to model the trajectory. Aircraft A28 was approaching its localizer to runway 18R at DFW while A39 was simultaneously approaching its localizer on the parallel runway 17C at DFW. The runway centerline separation was

1.5 n miles. The symbology is the same as defined in Fig. 3. The thick circles indicate the predicted LOS based on the thick solid lines of the DR trajectories. The thin circles indicate the closest point of approach. The circles have diameters of 1.5 n miles, which is the separation minima based on the safety-alert thresholds discussed earlier in Sec. III.C.2. The altitude profiles show they were not separated vertically. T-TSAFE in the ALR mode correctly predicted no conflict because its trajectory modeling is made more accurate with the incorporation of flight-intent information. Even though aircraft A28 did penetrate the localizer, but it was not severe enough to violate the alert threshold of 1.5 n mile. Conflict Alert predicted this aircraft pair to be in conflict even though its horizontal alert threshold was set at 70% of the runway separation. Thus, this alert is false for both T-TSAFE's DR mode and CA assuming the nominal interior routes of the aircraft are available intent information.

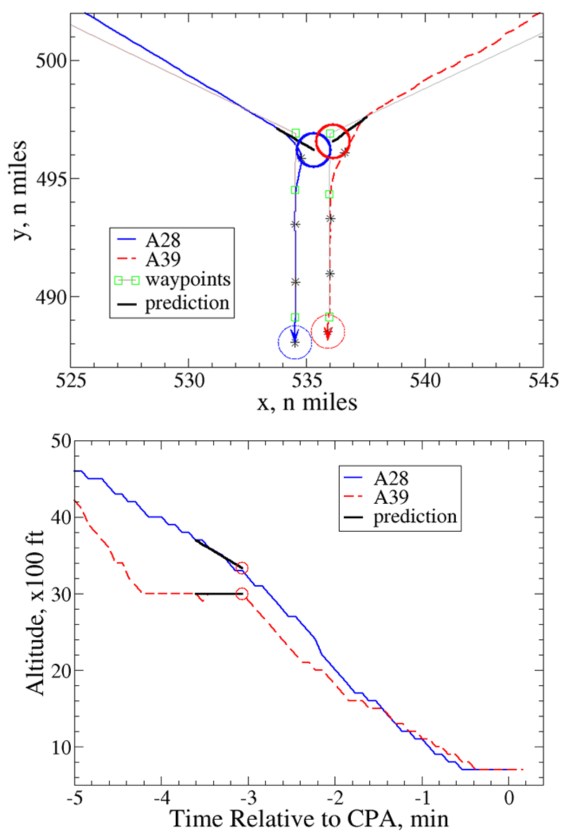

Fig. 6 Ground tracks and altitude profiles for aircraft predicted to conflict in both T-TSAFE DR mode and Conflict Alert due to potential track crossing of the localizers.

Figure 7 illustrates a case in which one of the aircraft was predicted to penetrate an altitude restriction at 8000 ft. Aircraft N893 was an arrival approaching runway 17C at DFW. It is flying by the waypoint named LEMYN which has an altitude restriction to remain at or above 8000 ft. Aircraft N595 was a VFR overflight crossing the track of N893. As can be seen, the two aircraft would be in conflict without the altitude restriction. Indeed, T-TSAFE DR mode predicted a conflict as indicated by the thick solid circles, the diameters of which are 1.5 n miles. The CPA is indicated by the thin circles, which almost overlap with each other; the time at the CPA is the origin in the altitude plots. Thus, this alert is again a false alert for both T-TSAFE's DR mode and CA if the altitude restriction is available intent information.

Among the 26 major CA–DR-only alerts in Table 1, twelve were similar to Fig. 6 with trajectories predicted to cross rather than capture the localizers and 14 were similar to Fig. 7 with trajectories predicted to cross through unknown altitude restrictions. They were all false alerts. Examining the five CA-only alerts also showed that they were false either because the rules of *m* of *n* cycles were not satisfied or they did not violate the safety-alert thresholds even though T-TSAFE alert thresholds are larger than those of CA. Given Outside-Class-BC alerts are false as controllers do not provide alerts for VFR flights outside class B and C airspace, we can estimate the CA false alert rate to be (85 ± 11)% at the 95% confidence level. This result supports the analysis in Ref. [5] as false alerts are nuisance.

