Flight Deck Surface Trajectory-Based Operations
David C. Foyle, Becky L. Hooey, NASA Ames Research Center
Deborah L. Bakowski, San Jose State University / NASA Ames

POCs:
David.Foyle@nasa.gov
Becky.L.Hooey@nasa.gov
Debi.Bakowski@nasa.gov
Mission:
• Develop **principled and robust procedures** and user interfaces with appropriate human-automation function allocation

• Develop **safe and efficient systems** that minimize pilots’ cognitive/visual **workload** and increase **situation awareness**

Research Focus Areas:
• Flight Deck Human Factors
• NextGen surface operations and departure concepts (25+ years)
• KCLT ATD-2 Integrated Arrival, Departure & Surface (IADS) demonstration project
OVERVIEW

• Airport Surface Operations: Taxi-out/Departures and Surface Trajectory-Based Operations (STBO: taxi with time requirements)

• Continuum of Surface Operations:
  Manual $\rightarrow$ Automated $\rightarrow$ Autonomy

• Current-day; near-term and far-term STBO

• Research on Pilot/Flight deck STBO

• 4DT STBO: A candidate for autonomous operations
  - Research Issues
OVERVIEW
Surface Trajectory-Based Operations (STBO)

STBO = Adding time component to Surface Operations (taxi/departure)

• Current Day Surface Operations

• Current Day (EDCT – APREQ/CFR)

• Near-term (e.g., FAA STBO/NASA ATD2) - without flight deck component

• Future 4DT Surface Trajectory-based Operations (STBO) Vision (NASA/DLR) - with flight deck component

Increasing use of Time Information

Increasing Flight deck Coordination
Continuum of Surface Operations Technologies
Manual → Increased Automation → Autonomy

<table>
<thead>
<tr>
<th>Pilot(s) / Flight Deck</th>
<th>ATC / Surface Traffic Manager (STM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual (Voice)</td>
</tr>
<tr>
<td></td>
<td>Manual (Voice) w/ Decision Aids</td>
</tr>
<tr>
<td></td>
<td>Autonomous STM</td>
</tr>
<tr>
<td>Manual A/C Control</td>
<td></td>
</tr>
<tr>
<td>Manual A/C Control w/ Display Aids</td>
<td></td>
</tr>
<tr>
<td>Autonomous A/C Operations</td>
<td></td>
</tr>
</tbody>
</table>
Continuum of Surface Operations Technologies
Manual → Increased Automation → Autonomy

<table>
<thead>
<tr>
<th>Pilot(s) / Flight Deck</th>
<th>ATC / Surface Traffic Manager (STM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual (Voice)</td>
</tr>
<tr>
<td></td>
<td>Manual (Voice) w/ Decision Aids</td>
</tr>
<tr>
<td></td>
<td>Autonomous STM</td>
</tr>
<tr>
<td>Manual A/C Control</td>
<td>Current Day</td>
</tr>
<tr>
<td>Manual A/C Control w/ Display Aids</td>
<td></td>
</tr>
<tr>
<td>Autonomous A/C Operations</td>
<td></td>
</tr>
</tbody>
</table>
Current Day Surface Operations

Flight Deck:
1. Pushback Time

ATC:
1. Manage departure sequence

• Pilots manage pushback time to meet:
  - Scheduled departure/take-off time
Current Day (EDCT – APREQ/CFR)

Flight Deck:
1. Pushback Time

ATC:
1. Manage “wheels-up” time (EDCT - APREQ/CFR)

- Flight deck/pilots manage pushback time to meet:
  - “Wheels-up time”
- Flight deck/pilots have no information about:
  - Expected taxi time
  - Surface congestion
  - Departure queue size
<table>
<thead>
<tr>
<th>Pilot(s) / Flight Deck</th>
<th>ATC / Surface Traffic Manager (STM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual (Voice)</td>
</tr>
<tr>
<td></td>
<td>Manual (Voice) w/ Decision Aids</td>
</tr>
<tr>
<td></td>
<td>Autonomous STM</td>
</tr>
<tr>
<td>Manual A/C Control</td>
<td></td>
</tr>
<tr>
<td>FAA STBO / NASA ATD2</td>
<td></td>
</tr>
<tr>
<td>Manual A/C Control w/ Display Aids</td>
<td></td>
</tr>
<tr>
<td>Autonomous A/C Operations</td>
<td></td>
</tr>
</tbody>
</table>
Near-term (e.g., FAA STBO/NASA ATD2) - without flight deck component

