National Aeronautics and Space Administration

Safely Conducting Airport Surface Trajectory-Based Operations

Denise Jones, Lance Prinzel, Randy Bailey, and Trey Arthur,
NASA Langley Research Center
Jim Barnes, Booz Allen Hamilton Engineering Services, LLC

denise.r.jones@nasa.gov
www.nasa.gov

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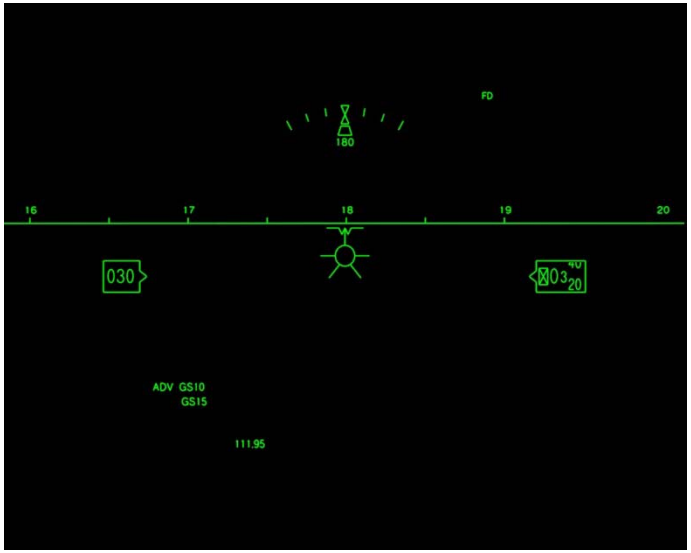
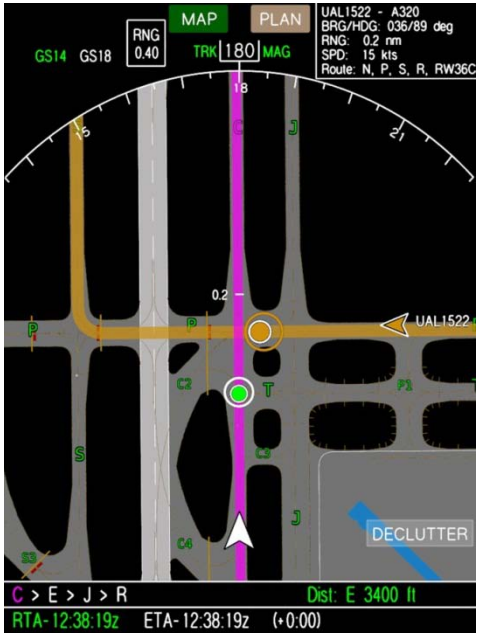
Surface Trajectory-Based Operations (STBO)

- NextGen concept of time-based surface operations to safely optimize the airport traffic flow to maximize aircraft throughput
- Advantages: reduced taxi times, departure queues, runway crossing wait times, fuel burn, environmental emissions
- Surface traffic management systems for air traffic control: airport configuration management, runway assignment, scheduling and sequencing, taxi routing
- Datalink of time-based taxi clearances to flight deck
- Effective flight deck presentation methods that enable STBO conformance





Objectives

- Evaluate ability to safely conduct Surface Trajectory Based Operations (STBO), by assessing the impact of:
  - Traffic intent information
  - Conflict Detection and Resolution (CD&R) system capability
  - Display of speed/time-based guidance information on the Airport Moving Map (AMM) and head-up display (HUD)

Definitions:

- CD&R – Conflict detection and resolution in the airport environment, 3 miles from the runway threshold and below 1000 ft AGL

Environment

- Research Flight Deck with motion
- Memphis (KMEM) airport
- 1800 ft RVR
- Transport category aircraft model
- Simulated ATC environment, human back-up
- ATC instructions via voice & data-link
- Head and eye tracking system
- ADS-B for traffic data

Research Flight Deck

- Electronic Flight Bags (EFB) – maximum primary field-of-view (AC 25-11A)
- HUD – left seat only

ADS-B Model

- Gauss-Markov process to simulate time correlation between position measurement errors
- ADS-B transmission qualities and effects not modeled
- Positional data updated at 1 Hz rate
- NACp accuracy levels can be assigned to traffic individually

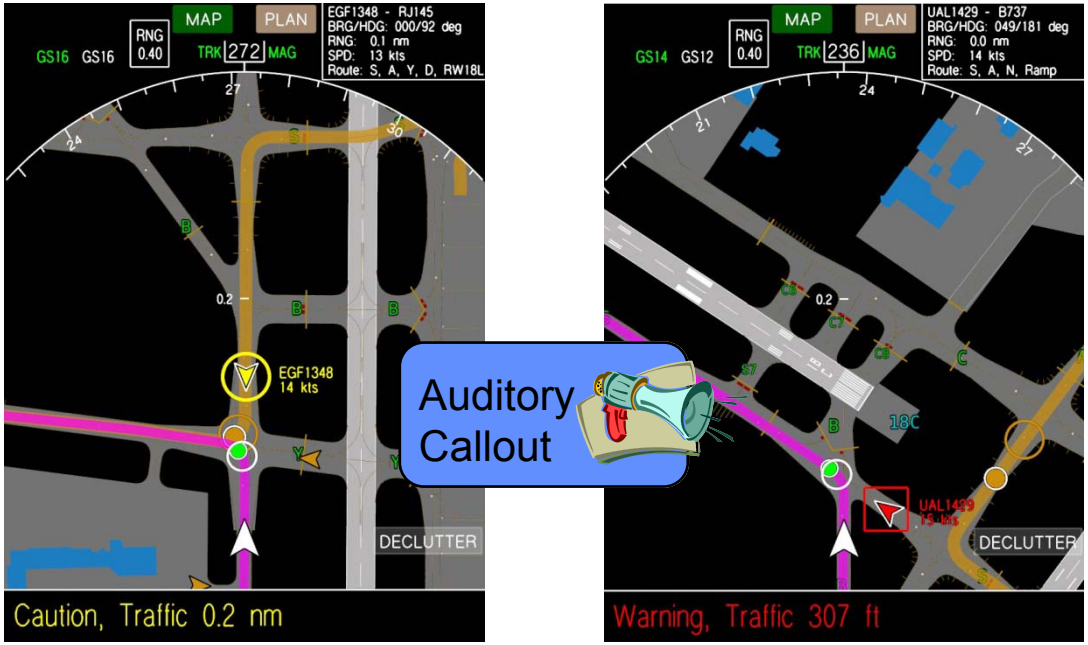
Definitions:

- NACp = Navigation Accuracy Category - Position
- 95% horizontal accuracy bound means that 95% of the time the horizontal position value will be within the bound listed
- EPU = Estimated Position Uncertainty

NACp	95% Horizontal Accuracy Bound (EPU)
9	EPU < 30 m (99 ft)
10	EPU < 10 m (33 ft)
11	EPU < 3 m (9.9 ft)

Conflict Detection & Resolution (CD&R)

- NASA algorithm research used for taxiway conflict alert generation
- Utilizes traffic surveillance information from ADS-B In
- NACp 10 and 11 traffic qualified for CD&R application
- Alerts
  - Caution – for conditions that require immediate flight crew awareness and subsequent flight crew response
  - Warning – for conditions that require immediate flight crew awareness and immediate flight crew response



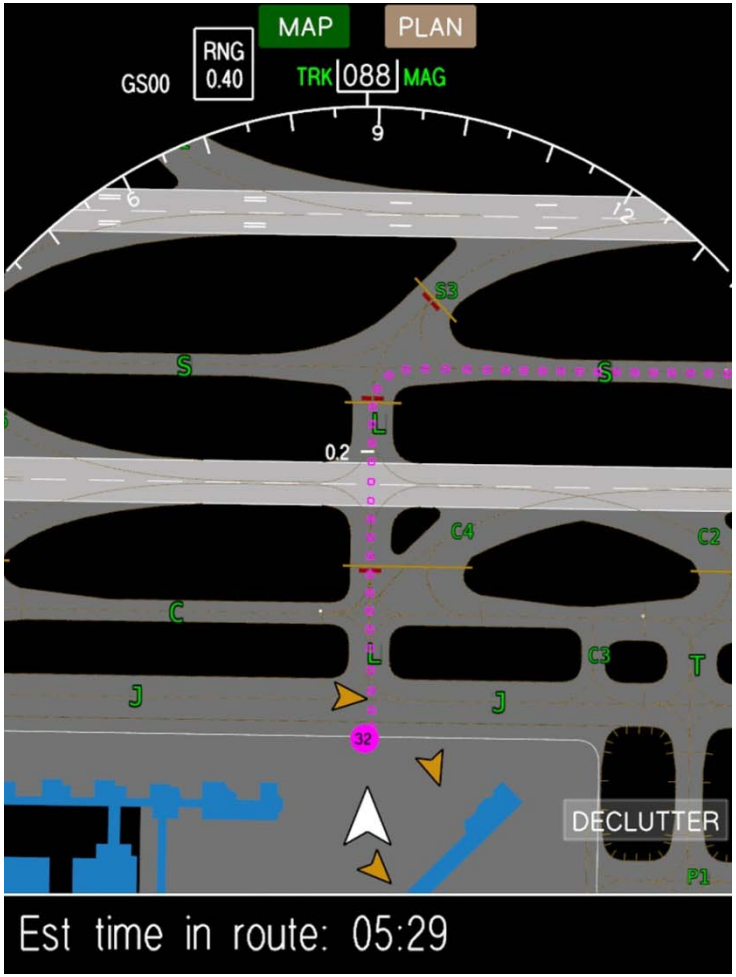
Test Method

- 6 test trials per crew (4 nominal, 2 off-nominal)
- 2 AMM display conditions shown on EFB only
- HUD – 2 conditions
- Traffic position accuracy mix of NACp 9 to 11 (all traffic displayed on AMM)
- Taxi from ramp to runway hold line
- Follow ATC instructions and STBO guidance
- ATC instructions verbal and data-linked (EFB interface)
- 12 commercial flight crews
- Crews briefed and trained with concept

STBO Taxi Procedure

- After operate, expected taxi clearance received via datalink only.

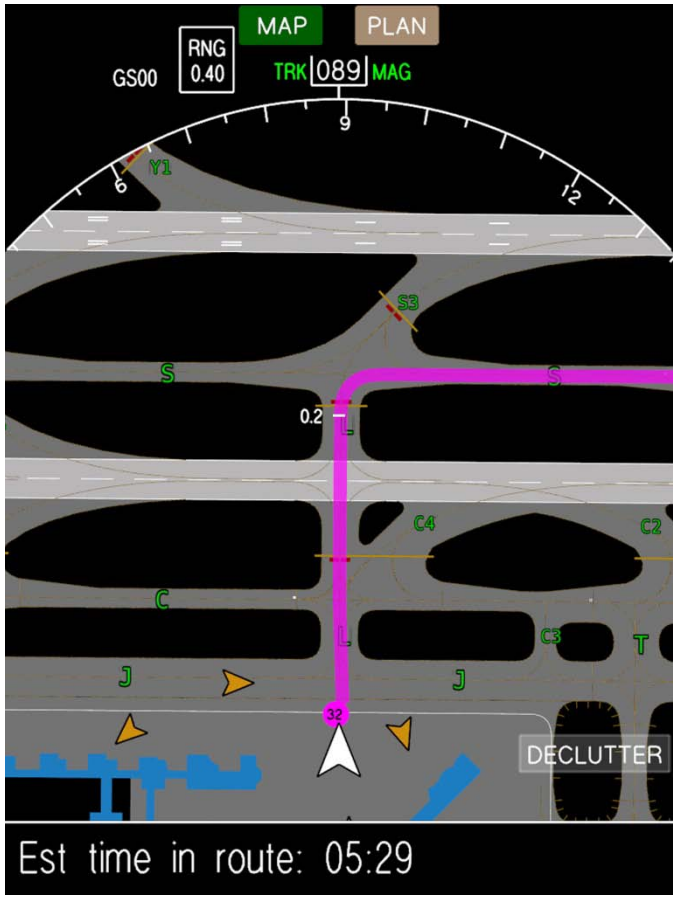
  "Expect taxi to Rwy X from Spot X via x-x-x with expected taxi release time 12:32:00z. Monitor ground 121.9."