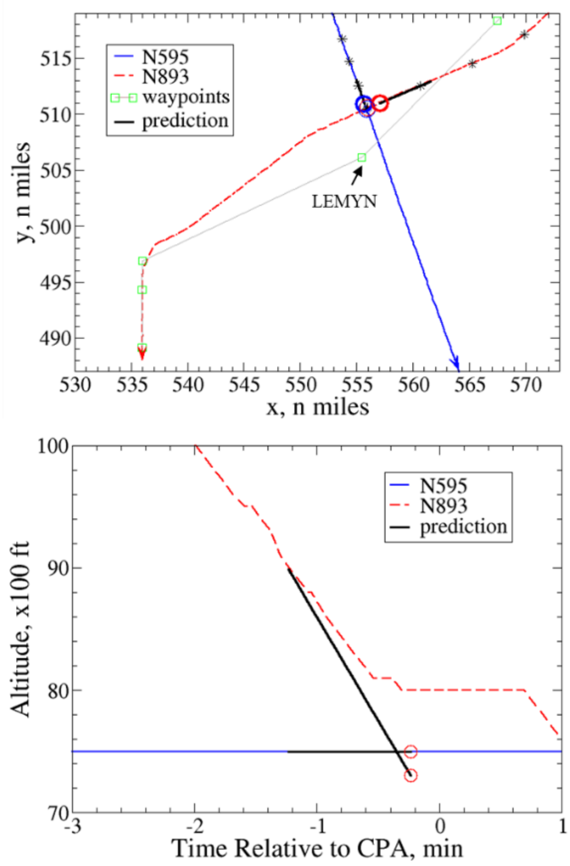

Fig. 7 Ground tracks and altitude profiles for aircraft predicted to conflict in both T-TSAFE DR mode and Conflict Alert due to penetration of an altitude restriction.

There were nine major CA–CA alerts for the SCT traffic data. Among these nine alerts, six were CA–DR-only for which two were similar to Fig. 6 and four were similar to Fig. 7. The number of these alerts alone are not large enough to provide an accurate enough estimation of the false-alert rate, but together with that of the D10 would make the estimation more accurate.

3. T-TSAFE's Safety Alerts

The safety alerts of T-TSAFE (in the normal ALR mode) included those involving aircraft conducting visual approaches (VA) and those involving VFR and MCI flights. Separation alerts involving IFR departure flights were generated as well. The major T-TSAFE alerts involving at least one departure or arrival of the major airports are grouped into VA wake (turbulence), VA nonwake, separation, VFR, and MCI alerts. The numbers of different major T-TSAFE alerts for the D10 and SCT traffic data are shown in Table 3. The trajectories that prompted the alerts were examined to determine the alert validity and identify the removable ones. The removable alerts are those that would not occur if proper flight-intent information were provided, such as level nonrestriction altitudes or flight-plan changes. The nonrestriction altitude clearances are expected to be entered into the automation system. The validity of the alerts in Table 3 is described in the following.

Table 3 Numbers of various major T-TSAFE alerts for the D10 and SCT traffic data

	D10 LOS	D10 Non-LOS	SCT LOS	SCT Non-LOS
VA Nonwake	1	3	1	2
VA Wake	5	4	11	2
Separation	4	17	8	17
VFR	3	5	1	6
MCI	1	1	0	2
Total	14	30	21	29
Total Less Removable	14	14	17	14

The four D10 LOS separation alerts are valid. One of them was also alerted by CA. Eleven of the 17 D10 non-LOS separation alerts are removable. The other six consist of one valid alert and five false alerts resulting from inaccuracy in the trajectory predictions.

The eight SCT separation LOS alerts consist of three valid alerts and five removable ones. The 17 SCT separation non-LOS alerts consist of three valid, three false, and 11 removable alerts. The false alerts were due to inaccurate trajectory predictions. Note that LOS alerts may be removable as the separation criteria may change when flight-intent information becomes available such as independent runways.

The three major D10 LOS VFR alerts are valid with two of them being common with CA. The five major D10 non-LOS VFR alerts consist of two false alerts involving inaccurate trajectory predictions of the IFR aircraft and three removable ones. One of the removable alerts is common with CA. The two major MCI D10 alerts consist of one valid LOS alert involving a DFW departure, which was too close to an unassociated aircraft, and one false alert involving a DFW arrival and an unassociated flight, which made an unexpected vertical climb before leveling off.