Pilots manage pushback to meet:
- “Wheels-up time” (at KCLT, about 10% of flights)

Pilots have no information about:
- Expected taxi time
- Surface congestion
- Departure queue size

ATC/Ramp manages (with Decision Support Tools, DSTs):
1. Pushback (re: gate holds) – Target Off-Block Time (TOBT)
2. Target Airport Movement Area entry time (TMAT)
3. Target/Calculated Take-Off Time (TTOT/CTOT) re: Departure time or “wheels-up” time, EDCT - APREQ/CFR

Maintain smaller Runway queue
## Continuum of Surface Operations Technologies

**Manual** → **Increased Automation** → **Autonomy**

<table>
<thead>
<tr>
<th>Pilot(s) / Flight Deck</th>
<th>ATC / Surface Traffic Manager (STM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual (Voice)</td>
</tr>
<tr>
<td>Manual A/C Control</td>
<td></td>
</tr>
<tr>
<td>Autonomous A/C Operations</td>
<td></td>
</tr>
</tbody>
</table>

- **Controller**: Manual/voice ops, manual sequencing/scheduling aids, manual deconfliction
- **Pilot**: Controls manually, infoDisplays for 4DT STBO

- **Controller**: Auto-routing, auto-deconfliction, auto-sequencing/scheduling, position timing
- **Pilot**: Controls manually, infoDisplays for 4DT STBO
Future 4DT Surface Trajectory-based Operations (STBO) Vision (NASA/DLR) - with flight deck component

- Requirement to be at locations at specific time; defined \((x_t, y_t)\) with certain tolerance
- DLR TRACC Surface Management System dynamically creates conflict-free routes
- Coordination between Flight Deck – ATC/Ramp re: location and times

Transition from “first-come, first-served” operations

Hold at gates until taxi with minimal interruption is possible

4DT = Expected location + Allowable Deviation, at all Times, \(t\)
Future 4DT Surface Trajectory-based Operations (STBO) Vision (NASA/DLR) - with flight deck component

• Enables dynamic surface flow re-planning
• Enables increasingly precise taxi routing plans for improved surface traffic flow efficiency
• Flight deck component allows for coordination with ATC re: schedule issues (e.g., maintenance, FMS, weights/balances, RWY changes, etc.)
• Extension of FAA/NASA STBO concept
• Would enable aircraft traffic to continue rolling through Active RWY Crossings, instead of stopping aircraft and requiring ATC to do “batch” crossings of arrivals
• Facilitate timed runway take-off window conformance (+/- 5 min EDCTs, -2/+1 min APREQ/CFRs)
### 4DT STBO: Taxi Clearances w/ Speed Commands: Taxi Time-based Conformance


<table>
<thead>
<tr>
<th>Taxi Clearance</th>
<th>Required time of Arrival (RTA) Performance</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Non-specified acceleration/deceleration speed profile (n = 8 pilots)</td>
<td>Not able to achieve accurate RTAs</td>
<td>Slightly increased visual demand, as compared to baseline</td>
</tr>
</tbody>
</table>
| • Specified acceleration/deceleration profile (1kt/sec)  
  • Speed-conformance bound (+/- 1.5 kts) (n = 18 pilots) | Good RTA performance | • Increased workload and visual demand  
  • 14/18 pilots rated “unsafe” |

• Taxiing Captain cannot “tightly control/track” speed, navigate, and maintain separation.  
  • “Open-loop” control compounds error

**ConOps Implications:**
• Incorporating speed into the taxi clearance alone is not sufficient for the performance/safety balance  
• There is a requirement for human-centered flight deck display algorithms
4DT STBO: Flight Deck Display Design

“3.5-DT” / 4DT Speed-based Flight Deck Display

- "Closed-loop" speed control to specific airport locations

<table>
<thead>
<tr>
<th>Taxi Clearance</th>
<th>Required time of Arrival (RTA) Performance</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Non-specified acceleration/deceleration speed profile (n = 8 pilots)</td>
<td>Not able to achieve accurate RTAs</td>
<td>Slightly increased visual demand, as compared to baseline</td>
</tr>
</tbody>
</table>
| • Specified acceleration/deceleration profile (1kt/sec)  
• Speed-conformance bound (+/- 1.5 kts) (n = 18 pilots) | Good RTA performance | • Increased workload and visual demand  
• 14/18 pilots rated “unsafe” |
| • “3.5-DT” Speed Display (n = 8 pilots) | Good RTA performance | Low visual demand |
4DT STBO: Flight Deck Display Design/Philosophy