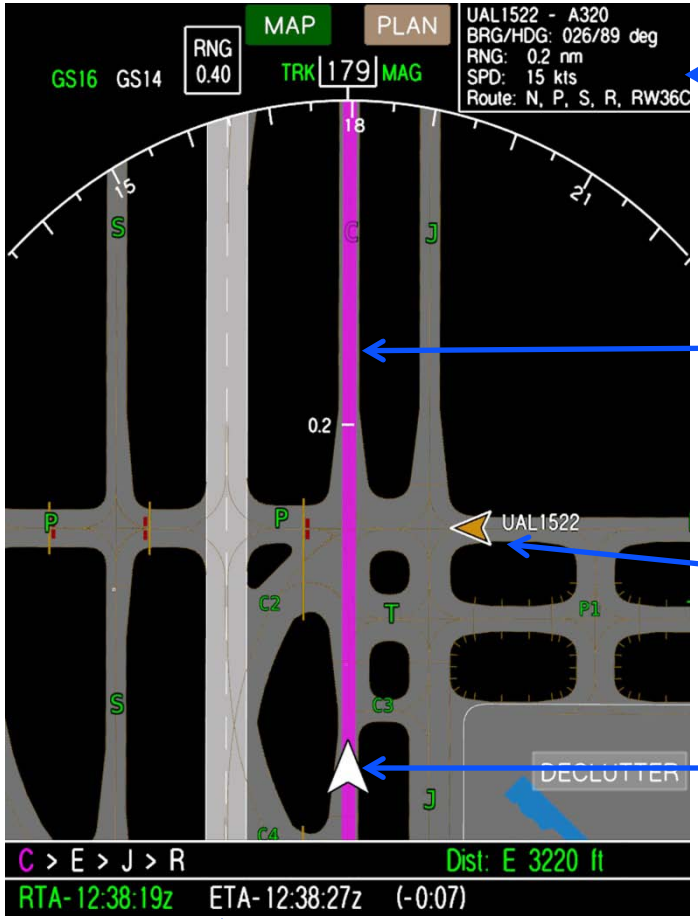
STBO Taxi Procedure Continued

- After taxi to spot, taxi clearance received via voice and data-link.

  "Taxi to Rwy X by 12:38:49z via x-x-x. Taxi release time 12:32:00z."
- Crew responded to taxi clearance via voice and data-link.
- Began taxi as close to taxi release time as possible. Notified ATC commencing taxi.



Map C Display Condition



Selected Traffic Information

Advised GS

Own route

RTA Point

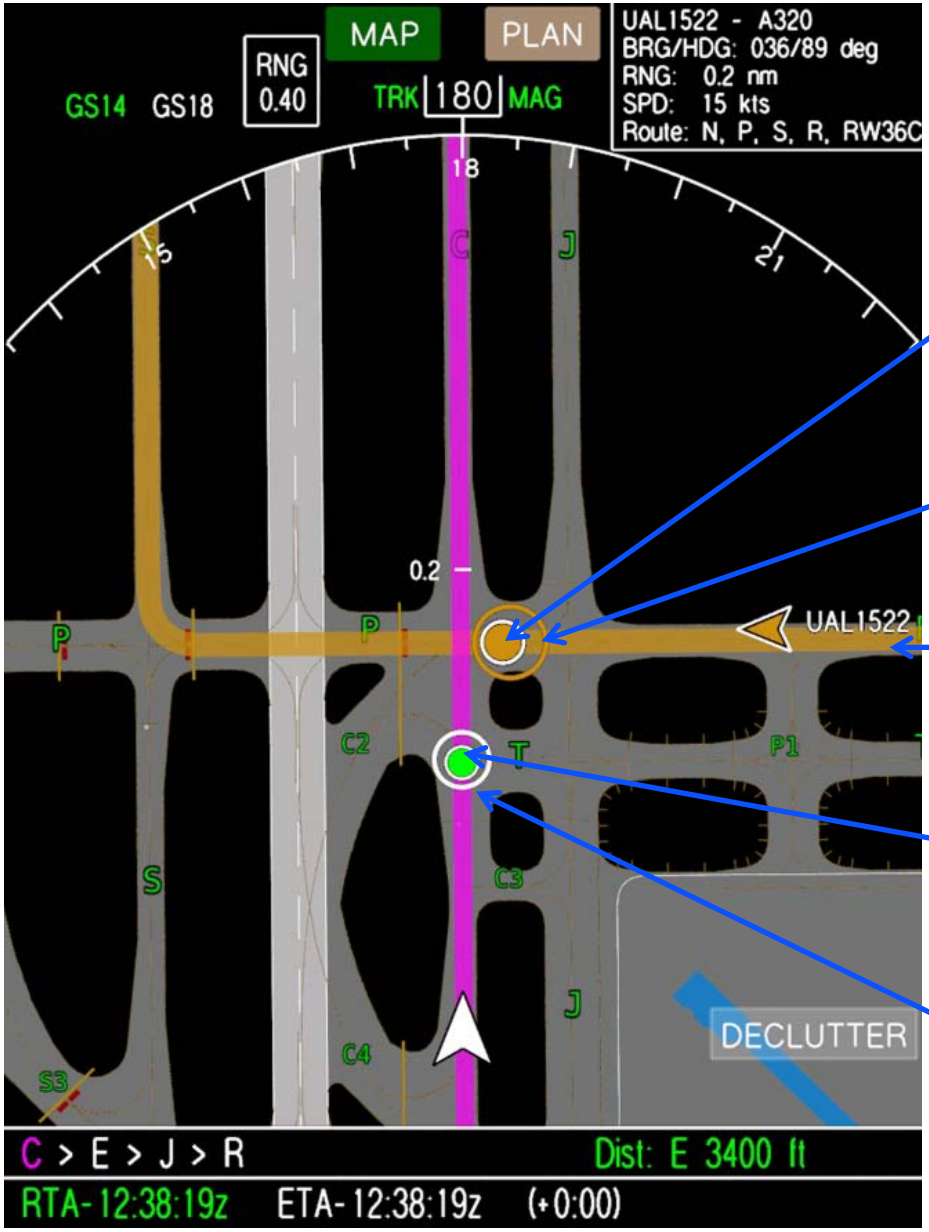
Traffic

Ownship

RTA, ETA, Time early/late

- Advised GS (ground speed)
  - Used as a reference – not required to track precisely
  - Never > 30 kts, 5 kts in turns
- Acceptable performance if met RTA within +/- 15 seconds

Map D Display Condition



Selected Traffic Intent Symbol - Indication of position required in 30 seconds to achieve RTA

Selected Traffic's Trend Symbol - Indication of position in 30 seconds based on planned speed required to meet RTA

