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Concept and Requirements for Airport Surface Conflict Detection and Resolution

Sai Vaddi[1], Gregory D. Sweriduk[2], Jason Kwan[3], Vivian Lin[4], Jimmy Nguyen[5], and Victor H. L. Cheng[6]
Optimal Synthesis Inc., Los Altos, CA, 94022

The paper deals with the concept and requirement for airport surface Conflict Detection and Resolution (CD&R). The scope of the proposed CD&R concept spans across three different timeframes: (i) near-term (2015), (ii) mid-term (2020), and (iii) far-term (2025). Enabling technologies such as (i) surveillance, (ii) airport surface operations planning automation, (iii) clearance delivery mechanism, (iv) clearance information available to CD&R automation, and (v) flight-deck automation are studied. The paper identifies the functional requirements for the CD&R automation system such as aircraft state estimation module and aircraft trajectory prediction module. Detalied descriptions of the individual algorithms are beyond the scope of the current paper and will be presented in a future paper. However, preliminary closed-loop simulation results obtained with the conflict detection and resolution system are presented.

I. Introduction

Current-day operations require the Air Navigation Service Provider (ANSP) to specify the taxi routes, control the order of merging at intersections, sequence runway crossings and departures at the runways, and require the pilots to provide separation visually. To enhance situational awareness of the ANSP, the FAA is introducing new surface surveillance technologies such as Airport Surface Detection Equipment – Model X (ASDE-X)[1] and Automatic Dependent Surveillance – Broadcast (ADS-B)[2], which provide aircraft position data in all-weather situations and support the prediction of future aircraft trajectories more accurately than before. Other technologies useful for conflict and incursion detection or prevention include the Airport Movement Area Safety System (AMASS)[3,4] and Runway Status Lights[5]. Previous NASA research for improving situational awareness on the flight deck include the Taxiway Navigation and Situation Awareness (T-NASA) System[6,7] developed at NASA Ames Research Center, and the Runway Incursion Prevention System (RIPS) [8,9] developed at NASA Langley Research Center. Researchers at NASA Langley are also building on the earlier RIPS technologies to develop flight-deck technologies for collision avoidance[10] referred to as Collision Avoidance for Airport Traffic (CAAT). The Runway Incursion Alerting System (RIAS)[11] consisting of millimeter-wave radar and pan/tilt/zoom cameras was developed by QinetiQ.

The Surface Management System (SMS)[12], developed by NASA in cooperation with the FAA, is a valuable decision-support tool for service providers and users of the National Airspace System (NAS) for providing situational awareness of the airport traffic [13]. Researchers from Mosaic ATM used the route generation capability of the Surface Decision Support System (SDSS)—the SMS testbed fielded by the FAA—to study the feasibility of a conformance monitoring function[14]. Mosaic ATM is currently investigating surface trajectory prediction and taxi conformance monitoring under a NASA Research Announcement (NRA) award[15].

The EUROCONTROL Advanced Surface Movement Guidance and Control System (A-SMGCS)[16] concept includes research on optimization of airport taxi scheduling[17]. A-SMGCS Level 2 consists of automated monitoring and alerting functions, and includes the prediction of conflicts on active runways or incursions into restricted areas.

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[1] Research Scientist, 95 First Street, Ste 240, AIAA Member.
[2] Research Scientist, 95 First Street, Ste 240, AIAA Senior Member.
[3] Research Enginner, 95 First Street, Ste 240.
[4] Research Engineer, 95 First Street, Ste 240.
[5] Research Engineer, 95 First Street, Ste 240.
[6] Vice President, 95 First Street, Ste 240, AIAA Associate Fellow.

The European Airport Movement Management by A-SMGCS (EMMA) project defined A-SMGCS operational requirements[18] for the ANSP and flight deck, and other important services (e.g., communication, navigation, and surveillance (CNS)[19]). Further development of A-SMGCS services, procedures, and operational requirements has been documented as part of the EMMA2 effort[20].

II. CD&R Automation System

The primary objective of the proposed research is to study the concepts and requirements for a CD&R automation system that is suitable for current-day operations as well as futuristic 4D-trajectory operations envisioned for the Next-Generation Air Trasportation System (NextGen). Other systems such as the SMS, AMASS and ASDE-X were not designed for 4D-trajectory operations. Moreover, although these systems have the ability to alert controllers of conflicts resulting from safety violations, they do not seem to have any conflict resolution capability. Surface Operation Automation Research (SOAR)[21–25], the seminal research in surface 4D-trajectory operations pioneered by Optimal Synthesis Inc (OSI), takes a holistic approach to the problem. During SOAR, OSI developed collaborative automation systems for the tower as well as for the flight deck to enable 4D-trajectory operations. The SOAR concept examined the surface traffic control problem as an integrated system involving the ANSP, the flight deck, and their associated automation systems and other enabling technologies. The planner envisioned under the SOAR concept not only assigns taxiways and runways but also computes a Required Time of Arrival (RTA) at select nodes along the taxiways and the runways. The planner schedules the flights with tighter inter-aircraft time separation at nodes under the assumption that the flights can realize these RTAs using flight-deck automation technologies such as Flight Deck Automation for Reliable Ground Operations (FARGO)[26–28]. Whereas the tight inter-aircraft time separation leads to increased efficiency and throughput, the tighter operational margins make the system more prone to multiple conflicts even if one flight underperforms and does not adhere to its RTAs. Such conflicts will require replanning of all the flights that are affected by the conflicts.

The following are the objectives of the airport surface CD&R automation system:

- Enhance situational awareness of tower controllers by continually monitoring the airport surface traffic and predicting conflicts on taxiways and runways.
- Take into account the intent information of the aircraft resulting from airport surface operations planning to predict conflicts.
- Detect and alert tower controllers of conflicts over two different time horizons: (i) short-term, and (ii) long-term. These time horizons are different from the operational timeframes defined in the Abstract and in the Scope section below. These time horizons define time segments pertinent to the arrival and departure flights.
    - Short-term conflicts are impending conflicts and are expected to occur in a time horizon that is comparable to the time it takes to communicate to the pilot plus the time it takes an aircraft to come to a complete stop. The time horizon for short-term conflicts could be less than 30 s.
    - Long-term conflicts are relevant in the context of mid-term and far-term operations where the intent of the aircraft is known. In the case of mid-term operations, the scheduled ramp spot release time, assigned taxi route of the aircraft, and the scheduled departure time of the aircraft form the intent of the aircraft. In the case of far-term operations, the complete 4D route of the aircraft described in terms of a node sequence with a time of crossing for each node form the intent of the aircraft. Intent of the aircraft facilitates longer term trajectory prediction and thereby long-term conflict detection.
- Assist controllers in resolving conflicts in an efficient manner:
    - Generate route, sequence, start time, and speed advisories for resolving conflicts.
    - Generate options for replanning in response to long-term conflicts.

A. Scope

The physical scope of the proposed CD&R system comprises the following:

- Departure Aircraft: Starting from the ramp spot, followed by taxiways, runway crossing, and takeoff roll to takeoff.
- Arrival Aircraft: Starting from the moment they are cleared for landing, or when they cross the outer marker, or when they are first registered on the ground-based surveillance system, through flare, touchdown, and rollout, followed by runway exits and runway crossings, through taxiways to the ramp spot.

The scope of the system also extends across different technological and operational timeframes recognized as (i) Near-Term (2015), (ii) Mid-Term (2020), and (iii) Far-Term (2025 and beyond).

- Near-Term: An operational timeframe where the operations and technology are reflective of current-day operations and capabilities. The phrases “near-term” and “current-day” are used interchangeably in this paper.
- Far-term: An operational timeframe where the operational concepts are based on NextGen 4D-trajectory operations. Again, the phrases “far-term” and “4D-trajectory operations” are used to describe operations in the same timeframe in this paper.
- Mid-term: A transitional timeframe between the near-term and far-term timeframes where the operations are the same as current-day, but technological improvements in surveillance and automation systems are expected.

The scope of the system in terms of the personnel expected to interact with the automation includes the following:

- Ground controllers for arrival and departure flights
- Local controllers for arrival and departure flights
- Flight crew on the flight decks (i.e., pilots and first officers)

B. Airport Surface Conflicts

A conflict in the en route airspace is defined based on separation requirements of 5 NM inter-aircraft separation in the horizontal plane or 1000 ft inter-aircraft separation in altitude. Unfortunately, no such simple definition of a conflict exists for surface operations. At the simplest level, a conflict can be defined as a violation of safe inter-aircraft separation. There are no standards for separation regarding taxiing aircraft; safe distances are left to the judgment of the pilot. There are recommendations for safe distances behind an aircraft that relate to jet blast and foreign object damage if the aircraft has to increase its throttles above idle, which may happen if the aircraft has stopped and would resume movement.

1. Taxiway Conflicts

When there is crossing traffic, such as at intersections between two taxiways, a taxiway and a runway, or two runways, there are prescribed distances that an aircraft must stay behind in order to insure being clear of crossing traffic. These are illustrated in Figure 1; distances are given in Table 1 and Table 2. These distances are not strictly enforced on taxiway intersections, though, and a flight may be cleared to proceed even though the crossing traffic may not have completely cleared the intersection. Such clearances are issued with the proviso that it is left to the pilot’s discretion that there is adequate separation, which has in some cases resulted in a collision.

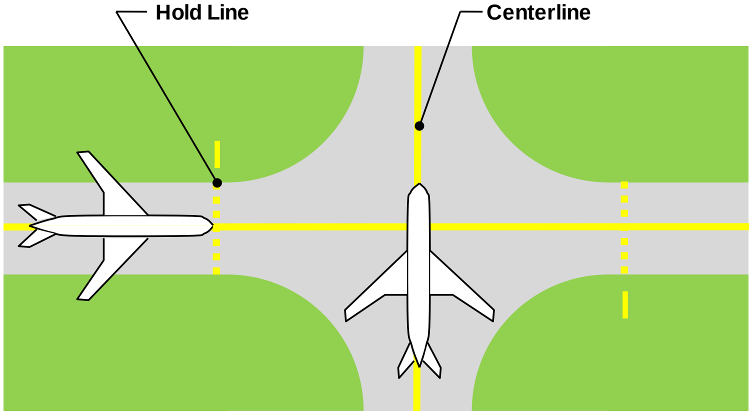


Figure 1. Intersection Hold Distance

Table 1. Holding Position Markings for Taxiway-Taxiway Intersections [29]

Design Group	I	II	III	IV	V	VI
Hold Distance	44.5 ft (13.5 m)	65.5 ft (20 m)	93 ft (28.5 m)	129.5 ft (39 m)	160 ft (48.5 m)	193 ft (59 m)

Table 2. Holding Position Markings for Runway-Runway/Taxiway Intersections [30]

Aircraft Approach Category	**Airplane Design Group**	**Visual and Nonprecision Instrument**	**Precision Instrument**
A & B	I, II	125 ft (38 m)	175 ft (53 m)
	III	200 ft (60 m)	250 ft (75 m)
	IV	250 ft (75 m)	250 ft (75 m)
C & D	I – IV	250 ft (75 m)	250 ft (75 m)
	V	250 ft (75 m)	280 ft (85 m)
	VI	250 ft (75 m)	280 ft (85 m)

Table 3. Aircraft Design Group Definitions

Design Group		I	II	III	IV	V	VI
Wingspan (feet)	min (≥)	–	49.0	79.0	118.0	171.0	214.0
	max (<)	49.0	79.0	118.0	171.0	214.0	264.0

Table 4. Aircraft Approach Category Definitions

Approach Category		A	B	C	D	E
$\mathbf{V_{REF}}$ (knots)	min (≥)	–	91	121	141	166
	max (<)	91	121	141	166	–

2. Runway Incursions

FAA defines runway incursion as any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and take-off of aircraft . An incursion may occur either because an aircraft or ground vehicle did not have the proper clearance, or because the controller made an error when issuing a clearance. If an aircraft has been cleared to land on or take off from a runway, then all other aircraft and ground vehicles must be clear of that runway; i.e. they must observe the hold lines (see Figure 2). Otherwise, a runway incursion has occurred (in the example of Figure 2, Aircraft 2 has crossed the hold-short line when Aircraft 1 is already cleared to land on the runway). The aircraft that is cleared to use that runway does not have to be on the ground or have started its takeoff roll for there to be an incursion.