“3.5-DT” / 4DT Speed-based Flight Deck Display

• “Closed-loop” speed control to specific airport locations

\[ s_t = \frac{d_{rem}}{t_{rem}} \]

Full 4DT Location-based Flight Deck Display
Bakowski, Hooey, Foyle, & Wolter, 2015, AHFE
Bakowski, Hooey, & Foyle, 2017, DASC

• Status-at-a-glance display to maximize ‘eyes-out’ time
• Enable strategic use – pilots do not need to track speed continuously (anywhere in pink band is ‘in conformance’)
• Display expected position with tolerance and allow pilots to use expertise to control aircraft (e.g., “human/pilot-centered”)

Cleared-to-Taxi Route

4DT with allowable deviation

Taxi Route

Ownship icon
# Continuum of Surface Operations Technologies

Manual → Increased Automation → Autonomy

<table>
<thead>
<tr>
<th>Pilot(s) / Flight Deck</th>
<th>ATC / Surface Traffic Manager (STM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual (Voice)</td>
</tr>
<tr>
<td></td>
<td>Manual (Voice) w/ Decision Aids</td>
</tr>
<tr>
<td></td>
<td>Autonomous STM</td>
</tr>
<tr>
<td>Manual A/C Control</td>
<td></td>
</tr>
<tr>
<td>Manual A/C Control w/ Display Aids</td>
<td></td>
</tr>
<tr>
<td>Autonomous A/C Operations</td>
<td>Future</td>
</tr>
</tbody>
</table>
Autonomous Surface Operations:
- Enables 4DT STBO efficiencies
- Distributed architecture (Airport/Tower/Aircraft)
- Surface traffic manager
  - 4DT STBO operations (i.e., times at AMA entry, taxi merge points, rolling runway crossings, runway departure queue)
  - Routing/re-routing
  - Traffic de-confliction
- Candidate Auto-taxi propulsion
  - Wheel-bots
  - Electric tugs
  - Auto-taxi aircraft

TRACC: “Taxi Routes for Aircraft: Creation and Controlling” Surface Management System – Germany’s DLR
- Creates conflict free routes/re-routes
- Non-Conformance within 50 m (164 ft) of deviation from expected x, y position
- Dynamic, multiple speed changes (up to 5) along taxi route

TRACC: “Taxi Routes for Aircraft: Creation and Controlling” Surface Management System – Germany’s DLR
- Creates conflict free routes/re-routes
- Non-Conformance within 50 m (164 ft) of deviation from expected x, y position
- Dynamic, multiple speed changes (up to 5) along taxi route
**TRACC:** “Taxi Routes for Aircraft: Creation and Controlling” Surface Management System – Germany’s DLR

- Creates conflict free routes/re-routes
- Non-Conformance within 50 m (164 ft) of deviation from expected x, y position
- Dynamic, multiple speed changes (up to 5) along taxi route

**Autonomous Surface Operations:**
Candidate initial architecture (NASA/DLR Concept):

- Ground/Tower: Surface Traffic Management
  - Issue STBO Clearances (Routes w/ times)
  - Re-routing for efficiency or non-conformance
  - Traffic deconfliction
- Aircraft:
  - Aircraft navigation
  - Aircraft movement (steering, speeds, turns)
  - Additional On-board Conflict Detection and Resolution (CD&R)

<table>
<thead>
<tr>
<th>Function</th>
<th>ATC</th>
<th>Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scheduling</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Routing</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Deconfliction</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Execution</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Enabling Pilots/Flight deck Situation Awareness
Need for “status-at-a-glance” awareness and intent displays

<table>
<thead>
<tr>
<th>Pilot / Flight Deck</th>
<th>ATC / Surface Traffic Manager</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Manual</td>
</tr>
<tr>
<td>Manual</td>
<td>Current-day</td>
</tr>
<tr>
<td>Manual / Aided</td>
<td>NASA / DLR</td>
</tr>
<tr>
<td>Autonomous</td>
<td>Future</td>
</tr>
</tbody>
</table>
STBO with Autonomous flight deck component
Pilot(s) responsible for aircraft/crew & passenger safety
Enabling Pilots/Flight deck Situation Awareness
Need for “status-at-a-glance” awareness and intent displays