Traffic route

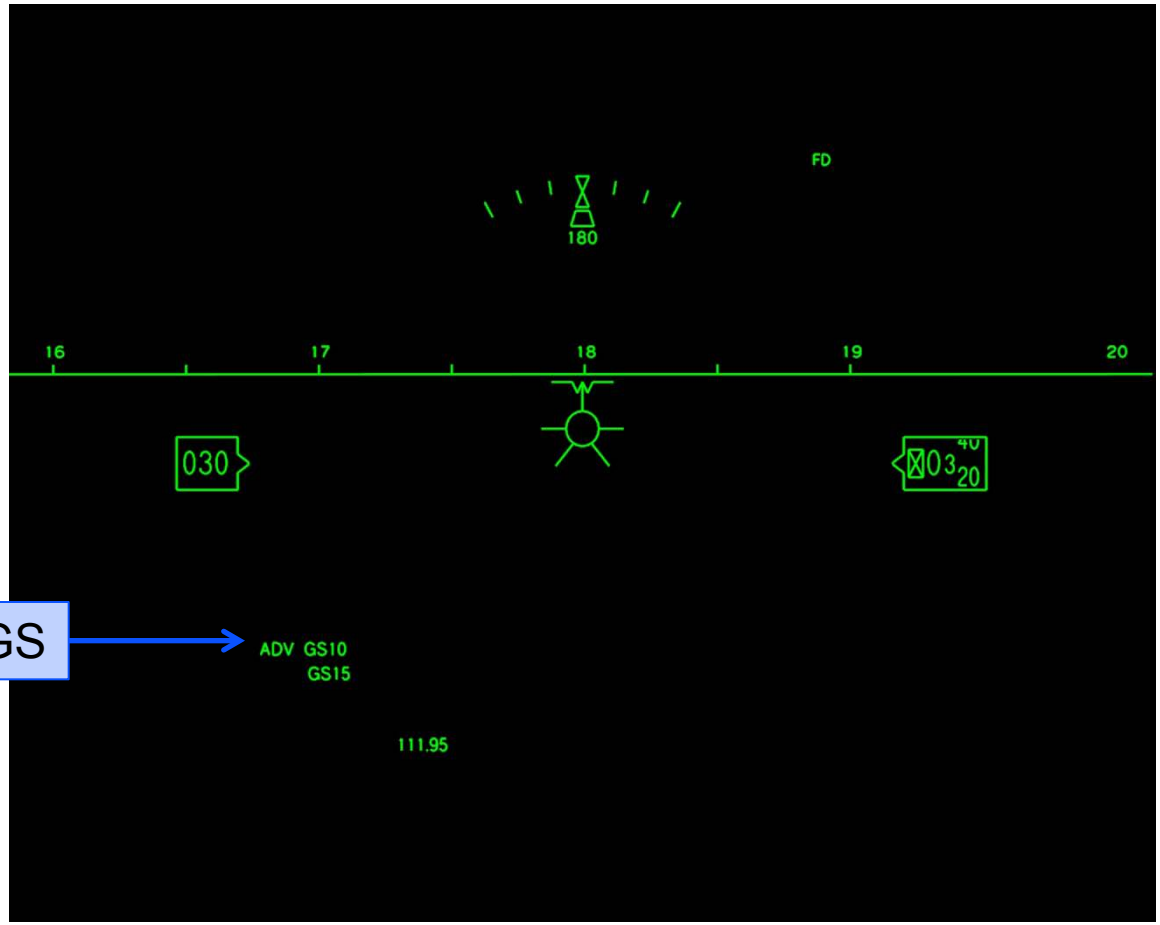
Ownship Intent symbol - Indication of position required in 30 seconds to achieve RTA

Ownship trend symbol - Indication of position in 30 seconds based on planned speed required to meet RTA

HUD Display

Two HUD Conditions

1. No HUD
2. HUD with standard symbology and STBO guidance information



Experimental Design

Nominal Trials – Evaluate flight crew's performance in following STBO taxi guidance using HUD and AMM symbology

- 4 departure taxi scenarios
- Independent variables: map condition, HUD
- AMM conditions between subjects, blocked by HUD condition

	No HUD	HUD
Map C	☐	☐
Map D	☐	☐

- Map C shows textual traffic information and ownship STBO guidance
- Map D shows textual and graphical traffic intent and ownship and traffic STBO guidance

Experimental Design Continued

Off-Nominal Trials - Evaluate collision avoidance capability during STBO surface operations – usefulness of traffic intent information and CD&R

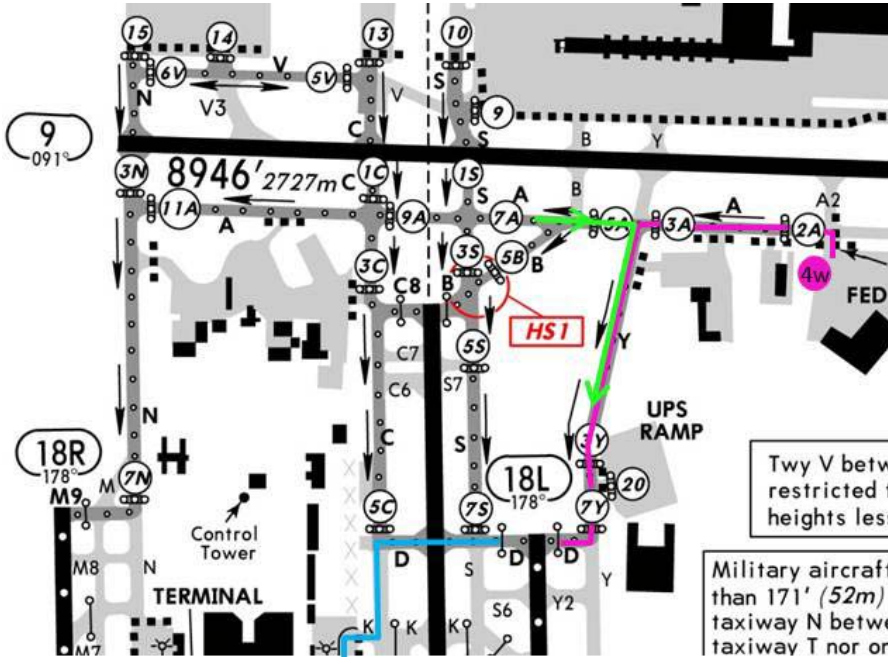
- 2 off-nominal trials, Test Runs 3 and 6 of 6 trials
- No HUD
- Data collected with 3 crews for each cell in table for each off-nominal