The one SCT LOS VFR alert was due to uncertainty around a level nonrestriction altitude. The six SCT non-LOS VFR alerts consist of three valid ones and three removable ones. The two SCT non-LOS MCI alerts are valid and were resolved because the unassociated aircraft made unexpected maneuvers.

The alerts involving aircraft conducting visual approaches were generated with alert thresholds of the conformance separation of 0.75 for nonwake and 0.70 for wake alerts as described in Sec. III. These alerts for D10 and SCT are discussed next.

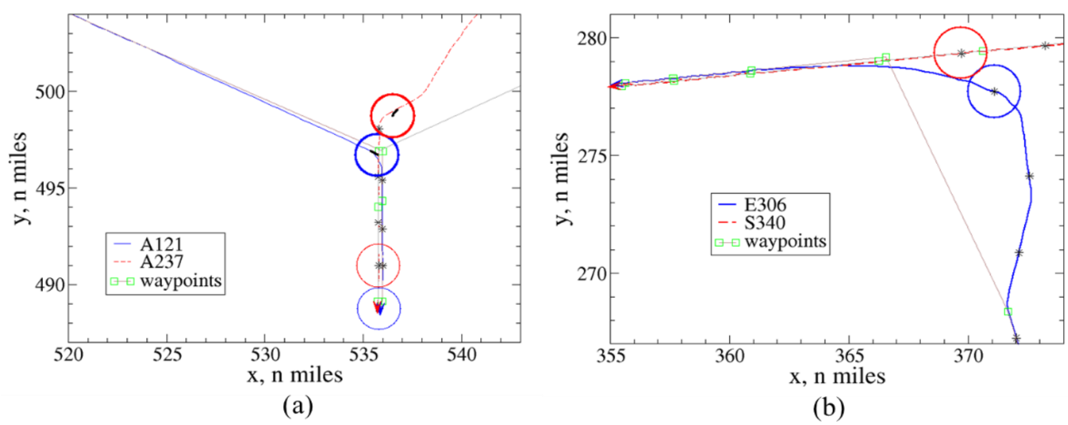

Fig. 8 Ground tracks for two pairs of aircraft on visual approaches from opposite sides of the runways with track crossing and runway separation less than 2500 ft.

One LOS and three non-LOS nonwake VA alerts were generated for the D10 traffic data. The LOS alert is valid since one aircraft deviated significantly from its localizer near its runway (13R). Two of the three non-LOS alerts are removable and the other is valid with the aircraft tracks shown in Fig. 8(a). At the point of potential conflict the altitudes (not shown) of the aircraft were both at 3000 ft with A121 just started to descend and A237 remained level at 3000 ft for about 50 seconds. Aircraft A121 and A237 were conducting simultaneous parallel approach to runways 17C and 17R at DFW, respectively, from opposite sides with track crossing. The runway separation was only 1300 ft with wake turbulence not applicable as both were of large weight class. The safety conformance alert threshold is 0.75, so the circles have diameters of 2.25 n miles (75% of 3 n miles). This is an example showing two aircraft at the same altitude, established on parallel runways less than 2500 ft apart but not closing up to nearly side-by-side positions. The predictions disappeared after about 15 seconds when A237 continued the relatively sharp base turn while A121 continued descending. This alert is valid based on the safety-alert thresholds. STARS CA did not alert this aircraft pair, as its alert threshold is 0.75 n miles horizontally in this type II area.

One LOS and two non-LOS nonwake VA alerts were generated for the SCT traffic data. One of the two non-LOS alerts is valid and it occurred when one of the two aircraft merging to the same waypoint changed to fly directly to the next waypoint to avoid the potential conflict. The other non-LOS alert was also valid and was due to a blunder when the two aircraft were on simultaneous approach to parallel runways 24R and 25L at LAX, separated by 5520 ft. The aircraft pair was also alerted in CA. The conflict resolved itself after the blunder aircraft turned back to its localizer. The LOS alert was a valid one with the aircraft tracks shown in Fig. 8(b). This setup was similar to that of Fig. 8(a). Aircraft E306 and S340 made simultaneous parallel approaches to runways 25L and 25R at LAX, separated by only 1070 ft. Both were descending near 4500 ft and separated by 200 ft. Wake turbulence did not apply here as it was a large aircraft trailing a small one; the safety-alert threshold was 0.75 with the LOS circles having diameters of 2.25 n miles. The prediction was 35 seconds before LOS and the LOS lasted 75 seconds. CA did not predict this alert.