Re-routing Pending

Current route with Other Traffic HOLD

Bakowski, Foyle, Hooey, Meyer & Wolter, AHFE 2012
Bakowski, Hooey, Foyle, Wolter & Cheng, DASC 2013
STBO with Autonomous flight deck component
Pilot(s) responsible for aircraft/crew & passenger safety
Enabling Pilots/Flight deck Situation Awareness and Flight Deck workflow/procedure integration

**Research issues, re: Pilot roles:**
- Taxi clearance (how to load? pilot approve if auto-load?)
- 4DT STBO – speed/time updates (approve? Auto-load?)
- Departing Runway (changes, FMS, weights, temps, etc)
- Runway crossings, “wheels-up” times
- Braking – hot brakes (take-off abort)
  - Airports are not flat; KCLT, DFW varies 50ft
  - 747-8 *1 Million lbs* fully loaded
- Monitoring: - Traffic (aircraft, pedestrian, vehicle) – Separation assurance
  - Ownship aircraft intent (stopping, turning, waiting to cross active runway)
- (Non) Conformance: - Mid-taxi stopping / abort – FMS, passengers, weights
  - For 4DT STBO – interactions re: dynamic STM system; # updates
- Pilot Intervention? Revert to manual or abort taxi, or unable to make time b/c of flight deck, equipment, passenger, baggage, etc. issues
Flight Deck Surface Trajectory-Based Operations
David C. Foyle, Becky L. Hooey, NASA Ames Research Center
Deborah L. Bakowski, San Jose State University / NASA Ames

POCs:
David.Foyle@nasa.gov
Becky.L.Hooey@nasa.gov
Debi.Bakowski@nasa.gov

URL: http://humansystems.arc.nasa.gov/groups/HCSL
Additional Slides
4DT Flight-Deck Display

Cleared-to-Taxi Route

4DT with allowable deviation

Ownship

Taxi Route

K > EK > L > EH
Start 23:08:06  14 KTS  Queue 23:13:36
STBO with flight deck component and Information Sharing Displays
Enables better flight deck workflow prior to departure

“For NextGen time-based operations, how useful were the following pieces of information in supporting time-based taxi (your ability to meet your takeoff time?)”

<table>
<thead>
<tr>
<th>Information Source</th>
<th>Not at all</th>
<th>Border-line</th>
<th>Very much</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assigned Pushback time</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Spot-release time</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Takeoff Time</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>Departure Sequence</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Speed Advisory on PFD</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Time Remaining to Takeoff Time</td>
<td>-</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

ATC-Pilot HITL Sim: Foyle, Bakowski, Hooey, Cheng & Wolter, HCI-Aero, 2014)
David Foyle, PhD, NASA
Becky Hooey, PhD, NASA
Debi Bakowski, MS SJSU
Glenn Meyer, MA Dell
Capt. Rob Koteskey, MA

POCs:
David.Foyle@nasa.gov
650-604-3053
Becky.L.Hooey@nasa.gov
650-604-2399

URL: http://humansystems.arc.nasa.gov/groups/HCSL
<table>
<thead>
<tr>
<th>Proof-of-Concept Study (2014)</th>
<th>4DT Display Comparison Study (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>– Proof-of-concept simulation.</td>
<td>– Compared 4DT display formats.</td>
</tr>
<tr>
<td>– Demonstrated the feasibility</td>
<td>– More robust operating conditions</td>
</tr>
<tr>
<td>of the 4DT concept, from</td>
<td>than 2014 study.</td>
</tr>
<tr>
<td>the pilot’s perspective.</td>
<td>• 4DT speed updates</td>
</tr>
<tr>
<td></td>
<td>• Range of taxi speeds</td>
</tr>
<tr>
<td></td>
<td>– Several parameters based on the</td>
</tr>
<tr>
<td></td>
<td>TRACC system.</td>
</tr>
</tbody>
</table>

Bakowski, Hooey, Foyle, & Wolter
*Applied Human Factors and Ergonomics (AHFE 2015)*