Map Condition	Conflict Traffic NACp 9	Conflict Traffic NACp 10
C	☐	☐
D	☐	☐

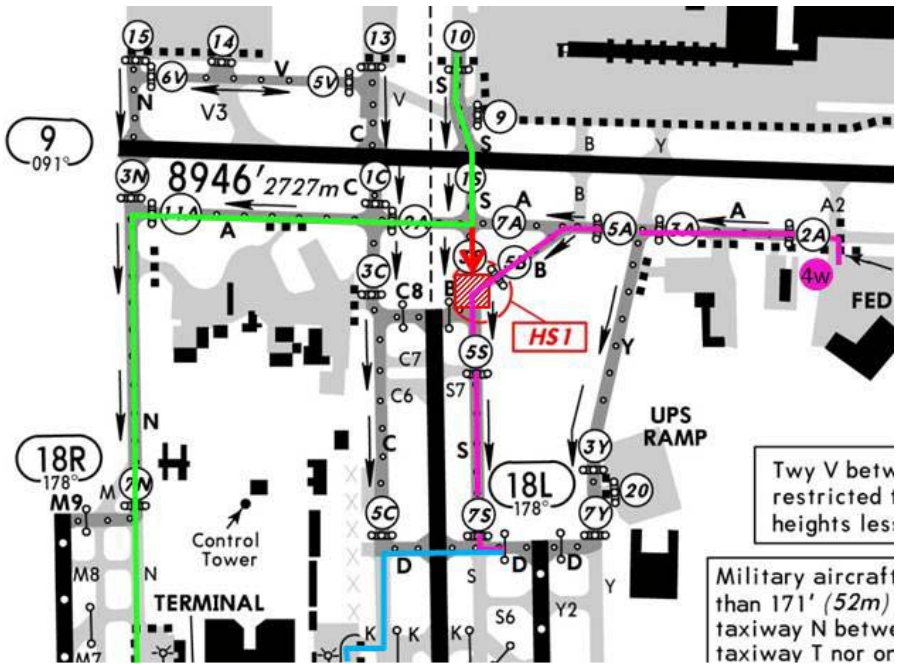
- No alerts with NACp 9, alerts with NACp 10 accuracy

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Off-Nominal Scenarios



Taxi Head-on



Taxi Intersection

- Magenta path represents ownship taxi clearance

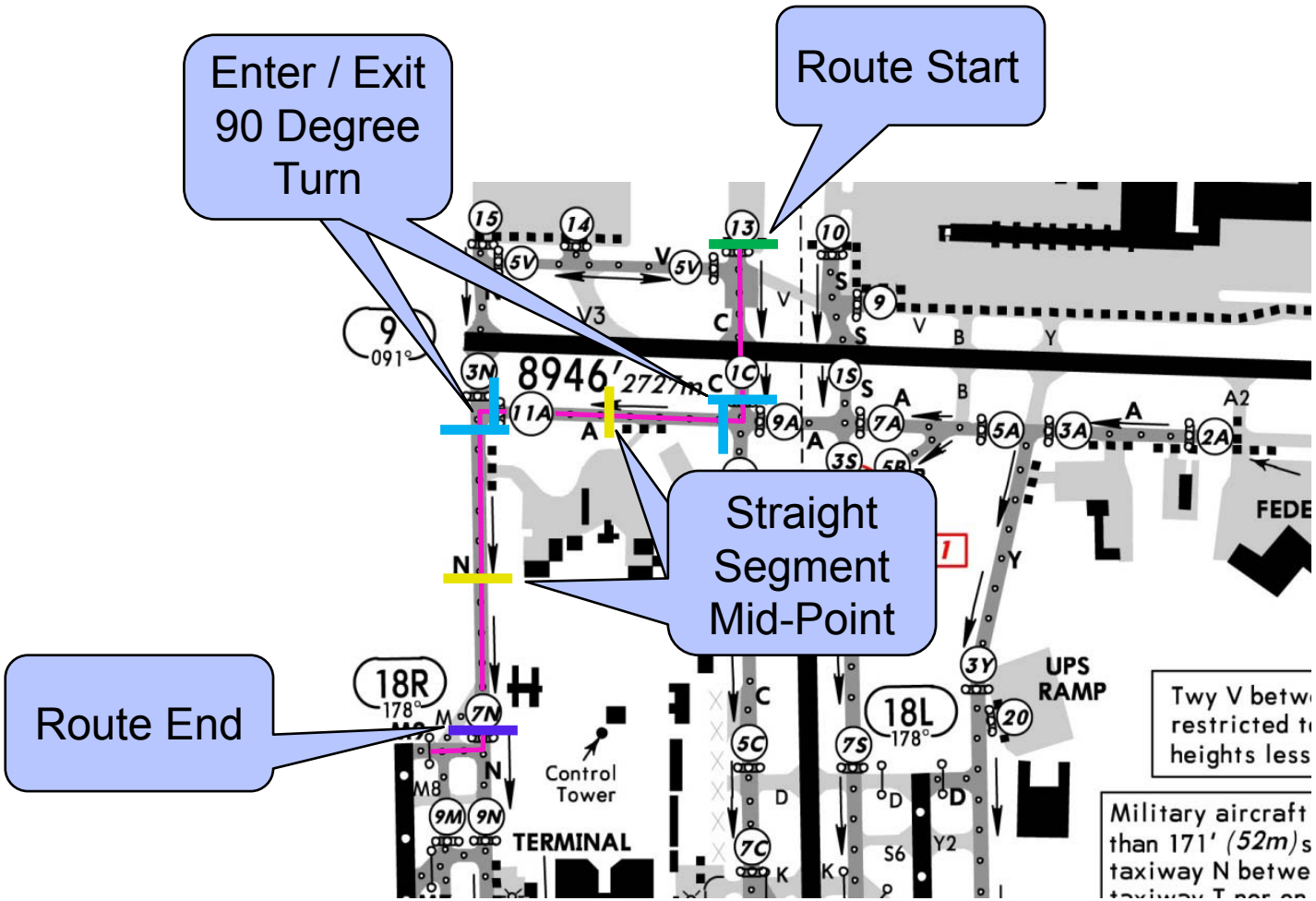
Metrics

For taxi conflicts –

- Near collision
  - Horizontal distance < 185 ft
- Collision
  - Horizontal distance < 150 ft