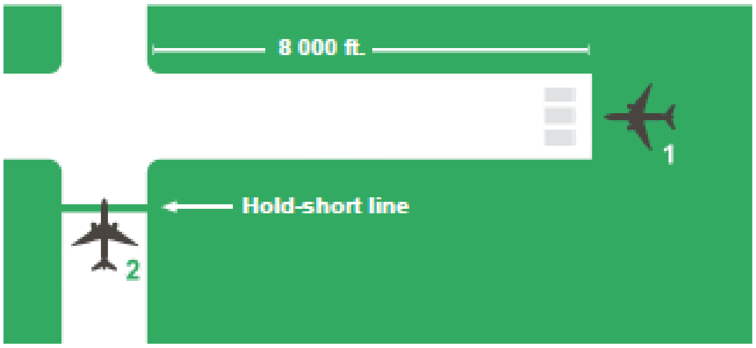


Figure 2. Runway Incursion Example [ICAO]

A runway incursion also occurs if two flights have been cleared to use two intersecting runways simultaneously (see Figure 3). Even though neither flight has improperly crossed a hold line, there is a significant possibility of a loss of separation leading to a collision. Another example of an incursion is when an aircraft mistakenly lands on or takes off from a runway for which it was not given a clearance. In each case a conflict can be detected based on trajectory predictions and intent inference, but it may not be possible to discriminate who is at fault without knowledge of the actual clearances.

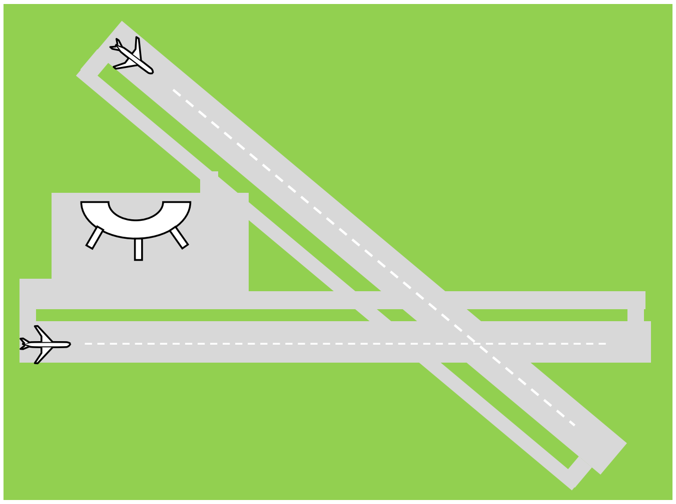


Figure 3. Intersecting Runway Incursion Example

The FAA uses three primary metrics to assess runway incursions: the frequency of runway incursions, the severity of runway incursions, and the types of runway incursions. Table 5 lists the categories of runway incursions.

Table 5. Severity Categories of Runway Incursions

Category	Definition
A	Separation decreases and participants take extreme action to narrowly avoid a collision, or the event results in a collision
B	Separation decreases and there is a significant potential for collision
C	Separation decreases but there is ample time and distance to avoid a potential collision
D	Little or no chance of collision but meets the definition of a runway incursion

3. *Wake Vortex Separation Violation*

Every aircraft generates a wake while in flight. Initially, when pilots encountered this wake in flight, the disturbance was attributed to "prop wash." It is known, however, that this disturbance is caused by a pair of counter-rotating vortices trailing from the wing tips. Vortex strength generally increases with aircraft size, so the vortices from larger aircraft pose problems to aircraft crossing behind or following that may encounter the wake. For instance, the wake of these aircraft can impose rolling moments exceeding the roll-control authority of the encountering aircraft. A wake encounter can be catastrophic: in 1972 at Fort Worth a DC-9 got too close to a DC-10 (two miles back), rolled, caught a wingtip, and cartwheeled, coming to rest in an inverted position on the runway. All aboard were killed. Serious and even fatal General Aviation (GA) accidents induced by wake vortices are not uncommon.

The following are the FAA mandates for wake-vortex avoidance[31]:

1. Separation is applied to aircraft operating directly behind a heavy/B757 jet at the same altitude or less than 1,000 feet below:
    (a) Heavy jet behind heavy jet: 4 NM.
    (b) Large/heavy behind B757: 4 NM.
    (c) Small behind B757: 5 NM.
    (d) Small/large aircraft behind heavy jet: 5 NM.
2. Also, separation, measured at the time the preceding aircraft is over the landing threshold, is provided to small aircraft:
    (a) Small aircraft landing behind heavy jet: 6 NM.
    (b) Small aircraft landing behind B757: 5 NM.
    (c) Small aircraft landing behind large aircraft: 4 NM.
3. Additionally, appropriate time or distance intervals are provided to departing aircraft:
    (a) Two minutes or the appropriate 4 or 5-NM radar separation when taking off behind a heavy/B757jet will be:
        (1) From the same threshold.
        (2) On a crossing runway and projected flight paths will cross.
        (3) From the threshold of a parallel runway when staggered ahead of that of the adjacent runway by less than 500 feet and when the runways are separated by less than 2,500 feet.
    (b) A 3-minute interval will be provided when a small aircraft will takeoff:
        (1) From an intersection on the same runway (same or opposite direction) behind a departing large aircraft.
        (2) In the opposite direction on the same runway behind a large aircraft takeoff or low/missed approach.

C. CD&R System Concepts

Figure 4 is a closed-loop description of the airport surface operation dynamics with the CD&R system. It shows the functional relationship of the proposed CD&R automation system with respect to the user (ATC), other surface automation systems and physical systems such as aircraft and surveillance systems. The CD&R module is expected to interact with two other automation systems: (i) an airport surface operations planner, and (ii) a conformance monitoring module. These two types of automation systems are themselves currently being developed and are not expected to be ready for the near-term timeframe. The CD&R automation system concept, however, is designed to to both work both with and without them.

Input-output depictions of the CD&R system are shown in Figure 5, Figure 6, and Figure 7 for the near-term, mid-term, and far-term timeframes respectively. Detailed description of the inputs and outputs is provided in the following sections. The differences in the inputs and outputs are a result of different enabling technologies in each of the three timeframes. An elaborate discussion of the enabling technologies is presented in Section III. The CD&R module is primarily driven by surveillance data which characterize the state of the traffic on the airport surface. The Planner, which is expected to be in place in the mid-term and far-term timeframes, is expected to provide the additional input that characterizes the intent of the different aircraft. In the absence of a planner, the tower controller (ATC) would issue tactical route clearances. Another module is the conformance-monitoring module that generates Non-Conformance Alerts (NC Alerts) for those aircraft that are deviating from the agreed-upon clearance. Speech recognition technology is observed as a possible candidate for transcribing voice-based clearances into a form suitable for CD&R automation. It is shown in dotted lines because at the moment it is recognized as a possibility. OSI is not aware of any deployment plans for such technology. Datalink capability between the tower and flight-deck is expected for the mid-term operations. Therefore, the possibility of transmitting conflict-alert messages directly to the flight-deck is recognized by the dotted line in Figure 6.

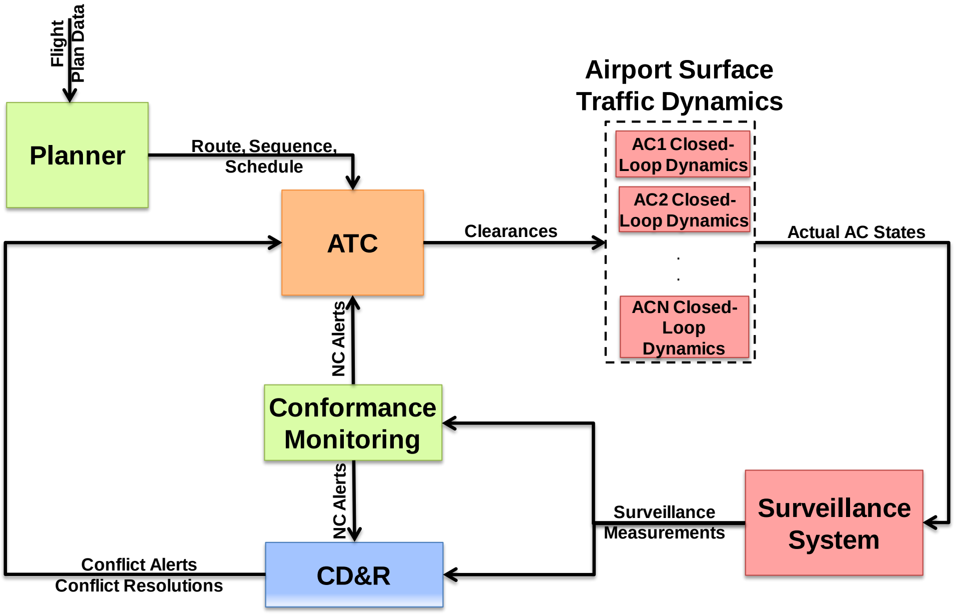


Figure 4. Closed-Loop Depiction of the Airport Surface Operation Dynamics

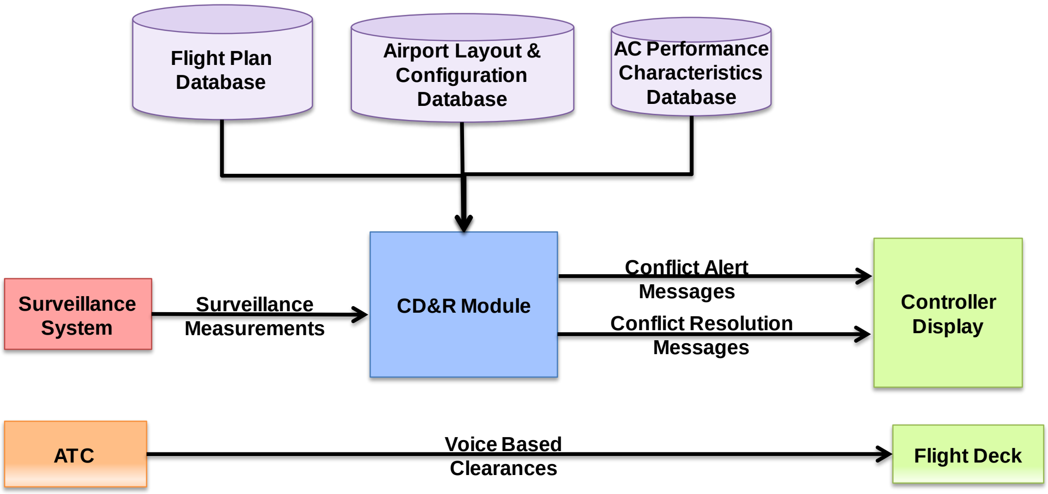


Figure 5. Inputs and Outputs of the CD&R Automation System for Current-Day Operations