Bakowski, Hooey, & Foyle
*Digital Avionics Systems Conference (DASC 2017)*
Airport and Terminal Area Simulator (ATAS)  
Human-Centered Systems Lab (HCSL)
Flight Deck 4DT Proof-of-Concept Study (2014)

Airport Moving Map (AMM)

Ownship's Ground Speed

Traffic displayed within de-clutter circle

Ownship
Flight Deck 4DT Proof-of-Concept Study (2014)

Airport Moving Map (AMM) Augmented with 4DT Clearance Information

- **Ownship's Ground Speed**
- **4DT Reference Markers** (expected 4DT location)
- **Ownship**
- **Cleared-to-Taxi Route** (spot to runway)
- **Traffic displayed within de-clutter circle**
- **Allowable 4DT Tolerance** (ownship's "real estate")
- **4DT Clearance Text**

**Ownship's Ground Speed**

**4DT Reference Markers** (expected 4DT location)

**Ownship**

**Cleared-to-Taxi Route** (spot to runway)

**Traffic displayed within de-clutter circle**

**Allowable 4DT Tolerance** (ownship's "real estate")

**4DT Clearance Text**
<table>
<thead>
<tr>
<th>Condition</th>
<th>Flight Deck Equipage</th>
<th>ATC Schedule Information</th>
<th>Required Speed</th>
<th>Allowable Deviation</th>
<th>Flight Deck Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>Current-Day Flight Deck</td>
<td>Pushback Begin Taxi</td>
<td>Not Specified</td>
<td>Not Specified</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Condition 2</td>
<td>Speed Advisory</td>
<td>Pushback Begin Taxi</td>
<td>ATC-issued Speed</td>
<td>Not Specified</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Condition 3</td>
<td>4DT +/- 15 sec</td>
<td>4DT Speed Profile</td>
<td>4DT Speed Profile</td>
<td>+/- 15 sec</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Condition 4</td>
<td>4DT +/- 30 sec</td>
<td>4DT Speed Profile</td>
<td>4DT Speed Profile</td>
<td>+/- 30 sec</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Flight Deck 4DT Proof-of-Concept Study (2014)

Time-based allowable tolerance band (speed × time = distance)

<table>
<thead>
<tr>
<th>Speed (kts)</th>
<th>Allowable Time Deviation (sec)</th>
<th>Distance (Length) of Allowable Tolerance Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 kts</td>
<td>+/- 30 sec</td>
<td>+/- 216 m (+/- 709 ft)</td>
</tr>
<tr>
<td>14 kts</td>
<td>+/- 15 sec</td>
<td>+/- 108 m (+/- 354 ft)</td>
</tr>
</tbody>
</table>
Flight Deck 4DT Proof-of-Concept Study (2014)

• Dallas/Fort Worth Airport (DFW)
• 13 Captains
• Experimenter First Officer
  – assisted with navigation, DataComm
• 12 experimental trials
  – 4 experimental conditions
  – 3 speed/route combinations
  – practice trials before each block
  – 2 4DT conditions always last
• Spot and Runway Departure Advisor (SARDA):
  – surface management system
  – ran in closed-loop mode
  – triggered Pushback and Taxi
  – queue-entry derived from ToT
  – SARDA traffic appeared OTW
Flight Deck 4DT Proof-of-Concept Study (2014)

4DT Straightaway Speed was held constant in each trial
e.g., 14 kts

4DT Acceleration/Deceleration Rate
1 kt per sec
Beginning of 4DT Taxi Entering/Exiting Turns

4DT Turn Speed 10 kts

*Time-based tolerance band

Runway 17R
Terminal E
Ramp Spot
Transition from Ramp to AMA

Queue-Entry

4DT End
Flight Deck 4DT Proof-of-Concept Study (2014)

Example Trial
“ATS227, Pushback and Taxi to Spot 47.”
Flight Deck 4DT Proof-of-Concept Study (2014)
Flight Deck 4DT Proof-of-Concept Study (2014)

Queue Area

Queue Entry

4DT Start Time

Taxi Clr

Cleared-to-Taxi Route

4DT Clearance Information
(cyan until 4DT Start Time)

4DT Info

4DT Tolerance Band

4DT Start Time

K > EK > L > EH

Start 23:08:06 14 KTS Queue 23:13:36
Flight Deck 4DT Proof-of-Concept Study (2014)