* Distance is between CGs (center-of-gravity)

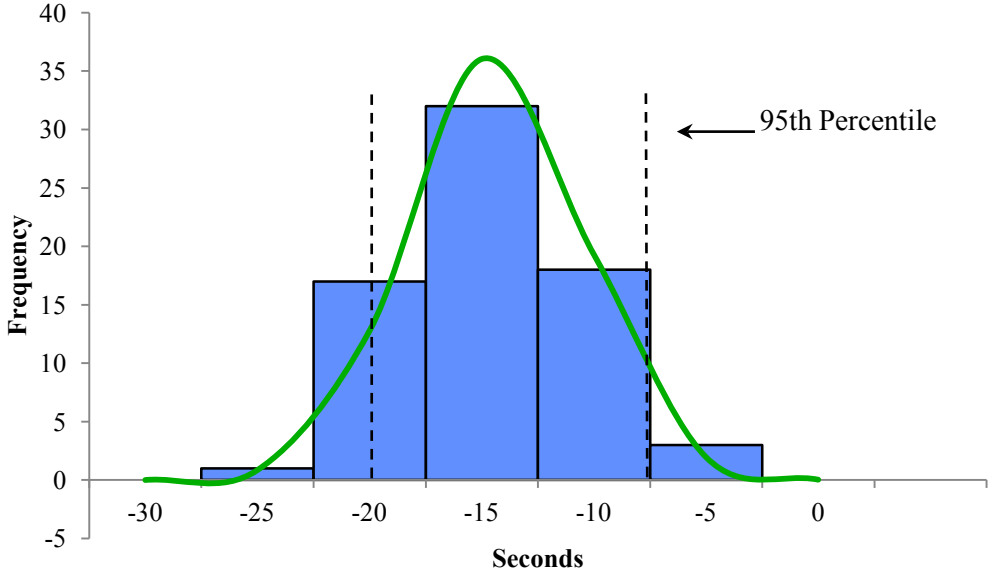
Results – STBO Taxi Conformance



Results – STBO Taxi Conformance

STBO Route Start Location

- Crew to begin taxi as close as possible to taxi release time
- Data for all STBO trials analyzed (nominal and off-nominal)
- Conformance measurement negative (late) for all trials
- Due to engine spool up
- Maintained +/- 15 seconds of guidance on 54.9% of trials (39 of 71)
- No significant effects for Map or HUD condition



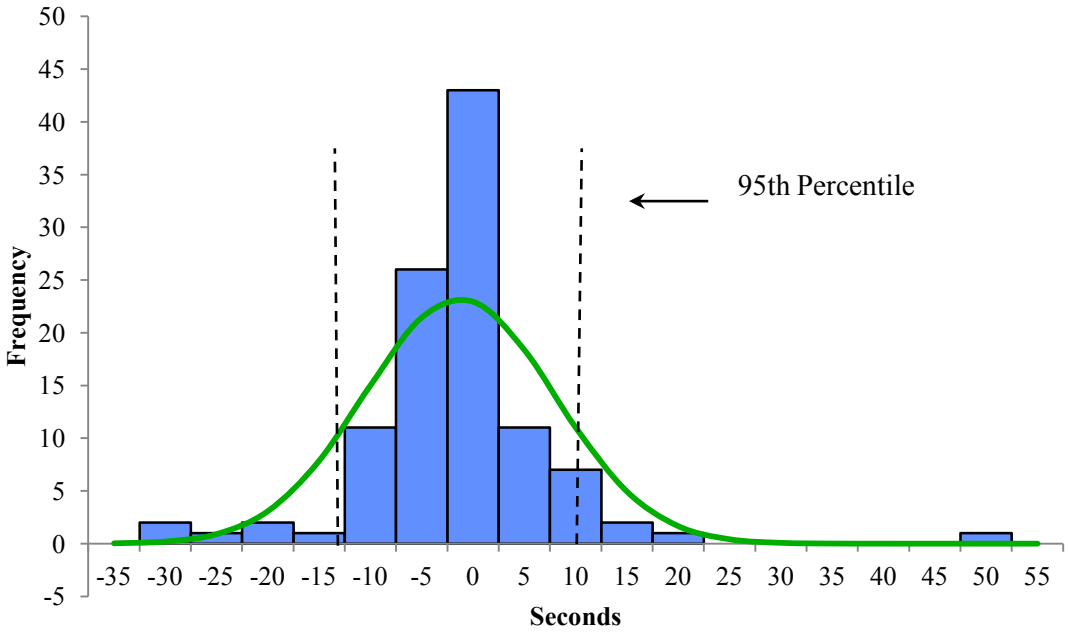
Map	HUD	Mean	SD	N
C	No	-13.54	3.61	24
	Yes	-15.35	3.74	12
	Total	-14.14	3.70	36
D	No	-14.57	4.27	23
	Yes	-14.71	3.91	12
	Total	-14.62	4.09	35
C+D	No	-14.04	3.94	47
	Yes	-15.03	3.75	24
	Total	-14.38	3.88	71

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Results – STBO Taxi Conformance

STBO Straight Segment Mid-Point Locations

- Mid-point of straight taxi segment
- Data for all STBO trials analyzed (nominal and off-nominal)
- Maintained +/- 15 seconds of guidance on 92.6% of segments (100 of 108)
- Significant effect for HUD condition, better conformance using HUD