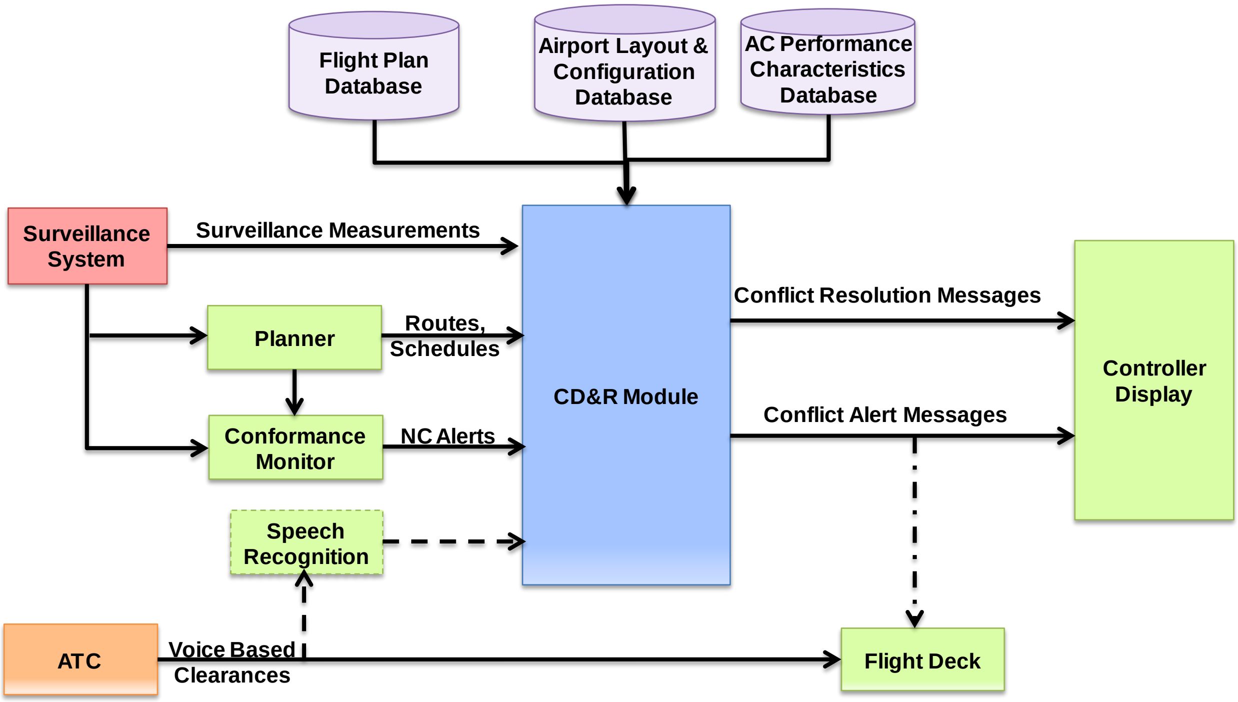


Figure 6. Inputs and Outputs of the CD&R Automation System for Mid-Term Operations

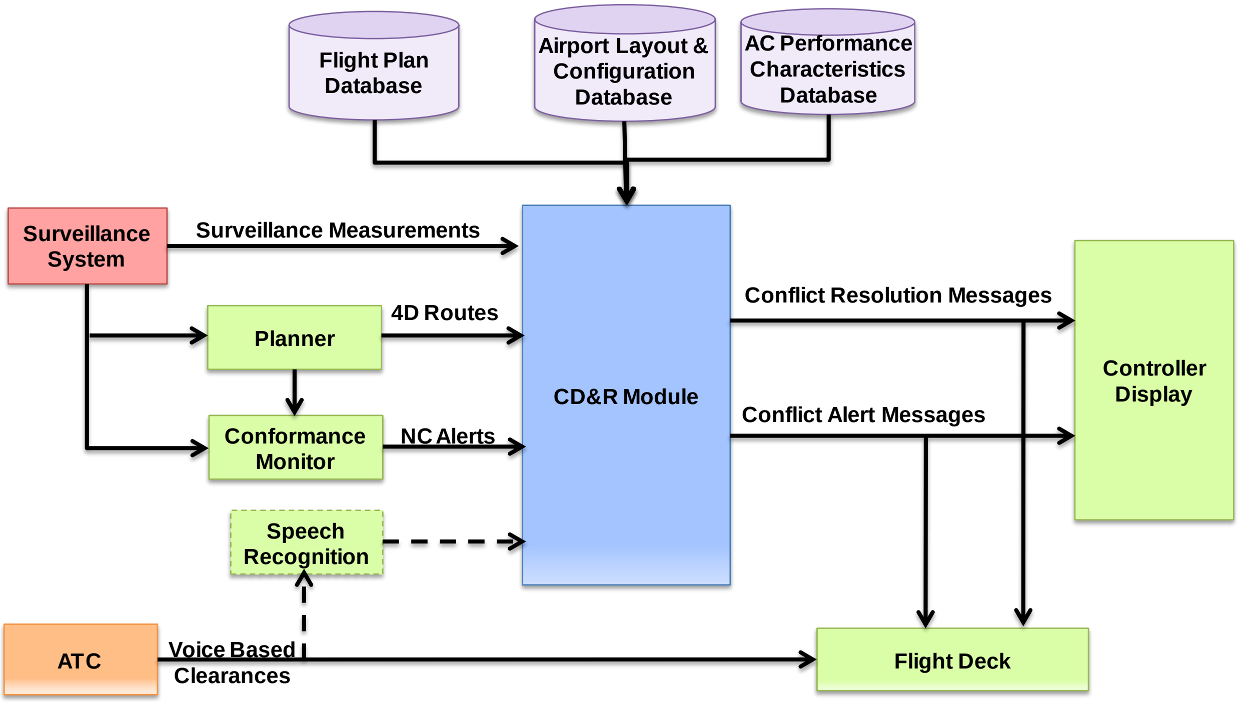


Figure 7. Inputs and Outputs of the CD&R Automation System for Far-Term Operations

D. Inputs to the CD&R Module

Airport Layout

A database describing the airport layout and the different airport configurations is expected by the CD&R automation system. The airport layout model is expected to be represented by a link-node model. Link-node models have been developed by OSI and others in the past and used in surface operation planning systems. The links are further characterized by attributes such as taxiways and runways. The nodes are characterized using attributes such as "gate," "taxiway intersection," and "runway crossing," etc.

Whereas the airport layout is static, the configuration of the airport can change dynamically. The configuration of the airport can be described in terms of the following:

- Directionality of the runways and taxiways
- Description of runways as arrival runways, departure runways, or mixed-operation runways

Aircraft Performance Characteristics Database

An aircraft performance characteristics database is expected to be available as an input to the CD&R automation system. The airport layout and configuration database contains the necessary data to infer the possible routes of travel for an aircraft. The aircraft performance characteristics database contains the necessary information to infer the possible speeds for an aircraft. It could also contain information pertaining to the geometry of the vehicles such as aircraft length, and wheelbase length. The information is expected to be specific to aircraft type (e.g., B737, A380). The following pieces of information are expected in the database for each aircraft type:

- Speed and acceleration values:
    - Minimum, maximum and preferred taxi speeds
    - Maximum taxiway acceleration and minimum taxiway deceleration
    - Minimum, maximum, and preferred turn speeds
    - Minimum, maximum, and preferred runway deceleration magnitudes
    - Nominal and maximum runway acceleration for takeoff roll
    - Minimum turning radius
    - Takeoff speed
    - Threshold speed
- Geometric information:
    - Length of aircraft
    - Wheelbase length
    - Wing span

Flight Plan Database

The flight plan database contains information about the expected traffic and their intent. The tower automation systems currently have the flight plan information; therefore it is reasonable to expect that the CD&R automation system will have access to this information in all three operational timeframes. The following pieces of information are expected to be available to the CD&R system from the flight plan database:

- Aircraft ID
- Call sign
- Origin airport
- Destination airport
- Scheduled time of arrival/departure
- Aircraft type
- Departure procedures
- Standard terminal arrival routes

Surveillance Data

A key input to the CD&R system is the surveillance data which reflects the current traffic scenario on the surface of the airport. The actual nature and quality of surveillance data depends on the surveillance system in place, e.g., primary surveillance radar, ADS-B. Characteristics of the surveillance data relevant to the CD&R system are as follows:

- Geometric scope of the surveillance systems (e.g., ramp area, taxiways, runways)
- Scope of the surveillance systems in terms of the types of aircraft and ground vehicles tracked by the surveillance system
- Nature of the data generated by the surveillance system (e.g., aircraft position, speed, heading)
- Update rate of the surveillance data
- Performance of the surveillance system defined in terms of metrics such as (i) accuracy, (ii) integrity, (iii) availability, and (iv) continuity.

Clearance Information

Airport operations involving the movement of flights are accomplished by clearances. Clearances in the current-day operations are communicated through voice-based communications and therefore are not expected to be available to the automation system. In the far term, however, 4D-trajectory clearances are expected to be delivered through datalink and therefore can be expected to be available to the CD&R automation system. Whereas the surveillance data reflects the current state of the airport surface traffic, the clearance information available to the CD&R automation system can be crucial in predicting the future intent of the aircraft. Clearances can contain the following pieces of useful information:

- Aircraft path information represented by taxiways, runways, ramp spots, gate, runway crossing, and runway exit assigned to the aircraft.
- Sequence information for taxiway intersections, runways, and runway crossings.
- Times at which the aircraft leaves a spot, crosses taxiway intersections, crosses runways, departure aircraft are expected to start rolling, and arrival aircraft are expected to touch down.

E. Outputs from the CD&R Module

The CD&R system takes in the inputs described in the previous section and evaluates these inputs for possible future conflicts and generates advisories. The following alerts and advisories are expected as outputs from the CD&R system (again depending on the technology):

- Conflict Alerts
  - ▪ Taxiway Conflict Alerts: Alert messages containing conflicting aircraft IDs, time to conflict, and expected location of conflict.
  - ▪ Runway Incursion Alerts: Alert messages containing the IDs of aircraft involved in a runway incursion, the time to runway incursion, and the runway ID at which the incursion is expected.
  - ▪ Wake Vortex Separation Violation Alerts: Alert messages containing the IDs of aircraft involved in a wake-vortex separation violation, and the time to violation.
  - ▪ Replanning Alerts: Alert messages consisting of the IDs of aircraft, and 4D clearance segment IDs that are affected by a conflict and hence need replanning. These alerts are applicable for far-term operations.
- Conflict Resolution Advisories
  - ▪ Halt Advisories: Advisory messages consisting of the IDs of aircraft that need to be stopped immediately to avoid imminent conflicts. These advisories could also contain a specific location such as a node where the aircraft is advised to stop.
  - ▪ Go-Around Advisories: Advisory messages consisting of arrival aircraft IDs that are recommended to go around by the CD&R system.
  - ▪ Go Behind Advisories: Advisory messages consisting of the IDs of a pair of aircraft, one of which is expected to go behind another aircraft at a taxiway crossing or a runway crossing.
  - ▪ Depart, Proceed, and Cross Advisories: Advisory messages consisting of the aircraft IDs that are cleared to depart from a specified runway, or proceed along a taxiway, or cross a specified runway. These advisories are expected to be preceded by a halt advisory.
  - ▪ Route and Schedule Advisories: Advisory messages consisting of route, sequence, and start time for taxiing aircraft affected by the conflict. Again these advisories are typically preceded by a halt advisory.