The VA wake alerts were valid based on a conformance separation threshold of 0.70. These were due to wake turbulence violations when the aircraft approached the same runway. The conformance threshold corresponds to a class-A operational error if the aircraft were conducting IFR approaches. This can be a good starting point for generating VA wake alerts. If the criterion for class-B operational errors, i.e. conformance threshold value of 0.85, was used as in the case of nonwake alerts, the number of alerts would increase significantly: the numbers of D10 LOS, D10 Non-LOS, SCT LOS, and SCT Non-LOS alerts became 26, 11, 30, and 7, respectively. This should be compared with the corresponding numbers of 5, 4, 11, and 2, respectively, in Table 3.

4. Avoidance of Dead-Reckoning False Alerts

It is interesting to see how the false alerts in the DR mode of T-TSAFE are avoided by different mechanisms. Table 4 shows the total numbers of all major alerts and of safety-only ones in different models for the two real-world traffic data sets. The models include T-TSAFE in the DR mode (T-TSAFE-DR), Conflict Alert (CA), T-TSAFE in the ALR mode (T-TSAFE-ALR), and T-TSAFE-ALR mode with controller entry of nonattributable altitude clearances (T-TSAFE). The alerts for the T-TSAFE mode are those of the T-TSAFE-ALR mode excluding the removable ones. After averaging over the two sets of data, the number of safety and separation alerts inside class-B airspace from T-TSAFE in the DR mode (T-TSAFE-DR) are reduced to 8, 16, and 10%, respectively, by the CA, T-TSAFE-ALR, and T-TSAFE models; the corresponding percentage reductions for safety alerts only are 15, 15, and 13%, respectively. CA achieves the reduction through reducing the alert thresholds, while T-TSAFE uses available flight-intent information. Note that the numbers of alerts for T-TSAFE and CA are not directly comparable since CA alerts would not include the separation alerts and VA wake alerts. In fact T-TSAFE model contains nine D10 and 13 SCT safety wake alerts that CA does not include, as shown in Table 3. If these wake alerts were not what the controllers want to see one can further reduce the alert thresholds for VA wake turbulence.

Table 4 Numbers of all major alerts and of safety-only ones for D10 and SCT for different models

	D10-All	SCT-All	D10-Safety	SCT-Safety
T-TSAFE-DR	379	216	210	102
CA	37	9	37	9
T-TSAFE-ALR	44	50	23	25
T-TSAFE	28	31	18	22

D. Summary

To summarize, the average alert lead time for T-TSAFE separation LOS alerts from the HITL traffic data for SCT is 45 seconds, agreeing with previous result and showing independence of the TRACONs. The false-alert rate for mainly separation alerts is 8% based on the same HITL data. The false-alert rate for CA's conflict alerts is 85% based on actual aircraft trajectories. These false alerts were avoided by T-TSAFE when published altitude restrictions were incorporated. Further improvement could be achieved if altitude clearances not attributable to published altitude restrictions were entered into the system by controllers, which would not result in significant workload increase [7].

T-TSAFE can reduce the number of alerts generated with pure dead-reckoning trajectories by 90% and CA can achieve similar reduction with smaller safety-alert thresholds. As a result, both T-TSAFE and CA have similar and thus manageable total number of safety alerts, but the common alert pairs between the two systems are small and the false safety alerts in CA are avoided in T-TSAFE. While the number of safety alerts for CA is manageable, there is an issue with its false-alert rate, which is shown to be 85%. The false rate for T-TSAFE major safety alerts is much smaller as only three safety false alerts (~15%) for the D10 data were found. Better flight-intent information such as the TSAS [22] terminal routes, which is being deployed, will help reduce false alerts further.

VI. Conclusions

Performance of a terminal alerting prototype system, with both separation and safety alerts to assist controllers in their separation task, has been evaluated with air traffic data from realistic Human-In-The-Loop experiment and real-world operations. Safety-alert thresholds for visual-approach flights based on conformance separation used in severity classification of operational errors have been proposed and shown to provide a good starting point for practical applications.

The average alert lead time of 45 seconds for separation alerts is confirmed for a different terminal airspace from before. The false-alert rate for mainly separation alerts is 8%. The number of safety alerts based on the real-world traffic data is similar to that of Conflict Alert. The false safety alerts of Conflict alert for major airports is 85% based on analysis of aircraft trajectories and they are avoided in the prototype system.

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