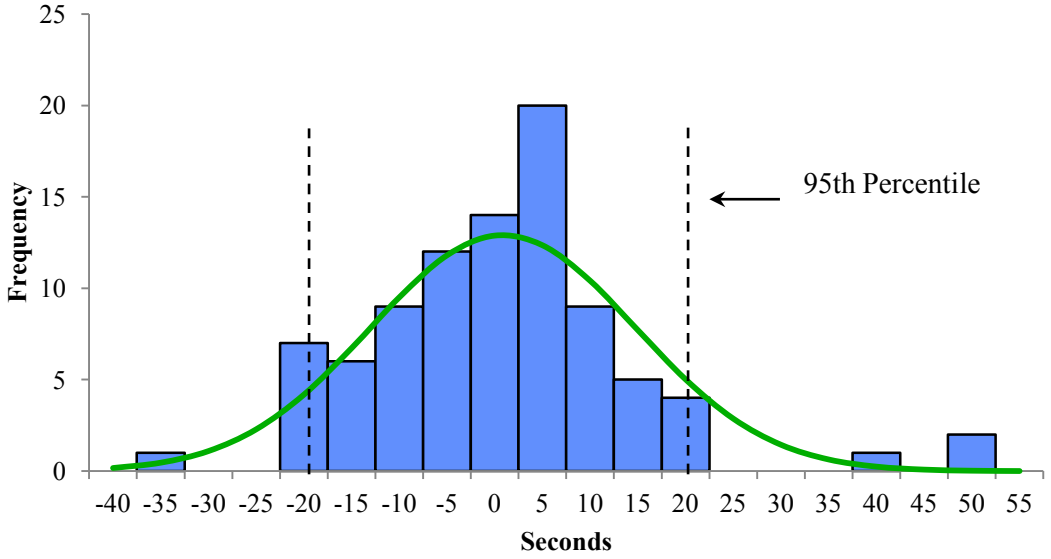
Map	HUD	Mean	SD	N
C	No	-3.25	7.16	36
	Yes	-1.47	6.75	18
	Total	-2.65	7.01	54
D	No	-1.93	8.66	36
	Yes	3.70	14.22	18
	Total	-0.05	11.02	54
C+D	No	-2.59	7.91	72
	Yes	1.12	11.28	36
	Total	-1.35	9.28	108

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Results – STBO Taxi Conformance

STBO Entering 90 Degree Turn Locations

- 20 seconds prior to center of turn based on planned route guidance
- Data analyzed for nominal trials only, no 90 degree turns during off-nominals
- On 3 trials using Map D wrong turn made, data not available, thought their aircraft was at location of trend symbol and turned early
- 3 trials outliers, held for taxiing traffic and very late entering turn
- Conformance early 51.1% of turns (46 of 90 trials)
- Maintained +/- 15 seconds of guidance on 78.9% of turns (71 of 90)
- No significant effects for Map or HUD condition



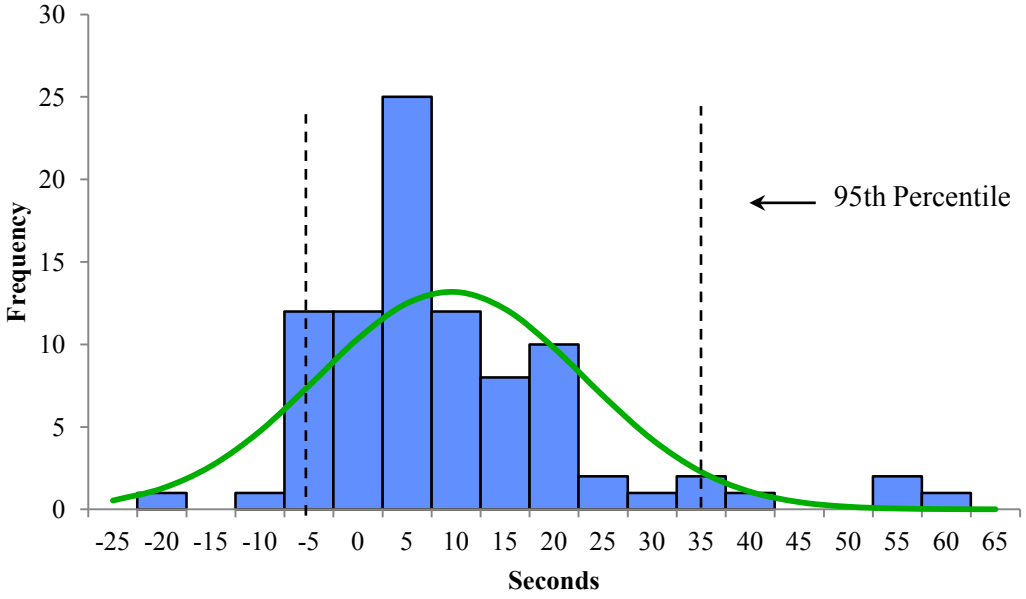
Map	HUD	Mean	SD	N
C	No	0.22	11.11	23
	Yes	-2.51	10.81	23
	Total	-1.14	10.93	46
D	No	0.62	16.30	21
	Yes	5.17	16.41	23
	Total	3.00	16.33	44
C+D	No	0.41	13.66	44
	Yes	1.33	14.28	46
	Total	0.88	13.91	90

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Results – STBO Taxi Conformance

STBO Exiting 90 Degree Turn Locations

- 20 seconds after the center of turn based on planned route guidance
- Conformance early 77.8% of turns (70 of 90)
- Actual turn speed higher (9.48 kts mean, 2.7 kts SD) than advised speed (4.47 kts mean, 1.36 kts SD)
- Maintained +/- 15 seconds of guidance on 73.3% of turns (66 of 90)
- No significant effects for Map or HUD condition
- Many pilots began going into turns late so could take turn faster



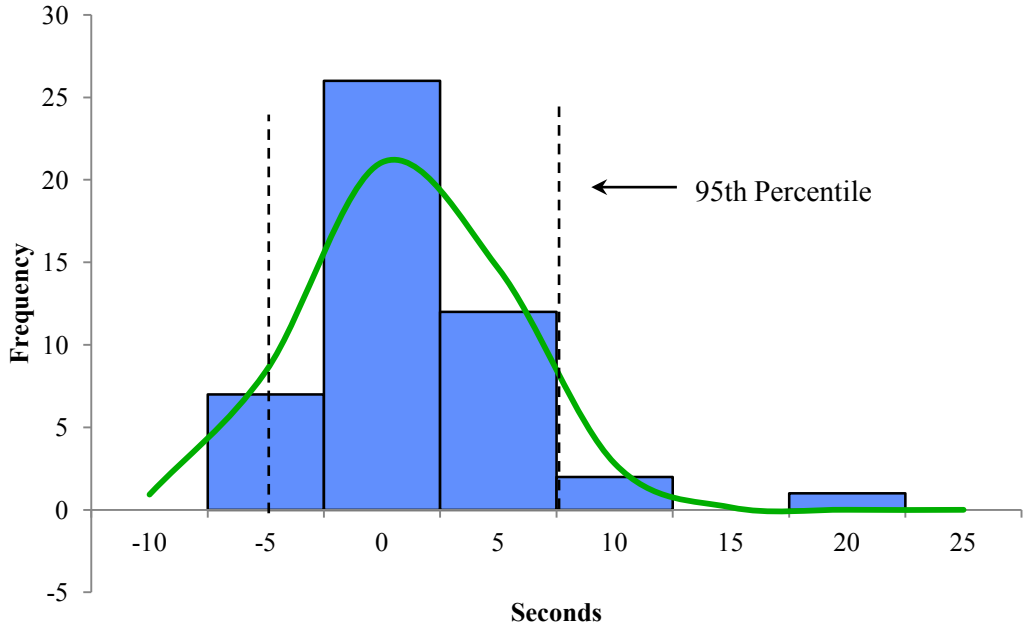
Map	HUD	Mean	SD	N
C	No	7.61	8.13	23
	Yes	6.29	8.70	23
	Total	6.95	8.36	46
D	No	10.21	17.30	21
	Yes	13.82	17.34	23
	Total	12.09	17.21	44
C+D	No	8.85	13.22	44
	Yes	10.05	14.09	46
	Total	9.47	13.61	90