III. CD&R Enabling Technologies

Enabling systems for the proposed automation system include: (i) a surveillance system, (ii) a tower-pilot communication system, (iii) an airport surface operation planning system, (iv) clearance information, and (v) a flight-deck automation system. These systems are themselves expected to evolve over time into the different timeframes. Individual descriptions of the enabling technologies are given in the following sub-sections.

A. Surveillance System

A key input to the CD&R system is the surveillance data which reflects the current traffic scenario on the surface of the airport. The actual nature and quality of surveillance data depends on the surveillance system in place, e.g., Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Multilateration, Automatic Dependent

Surveillance-Broadcast (ADS-B), Wide Area Augmentation System (WAAS), Ground-Based Augmentation System (GBAS). Characteristics of the surveillance data relevant to the CD&R system are shown in Table 6.

Table 6. Surveillance Data Characteristics

Timeframe	Incremental Technology	Position Accuracy	Velocity Accuracy	Update Rate
Near-Term	RADAR	2 m	1 m/s (measurement lag up to 10 s)	1 Hz
Mid-Term	Multilateration	6 m	0.25 m/s	1 Hz
	ADS-B (WAAS)	2 m	0.1 m/s	1 Hz (0.2 Hz if AC is Stopped)
Far-Term	ADS-B (GBAS)	1 m	0.1 m/s	1 Hz (0.2 Hz if AC is Stopped)

B. Communication Technologies

The mechanism of communication between the tower controller and the flight deck has an important bearing on the kind of conflict resolution strategies that can be employed. Conflict resolution strategies involving 4D trajectories require datalink communication. The clearance delivery mechanism also has a bearing on the clearance information available to the conflict detection module. Clearances delivered through voice-based communications are not expected to be available to the CD&R automation system without additional technologies such as speech recognition. The Federal Aviation Administration will set US carriers a 2017 deadline[32] to fit their fleets with VHF datalink Mode 2 (VDL-2) equipment. The equipment can send and receive controller-pilot datalink communications (CPDLC) as well as company or engineering information now handled by the lower capacity ACARS datalink system. Beyond 2017, the FAA proposes, aircraft without VDL-2 will be excluded from high traffic controlled airspace. The timetable has been proposed by the FAA's future communications architecture team at the agency's William J Hughes Technical Center at Atlantic City International airport in New Jersey.

Near-Term: Voice-based communications consistent with current-day communication technology between the tower and flight deck is assumed.

Mid-Term: Datalink capability for transmitting the conflict alerts from the tower automation to the flight deck is assumed.

Far-Term: Direct datalink-based communications between the tower automation and the flight-deck automation is assumed for transmitting all clearances.

C. Airport Surface Operation Planning System

The airport surface operations planning system is the central automation system for planning surface operations such as taxiway routing, taxiway scheduling, runway assignment, and runway scheduling including runway crossings, takeoffs and landings. Outputs from the planner help establish the intent of flights for the benefit of the CD&R system. Extensive research is currently being conducted in this area by the Safe and Efficient Surface Operations (SESO) research group at NASA Ames Research Center. OSI has also developed detailed surface operations planners as part of the SOAR concept. OSI's surface operation planner is based on the GoSAFE (Ground-Operation Situation Awareness and Flow Efficiency) concept[22,33]. GoSAFE handles the taxiway route assignment, runway assignment, taxiway sequencing and scheduling, departure runway scheduling, runway exit assignment and scheduling, and runway crossing operations.

Under the NASA NextGen Concept and Technology Development Project, the SESO Technical Area is supporting several efforts in the study of 4D trajectories. These include NRA activities by a GT/MIT/Sensis team and a SJSU/OSI team[34] to develop surface trajectory planning algorithms by considering the constraints and uncertainties of the problem. NASA in-house research includes SESO engineering researchers developing scheduling and routing algorithms. The concept and implementation of optimized airport surface traffic operations has been presented by SESO researchers in Ref. 31. The concept consists of a spot release planner[36] and a runway scheduler[37,38]. In other related efforts, taxiway routing and scheduling algorithms are also being developed by SESO researchers[39,40].

Near-Term: No planning automation system is assumed.

Mid-Term: In the transitional timeframe the spot release planner[36] and a runway scheduler[38] from NASA SESO group are assumed to be mature enough to be part of the airport surface operations planning system.

Far-Term: In the far term, a complete and integrated 4D-trajectory planner such as the envisioned GoSAFE from the gate to possibly the departure fix is assumed.

D. Clearance Information

Information pertaining to issued clearances is a most useful piece of information in determining the intent of an aircraft.

Near-Term: No information related to clearances is assumed for the near term.

Mid-Term: Route information such as taxiway route, runway, and gate assignments to the aircraft are expected to available to the CD&R automation system. Also, schedules resulting from the Spot Release Planner[36] and Runway Scheduler[37,38] are expected.

Far-Term: Complete 4D trajectory consisting of a list of nodes and the RTAs at those nodes is assumed to be available for the CD&R automation system.

E. Flight-Deck Automation

Flight-deck automation is crucial for the implementation of the 4D-trajectory operations. It can also play an important role in enhancing the pilot's situational awareness and generating conflict alerts.

Near-Term: No flight-deck automation is assumed for the near term.

Mid-Term: It is expected that technologies such as Cockpit Display of Traffic Information (CDTI) will be available during the mid-term.

Far-Term: It is expected that flight-deck automation systems such as the envisioned FARGO will be available in the far term. FARGO generates the necessary guidance and control commands/advisories for realizing the precise 4D trajectories.

F. Summary of Enabling Technology Assumptions

Table 7 shows a summary of the enabling technology assumptions across the three operational timeframes.

Table 7. Summary of Enabling Technology Assumptions

	Near-Term	Mid-Term	Far-Term
Surveillance	Primary Surveillance Radar, Secondary Surveillance Radar	Primary Surveillance Radar, Secondary Surveillance Radar, ADS-B (WAAS), Multilateration	Primary Surveillance Radar, Secondary Surveillance Radar, ADS-B (GBAS), Multilateration
Clearance Delivery	Simple Clearance for Turns, Routes, Takeoff, Landing, and Crossing Delivered using Voice-Based Communications	Simple Clearance for Turns, Routes, Takeoff, Landing, and Crossing Delivered using Voice-Based Communications	Complex 4D-Trajectory Clearances Delivered using Datalink
Airport Surface Operations Planner	None	Spot Release Planner, Runway Scheduler	Complete 4D-Trajectory Planner (Possibly Integrated with Collaborative

			Arrival Departure Planner)
Clearance Information	None	Gate, Runway, Taxiway, Clearance Information Pertaining to Crossings, Takeoffs and Landings	Complete 4D Trajectory
Flight Deck Automation	None	Airport Situational Awareness Display	Automation Supporting Situational Awareness, Guidance & Control for 4D Trajectories, Conflict Detection

IV. CD&R Automation Requirements

Whereas the preceding section discussed the technology requirements for the implementation of the CD&R automation system, functional requirements for the same system will be detailed in this section. Figure 8 shows the functional flow diagram of the envisaged CD&R automation system. Each function is shown as a block in different colors with a brief description of the inputs and outputs. The figure also shows the flow of information and the sequence in which the individual functions are executed. Further descriptions of the functions as to their purpose, inputs, outputs are presented in the following sub-sections. Detailed descriptions of the algorithms are beyond the scope of the current paper. They will be presented in a future publication.

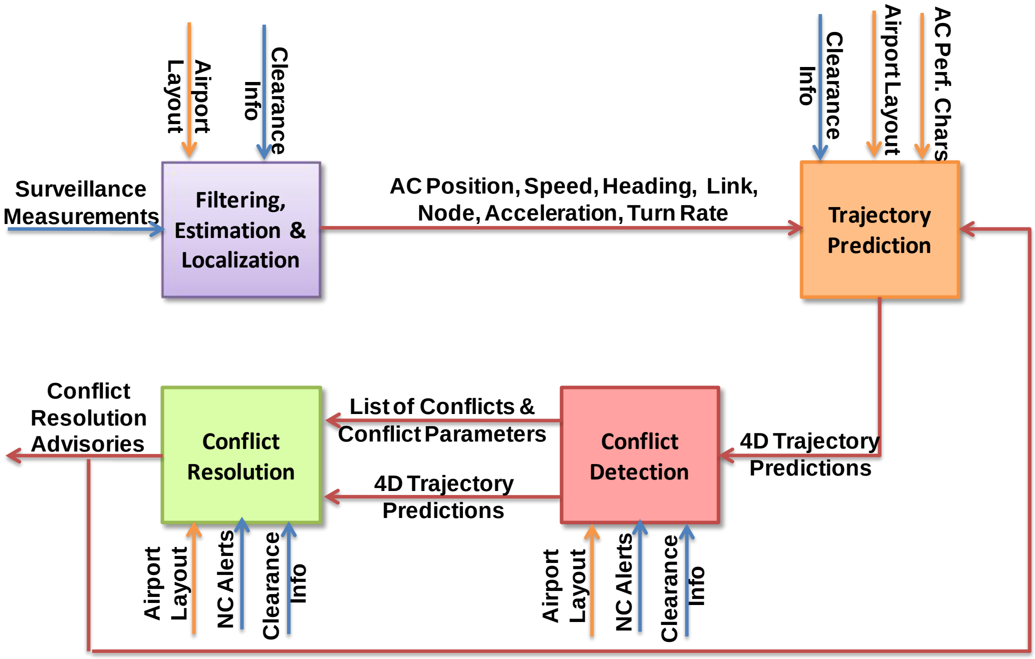


Figure 8. Functional Flow Diagram of the Envisaged CD&R Concept

A. Filtering, Estimation & Localization

Purpose: The purposes of this function are as follows:

(i) Filter Surveillance Data: Surveillance data is typically noisy which can impact the performance of the CD&R. Low-pass filters could be used to reduce the noisy nature of the raw surveillance measurements.

(ii) Estimate Higher-Order State Variables: Surveillance data depending on the actual surveillance system in use could contain limited aircraft state data. For example, the speed and heading of the aircraft are not directly measurable using current-day surveillance systems such as primary surveillance radar. The estimation function in this case would estimate the speed and heading angle of the aircraft. The estimation function can also be used to estimate acceleration level states which can be used to better predict the aircraft's future motion, in turn leading to more accurate conflict detection.

(iii) Localize the Aircraft: Whereas the surveillance data generates position coordinates of the aircraft with respect to some reference frame, it is of interest to map these coordinates on to the geometric layout of the airport and associate a link and node to each aircraft.

Inputs: Surveillance measurements. The nature of these measurements is dependent upon the type of surveillance system (e.g., PSR, ADS-B). The number of aircraft states available for measurement, their accuracy and update rate can be different for individual surveillance systems.

Outputs: Aircraft state vector. The aircraft state vector can consist of multiple pieces of aircraft information such as position (x, y) coordinates, link, node, speed, heading, and possibly acceleration and turn-rate also. The number of components of the state vector depends on their observability with respect to the available surveillance measurements.

B. Trajectory Prediction

Purpose: A rigorous approach to predicting conflicts requires accurate prediction of aircraft trajectories. An essential precursor to the prediction of trajectories is the inference trajectory parameters such as the route, speed, and turn rates. The parameters are then used to synthesize 4D trajectories suitable for conflict detection. Trajectory prediction can be done from a strategic perspective using intent information and also from a tactical perspective using only the current aircraft state information. Tactical trajectory prediction will also be useful for ground vehicles of which the intent is not necessarily known to the automation system. Another level of sophistication in trajectory prediction involves the usage of stochastic trajectory models to represent the uncertainty associated with the trajectory predictions.

Inputs: AC state estimates from the filtering, estimation, and localization module, layout of the airport, configuration of the airport, aircraft performance characterstics, and most importantly clearance information (if available, including conflict resolutions).

Outputs: Time history of the aircraft position variables (t, x, y, z) starting from the current time and ending at some selected time instant in the future. Stochastic trajectory predictions are also expected to output the uncertainty associated with the predictions using a probability distribution.

C. Conflict Detection

Purpose: The purpose of conflict detection function is to parse the 4D-trajectory predictions and determine if any pair of aircraft is expected to violate required safety criteria. The predicted states of every pair of aircraft are evaluated using a conflict definition. Conflict definition involves defining the conflicts in terms of a pair of aircraft states using mathematical and logical operators. The definition of conflict could simply be that two aircraft be separated by a certain pre-chosen distance or it could be more complex as is the case with runway incursions.

Inputs: Inputs for this function are the predicted 4D trajectories and non-conformance alerts.

Outputs: Conflicting aircraft IDs, time to conflict, location of the conflict, predicted minimum separation.

D. Conflict Resolution

Purpose: The purpose of the conflict resolution function is to stop or slow aircraft or cancel clearances as needed to avoid a collision or violation, re-plan aircraft movements to recover from the conflict situation, and issue advisories.

Inputs: List of conflicts and conflict parameters from the Conflict Detection module and non-conformance alerts from conformance monitoring function.

Outputs: In the near-term and mid-term NextGen timeframe, clearance advisories will take the form of the current voice communications that tell the flights to stop, go behind another aircraft, depart, cross, go around, and change taxi route. In the far term it is anticipated that advisories can be in the form of 4D trajectories.

V. Preliminary Results

OSI has developed deterministic trajectory prediction algorithms, deterministic conflict detection algorithms and conflict resolution algorithms suitable for mid-term operations. The current section describes the closed-loop simulation results obtained using these algorithms. The block diagram of the validation platform is shown in Figure 9. The performance of the CD&R algorithm is evaluated using a Monte-Carlo simulation framework. Different conflict scenarios were scripted in the GoSAFE planner for the purpose of these validation exercises; these artificial situations may not necessarily be encountered in the real world, e.g., operational procedures may be defined to prevent their occurence. The scenarios were developed for the Dallas/Ft. Worth International Airport (DFW) airport.

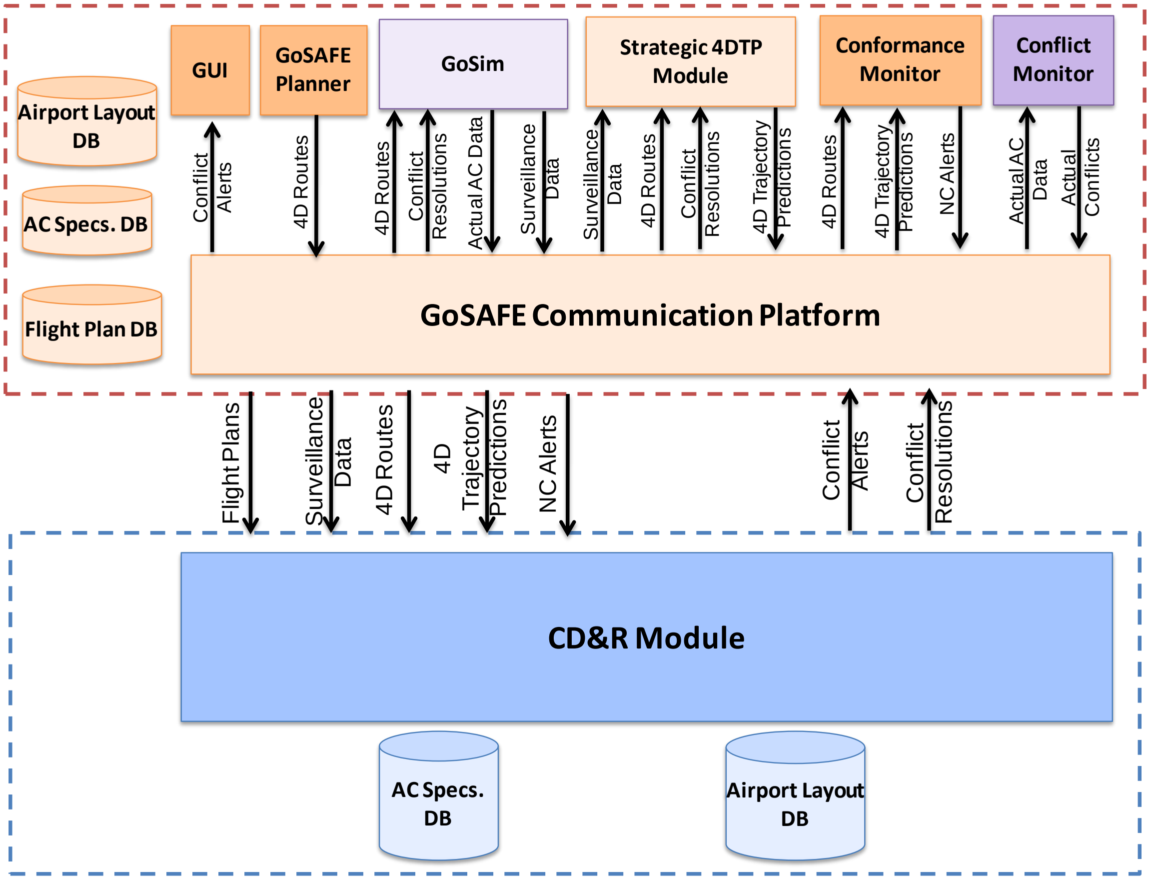


Figure 9. Block Diagram of the Validation Platform

A. Monte-Carlo Simulations

Monte-Carlo simulations are a standard approach to evaluate the performance of stochastic systems. In the current context they provide the ideal framework for evaluating the effect of random uncertainties such as surveillance errors, planning errors, and aircraft simulation errors. The same scenario is simulated a number of times using a different error sample in each run. In the current validation exercise only surveillance errors are varied in each Monte-Carlo run.

The performance of conflict detection algorithm is characterized by the following metrics:

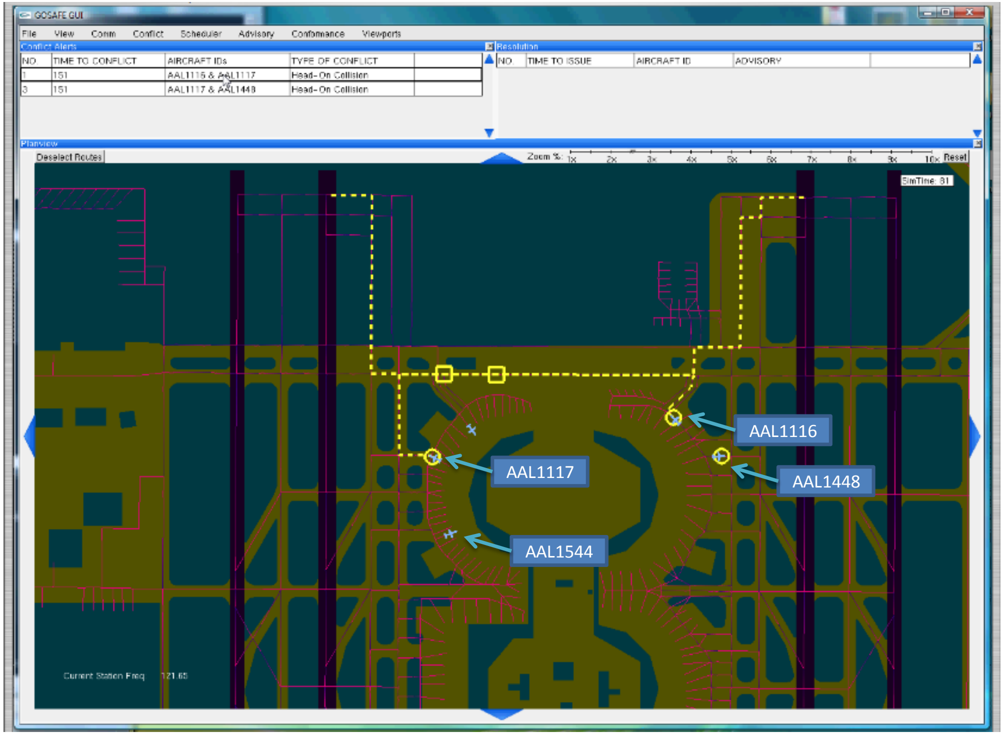
- Number of runs involving at least one missed primary conflict
- Time to conflict

The performance of the conflict resolution algorithm is characterized by the following metrics:

- Number of secondary conflicts
- Number of aircraft halted
- Number of aircraft rescheduled
- Delay incurred by the aircraft

B. Taxiway Head-On Collision

Figure 10 shows a snapshot of a taxiway head-on collision between flight AAL1117 and flight AAL1116 detected 170 seconds before the occurrence of the conflict. The conflicting aircraft are indicated by yellow circles and the locations of the aircraft at the time of the conflict are indicated in yellow squares. AAL1117 would make a right turn on to the link occupied by AAL1116 and AAL1448 at the time of conflict.