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Results – STBO Taxi Conformance

STBO Route End Location

- End of STBO taxi route guidance (green diamond)
- Data analyzed for nominal trials only, end of route never reached during off-nominal trials
- Acceptable performance if within +/- 15 sec of Required-time-of-arrival
- Within +/- 10 seconds of RTA on 97.9% of trials (46 of 47)
- Very early conformance on one trial due to focus on oncoming traffic
- No significant effects for Map or HUD condition



Map	HUD	Mean	SD	N
C	No	0.72	2.75	12
	Yes	0.1	2.97	12
	Total	0.41	2.82	24
D	No	3.63	6.05	12
	Yes	-0.14	4.71	11
	Total	1.83	5.67	23
C+D	No	2.17	4.83	24
	Yes	-0.01	3.81	23
	Total	1.1	4.45	47

Map C – textual traffic intent and ownship STBO guidance
Map D – textual and graphical traffic intent and ownship and traffic STBO guidance

Taxi Head-on Off-nominal Scenario Results

- Trial 3 of 6 trials

	NACp 9	NACp 10
Map C (textual intent)	2 stopped, 1 slowed: 3 utilized traffic intent	3 slowed: 2 near collision 3 utilized traffic intent
Map D (graphical intent)	2 stopped, 1 slowed: 3 utilized traffic intent	2 stopped, 1 slowed: 1 near collision 3 utilized traffic intent

- All crews slowed or stopped for traffic to turn ahead
- All crews utilized traffic intent information
- All pilots aware of conflict traffic on each trial, prior to alerts (when issued)

Taxi Intersection Off-nominal Scenario Results

- Trial 6 of 6 trials

	NACp 9	NACp 10
Map C (textual intent)	2 stopped, 1 slowed: 2 near collisions 3 utilized traffic intent	3 stopped: 1 near collision 2 utilized traffic intent
Map D (graphical intent)	1 stopped, 2 turned in front: 1 near collision, 2 collision 3 utilized traffic intent	3 stopped: 3 utilized traffic intent

- 11 of 12 crews (92%) utilized traffic intent information
- One or both pilots aware of conflict traffic on each trial
- 1 crew (Map C, NACp 10) did not utilize traffic intent, First Officer was not aware of conflict traffic, Captain aware but assumed traffic would hold, stopped based on receiving Caution alert
- Both crews that turned in front of conflict traffic were early (8 and 10 seconds) in following their planned STBO taxi guidance, traffic overran ownship

STBO Results

- Compared to current surface operational procedures, STBO would neither increase or decrease workload (4.2 mean, 2.0 SD) but would increase general situation awareness (6.2 mean, 1.2 SD)
- STBO would moderately increase efficiency (5.0 mean, 1.6 SD) and safety (5.0 mean, 2.0 SD) for ground movement of aircraft
- STBO would moderately increase head-down time compared to current-day operations (4.8 mean, 2.0 SD)
- To perform STBO adequately, info should be located on:
  - AMM on ND – 18 votes
  - HUD – 15 votes
  - AMM on EFB – 14 votes
  - PFD – 3 votes
- Display of advised ground speed on the HUD helped in meeting the RTA (5.8 mean, 1.8 SD) but perhaps other information should be displayed such as early/late status

* Rating scale: 1 = strongly disagree, 7 = strongly agree

STBO Results Continued

When provided with textual STBO guidance only (Map C):

- Easy to tell if going to reach guidance end point on time (6.4 mean, 0.9 SD)
- All STBO symbology elements useful, including selected traffic information (5.6 mean, 1.6 SD)

When provided with textual and graphical STBO guidance (Map D):

- Easy to tell if going to reach guidance end point on time (6.0 mean, 1.1 SD)
- All STBO symbology elements useful, including graphical traffic intent information (6.5 mean, 0.7 SD) and graphical STBO guidance (5.8 mean, 1.5 SD)
- Graphical traffic intent information was useful in determining intent of aircraft (6.0 mean, 1.2 SD) but selected (textual) traffic information was not as effective (4.4 mean, 2.0 SD)

- Traffic intent info was useful in identifying traffic conflict situations when using either map condition (Map C, 5.3 mean, 1.8 SD; Map D, 5.7 mean, 1.9 SD)
- CD&R was effective during STBO (5.5 mean, 1.1 SD)

Conclusions

- Acceptable STBO conformance in meeting RTA and during straight taxi segments
- Some design aspects of STBO identified (slow start-up at release time, slow speeds in turns)
- Traffic intent information useful
  - Determining intent of traffic
  - Identifying conflict situations
  - Graphical presentation preferred but must be optimized – caused wrong turns
- CD&R system minimally effective due to visibility – always aware of conflict traffic prior to any alerts being generated
- Neutral in ability of STBO to increase efficiency
- STBO would increase situation awareness
- Pilots commented STBO negatively impacts workload, increases head-down time, and reduces ability to watch for traffic

Acronyms

ADS-B	Automatic Dependent Surveillance Broadcast
AMM	Airport Moving Map
ATC	Air Traffic Control
CD&R	Conflict Detection & Resolution
CG	Center-of-Gravity
EFB	Electronic Flight Bag
ETA	Estimated Time-of-Arrival
GS	Ground Speed
HUD	Head-Up Display
NACp	Navigation Accuracy Category for Position
NextGen	Next Generation Air Transportation System
RTA	Required Time-of-Arrival
RVR	Runway Visual Range
STBO	Surface Trajectory-Based Operations