Conflict Alerts

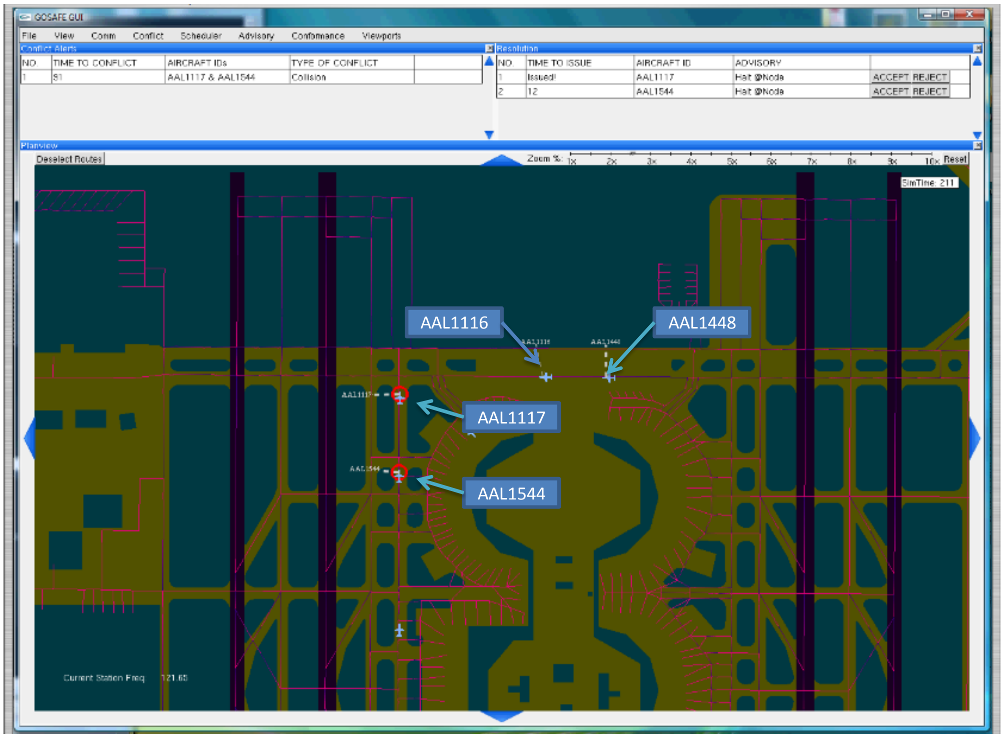
NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT	
1	151	AAL1116 & AAL1117	Head-On Collision	
3	151	AAL1117 & AAL1448	Head-On Collision	

Resolution

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY	

Figure 10. Snapshot of the CD&R GUI Capturing the Head-On Collision

The conflict resolution algorithm in this case first issues a halt advisory to AAL1117. However, this leads to a secondary conflict with AAL1544 which results in a halt advisory for AAL1544 as shown in Figure 11. The conflict resolution algorithm then computes new schedules for the two aircraft along the same taxiway routes that were assigned to them before the conflict.



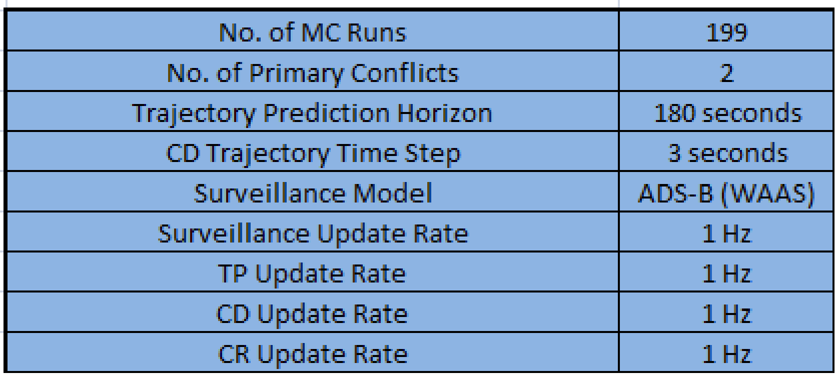
NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT	
1	81	AAL1117 & AAL1544	Collision	

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY	
1	Issued!	AAL1117	Halt @Noda	ACCEPT REJECT
2	12	AAL1544	Halt @Noda	ACCEPT REJECT

Figure 11. Snapshot of the CD&R GUI with the Halt Advisories Issued

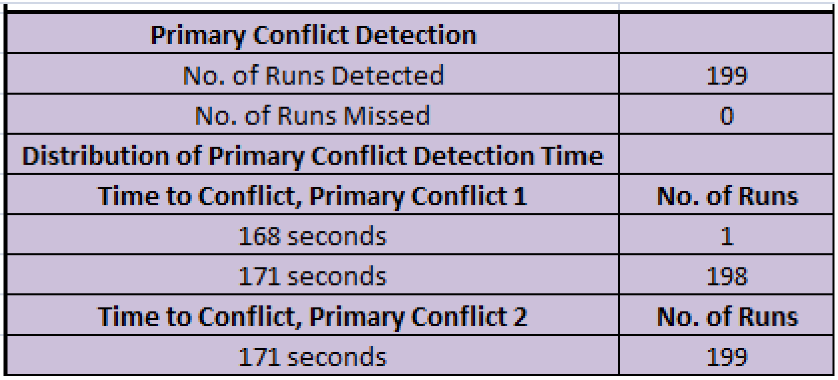
The performance of the CD&R algorithm has been evaluated in 199 Monte-Carlo simulations runs, each run resulting in a different surveillance time history. The Monte-Carlo simulation settings for this scenario are shown in Table 8. The CD trajectory time step refers to the time discretization used by the conflict detection algorithm. TP refers to trajectory prediction. The performance of the conflict detection and conflict resolution algorithms are shown in Table 9 and Table 10, respectively. The primary conflict is identified in all Monte-Carlo runs at least 168 seconds before the occurrence of the conflict. It should be noted that the time horizon for trajectory prediction is 180 seconds which also would be the upper limit on the "Time to Conflict."

Table 8. Monte-Carlo Simulation Settings



No. of MC Runs	199
No. of Primary Conflicts	2
Trajectory Prediction Horizon	180 seconds
CD Trajectory Time Step	3 seconds
Surveillance Model	ADS-B (WAAS)
Surveillance Update Rate	1 Hz
TP Update Rate	1 Hz
CD Update Rate	1 Hz
CR Update Rate	1 Hz

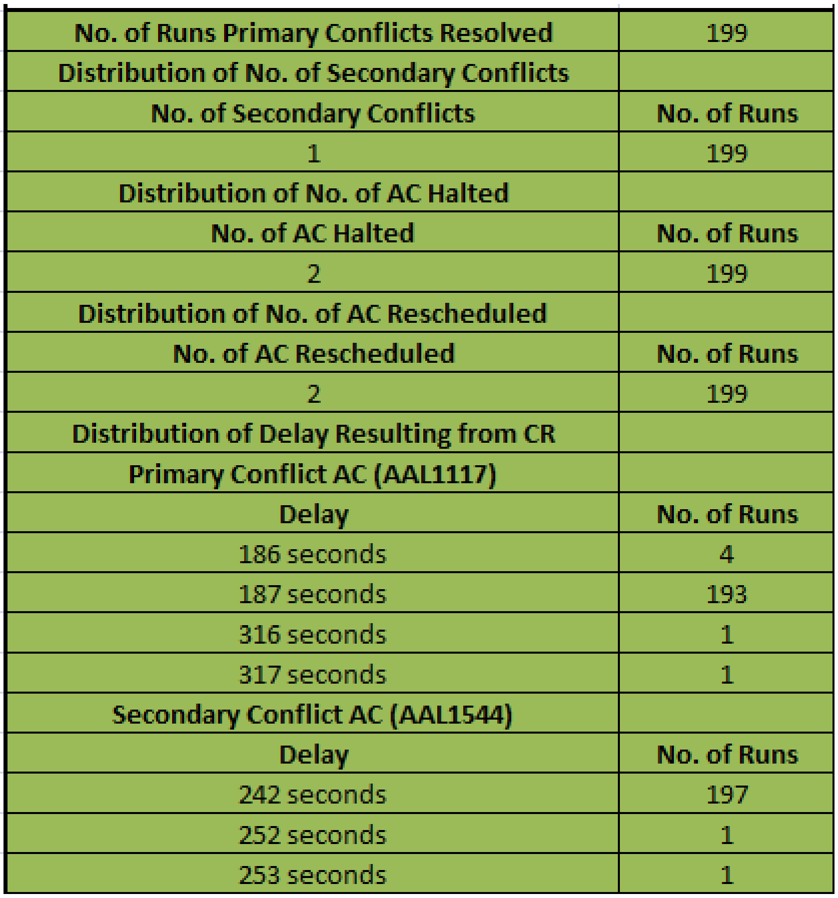
Table 9. Conflict Detection Performance



Primary Conflict Detection	
No. of Runs Detected	199
No. of Runs Missed	0
Distribution of Primary Conflict Detection Time	
Time to Conflict, Primary Conflict 1	**No. of Runs**
168 seconds	1
171 seconds	198
Time to Conflict, Primary Conflict 2	**No. of Runs**
171 seconds	199

The performance of the conflict resolution is consistent in all but one Monte-Carlo run that resulted in a delay of 316 seconds for AAL1117.

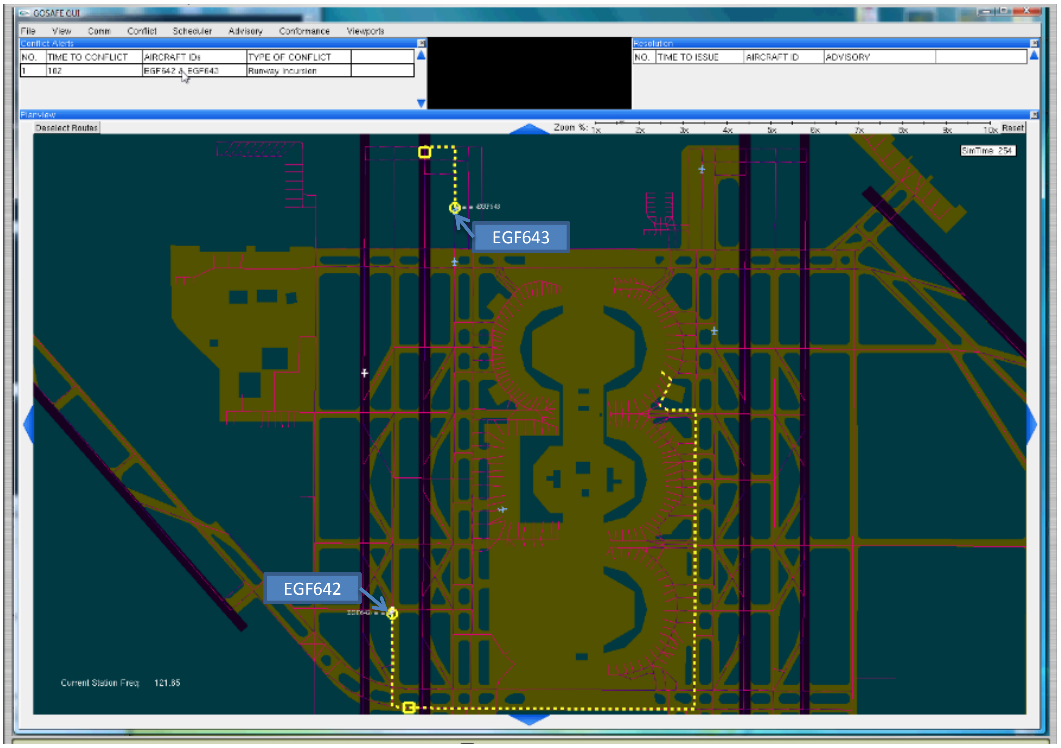
Table 10. Conflict Resolution Performance



No. of Runs Primary Conflicts Resolved	199
Distribution of No. of Secondary Conflicts	
No. of Secondary Conflicts	**No. of Runs**
1	199
Distribution of No. of AC Halted	
No. of AC Halted	**No. of Runs**
2	199
Distribution of No. of AC Rescheduled	
No. of AC Rescheduled	**No. of Runs**
2	199
Distribution of Delay Resulting from CR	
Primary Conflict AC (AAL1117)	
Delay	**No. of Runs**
186 seconds	4
187 seconds	193
316 seconds	1
317 seconds	1
Secondary Conflict AC (AAL1544)	
Delay	**No. of Runs**
242 seconds	197
252 seconds	1
253 seconds	1

C. Runway Incursion Scenario 1

The runway incursion scenario shown in Figure 12 involves a departure aircraft, EFG643, and an arrival aircraft, EFG642, which has just landed and is attempting to cross the same runway. In the current implementation of the conflict resolution algorithm for runway incursions, all the crossing aircraft are stopped and the departure aircraft are given precedence in using the runway. Figure 13 shows the halt advisories issued to EFG642 (in the upper right table of the display) as well as another crossing aircraft, AAL1118, which was supposed to cross the runway after EFG643 and before AAL730. The conflict resolution algorithm instead allows the two departure flights EFG643 and AAL730 to take off first and then issues the clearance for the crossing flights EFG642 and AAL1118. The second departure flight AAL730 benefits from this resolution and departs 23 seconds earlier. Detailed descriptions of the performance metrics is given in Table 11–Table 13.



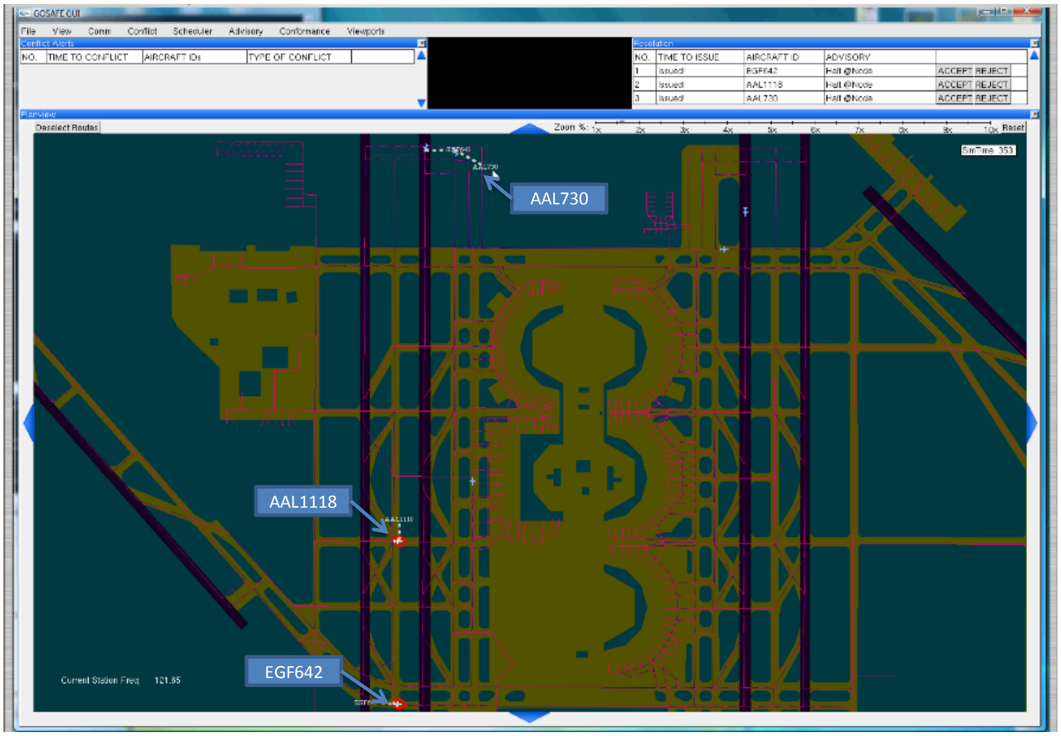
Conflict Alerts

NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT
1	102	EGF642 & EGF643	Runway Incursion

Resolution

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY

Figure 12. Snapshot of the CD&R GUI after the Runway Incursion Is Detected



Conflict Alerts

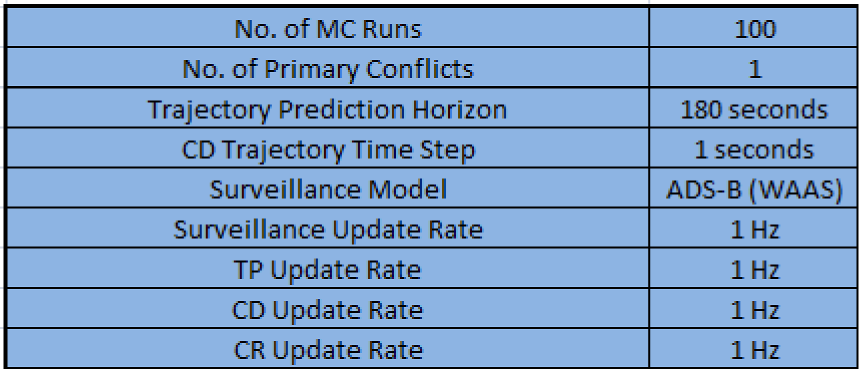
NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT

Resolution

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY	
1	Issued	EGF642	Halt @Node	ACCEPT REJECT
2	Issued	AAL1118	Halt @Node	ACCEPT REJECT
3	Issued	AAL730	Halt @Node	ACCEPT REJECT

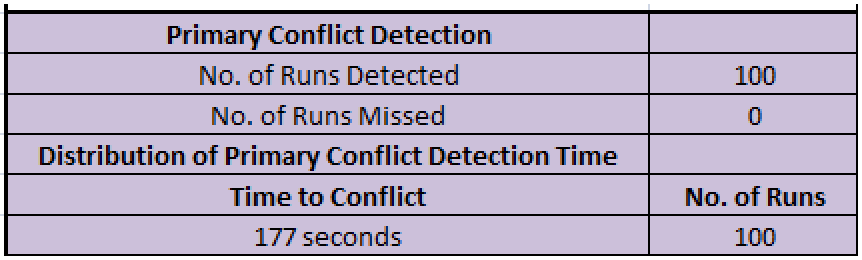
Figure 13. Snapshot of the CD&R GUI after the Halt Advisories Are Issued

Table 11. Monte-Carlo Simulation Settings



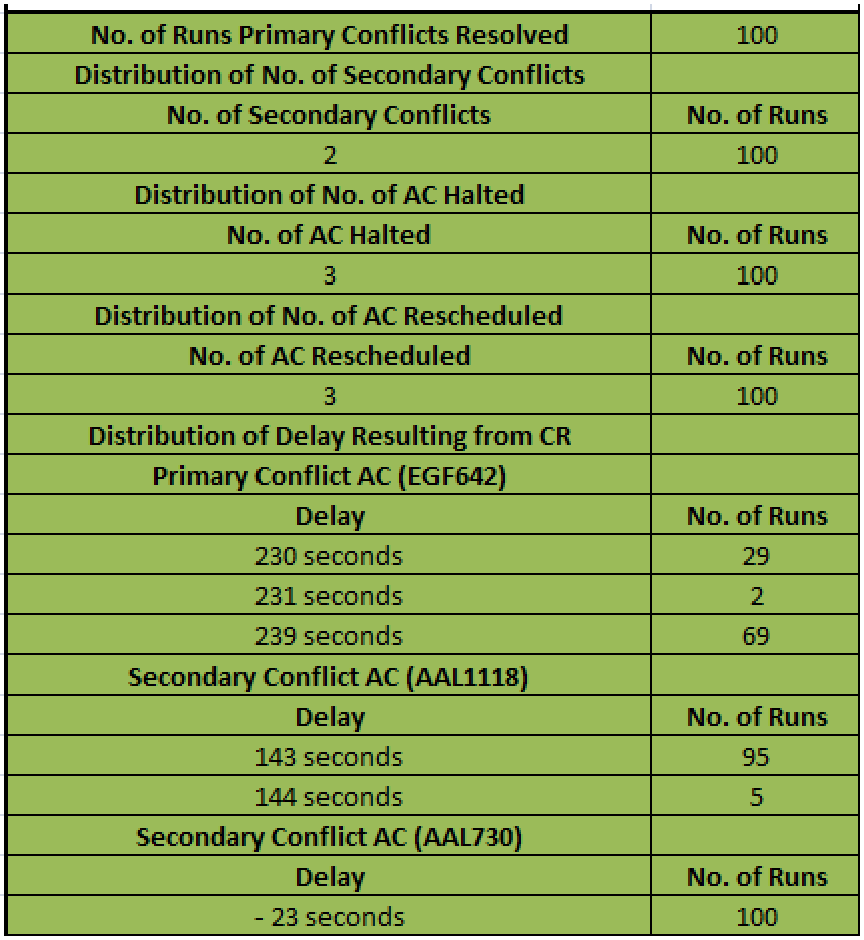
No. of MC Runs	100
No. of Primary Conflicts	1
Trajectory Prediction Horizon	180 seconds
CD Trajectory Time Step	1 seconds
Surveillance Model	ADS-B (WAAS)
Surveillance Update Rate	1 Hz
TP Update Rate	1 Hz
CD Update Rate	1 Hz
CR Update Rate	1 Hz

Table 12. Conflict Detection Performance



Primary Conflict Detection	
No. of Runs Detected	100
No. of Runs Missed	0
Distribution of Primary Conflict Detection Time	
Time to Conflict	**No. of Runs**
177 seconds	100

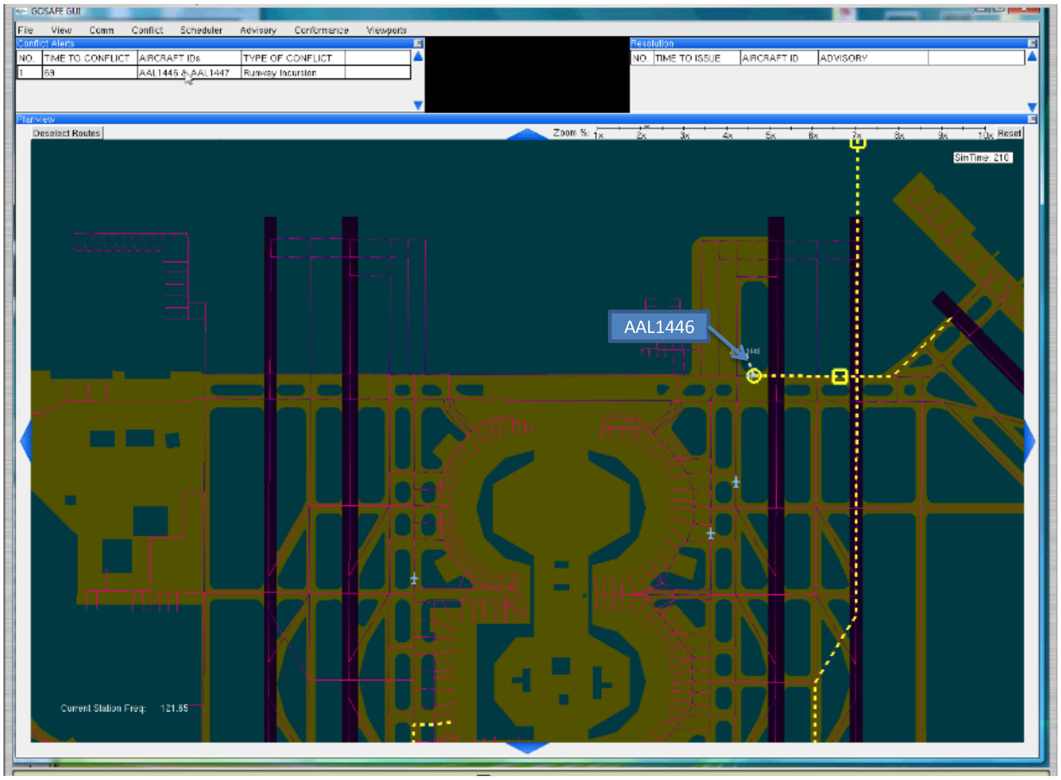
Table 13. Conflict Resolution Performance



No. of Runs Primary Conflicts Resolved	100
Distribution of No. of Secondary Conflicts	
No. of Secondary Conflicts	**No. of Runs**
2	100
Distribution of No. of AC Halted	
No. of AC Halted	**No. of Runs**
3	100
Distribution of No. of AC Rescheduled	
No. of AC Rescheduled	**No. of Runs**
3	100
Distribution of Delay Resulting from CR	
Primary Conflict AC (EGF642)	
Delay	**No. of Runs**
230 seconds	29
231 seconds	2
239 seconds	69
Secondary Conflict AC (AAL1118)	
Delay	**No. of Runs**
143 seconds	95
144 seconds	5
Secondary Conflict AC (AAL730)	
Delay	**No. of Runs**
- 23 seconds	100

D. Runway Incursion Scenario 2

The previous runway incursion scenario involved a conflict between departing aircraft and crossing aircraft. The current scenario involves a crossing aircraft, AAL1446, and an arrival aircraft, AAL1447, which is about to land. The locations of the conflicting aircraft at the time of the conflict are shown with yellow squares in Figure 14. Conflict resolution issues a halt advisory to AAL1446 which results in a secondary conflict with AAL1118 that is also halted as shown in Figure 15. Both flights AAL1446 and AAL1118 are issued new schedules. The performance of the CD&R algorithm evaluated using Monte-Carlo simulations is given in Table 14–
Table 16.



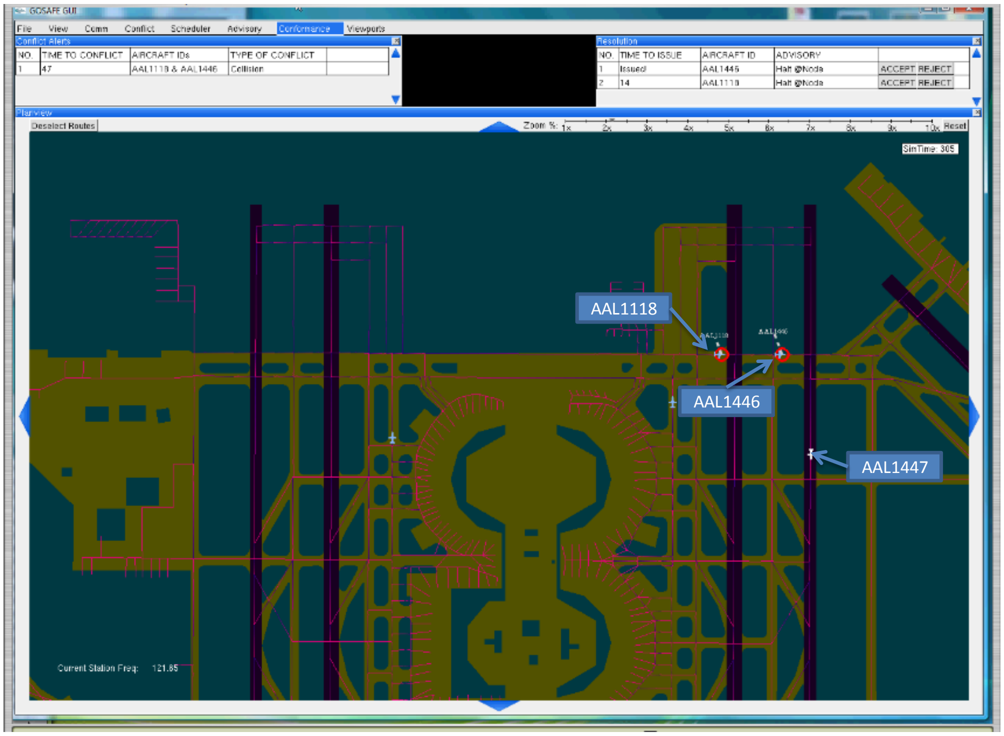
Conflict Alerts

NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT
1	69	AAL1446 & AAL1447	Runway Incursion

Resolution

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY

Figure 14. Snapshot of the GUI after the Runway Incursion Is Detected



NO.	TIME TO CONFLICT	AIRCRAFT IDs	TYPE OF CONFLICT
1	47	AAL1118 & AAL1446	Collision

NO.	TIME TO ISSUE	AIRCRAFT ID	ADVISORY	
1	Issued	AAL1446	Halt @Node	ACCEPT REJECT
2	14	AAL1118	Halt @Node	ACCEPT REJECT

Figure 15. Snapshot of the GUI after the Halt Advisories Are Issued

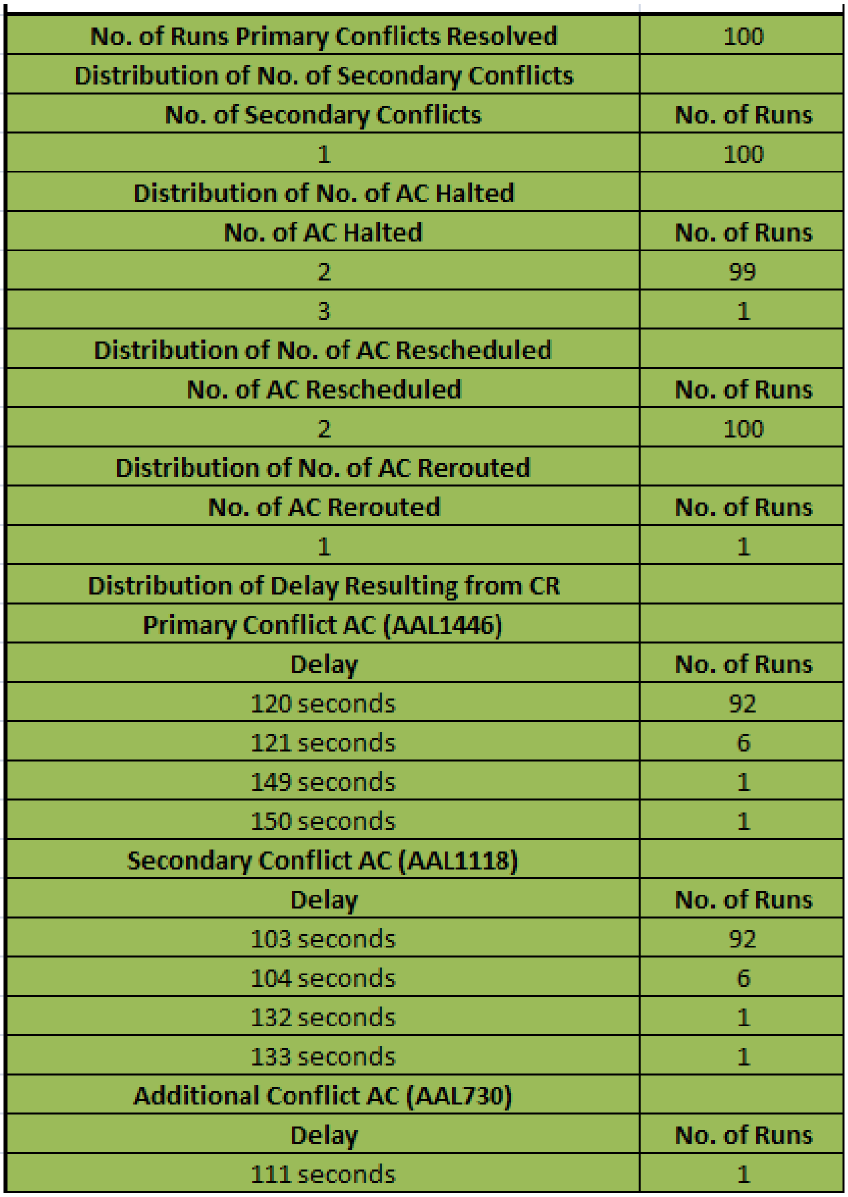
Table 14. Monte-Carlo Simulation Settings

No. of MC Runs	100
No. of Primary Conflicts	1
Trajectory Prediction Horizon	180 seconds
CD Trajectory Time Step	3 seconds
Surveillance Model	ADS-B (WAAS)
Surveillance Update Rate	1 Hz
TP Update Rate	1 Hz
CD Update Rate	1 Hz
CR Update Rate	1 Hz

Table 15. Conflict Detection Performance

Primary Conflict Detection	
No. of Runs Detected	100
No. of Runs Missed	0
Distribution of Primary Conflict Detection Time	
Time to Conflict	**No. of Runs**
105 seconds	1
108 seconds	99
Distribution of Additional Conflict Detection Time	
Time to Conflict	**No. of Runs**
0 seconds	1

Table 16. Conflict Resolution Performance



No. of Runs Primary Conflicts Resolved	100
Distribution of No. of Secondary Conflicts	
No. of Secondary Conflicts	**No. of Runs**
1	100
Distribution of No. of AC Halted	
No. of AC Halted	**No. of Runs**
2	99
3	1
Distribution of No. of AC Rescheduled	
No. of AC Rescheduled	**No. of Runs**
2	100
Distribution of No. of AC Rerouted	
No. of AC Rerouted	**No. of Runs**
1	1
Distribution of Delay Resulting from CR	
Primary Conflict AC (AAL1446)	
Delay	**No. of Runs**
120 seconds	92
121 seconds	6
149 seconds	1
150 seconds	1
Secondary Conflict AC (AAL1118)	
Delay	**No. of Runs**
103 seconds	92
104 seconds	6
132 seconds	1
133 seconds	1
Additional Conflict AC (AAL730)	
Delay	**No. of Runs**
111 seconds	1

VI. Conclusion

The paper discusses the role of a surface conflict detection and resolution automation system in the context of near-term, mid-term, and far-term operations. It draws out the differences in the enabling technologies that are expected to be available to the conflict detection and resolution system in the three different timeframes. Functional requirements generated as part of this paper are expected to form the basis for the design of conflict detection and resolution algorithms. Preliminary closed-loop simulation results indicate the importance of intent-based trajectory prediction algorithms for effective conflict detection as well as resolution. Work related to development as well improvement of the algorithms for estimation, localization, trajectory prediction, conflict detection, and conflict resolution is currently in progress.

Acknowledgments

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