- 4DT Start Time: 30 sec after Taxi Clearance.
- Defined by the 4DT speed profile.
- Auditory Chime and 4DT information turns magenta.
- Pilot enters the AMA and begins to taxi.
Flight Deck 4DT Proof-of-Concept Study (2014)

- 4DT Tolerance Band accelerates from 0 kts to 14 kts at 1 kt per sec.
- Pilot Instructions:
  - In compliance with the 4DT clearance when the ownship icon is within the tolerance band.
  - No need to track the 4DT reference markers precisely.
Flight Deck 4DT Proof-of-Concept Study (2014)

- 4DT straightaway speed held constant during each trial.
Flight Deck 4DT Proof-of-Concept Study (2014)

- 4DT speed in turns was 10 kts.
- Distance-based tolerance band.

Decelerate
14 kts $\rightarrow$ 10 kts
@ 1 kt per sec

Turn
10 kts

Accelerate
10 kts $\rightarrow$ 14 kts
@ 1 kt per sec
Flight Deck 4DT Proof-of-Concept Study (2014)

- End of 4DT taxi route at the queue-entry point.
- Upon reaching the queue entry, the tolerance band disappeared.
Flight Deck 4DT Proof-of-Concept Study (2014)

• Pilot enters the queue area at a safe speed and lines up behind any aircraft at the runway hold line.
Flight Deck 4DT Proof-of-Concept Study (2014)

- A verbal speed command, alone, may not support adequate 4DT conformance along the taxi route.
- Flight deck display required to aid pilots in conforming to the 4DT.
Flight Deck 4DT Proof-of-Concept Study (2014)

- A verbal speed command, alone, may not support adequate 4DT conformance along the taxi route.
- Flight deck display required to aid pilots in conforming to the 4DT.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equipment</th>
<th>Speed Advisory</th>
<th>4DT +/- 30s</th>
<th>4DT +/- 15s</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMM augmented</td>
<td>99.7%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td>with graphical</td>
<td>96.4%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>99.9%</td>
</tr>
<tr>
<td>representation</td>
<td>100%</td>
<td>72.4%</td>
<td>45.5%</td>
<td>66.3%</td>
</tr>
<tr>
<td>of allowable 4DT deviation</td>
<td>19.7%</td>
<td>78.7%</td>
<td>4%</td>
<td>3%</td>
</tr>
</tbody>
</table>

**Based Deviations from Expected Position (sec)**

- Current-Day Equipage
- Speed Advisory
- 4DT +/- 30s
- 4DT +/- 15s

**+-15 sec 4DT Tolerance Condition**

AMM augmented with graphical representation of allowable 4DT deviation.
Flight Deck 4DT Proof-of-Concept Study (2014)

- A verbal speed command, alone, may not support adequate 4DT conformance along the taxi route.
- Flight deck display required to aid pilots in conforming to the 4DT.
• A verbal speed command, alone, may not support adequate 4DT conformance along the taxi route.
• Flight deck display required to aid pilots in conforming to the 4DT.
<table>
<thead>
<tr>
<th></th>
<th>Proof-of-Concept Study (2014)</th>
<th>4DT Display Comparison Study (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable 4DT Deviation Band</td>
<td>Time-Based Band</td>
<td>Distance-Based Band</td>
</tr>
<tr>
<td>4DT Straightaway Speed</td>
<td>Held constant within each trial</td>
<td>4DT Speed Changes Mid-Taxi</td>
</tr>
<tr>
<td>4DT Speeds</td>
<td>14, 15, or 16 kts</td>
<td>Range of Realistic Taxi Speeds 8 kts – 25 kts</td>
</tr>
<tr>
<td>Start of 4DT Taxi Route</td>
<td>Ramp Spot</td>
<td>Near the Terminal</td>
</tr>
<tr>
<td>Airport</td>
<td>Dallas/Fort Worth Airport (DFW)</td>
<td>Charlotte Douglas Airport (KCLT)</td>
</tr>
</tbody>
</table>
## Flight Deck 4DT Display Comparison Study (2016)

<table>
<thead>
<tr>
<th>Condition</th>
<th>4DT Conformance</th>
<th>Allowable Deviation</th>
<th>Graphical 4DT Indicator</th>
<th>Flight Deck Display</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Condition 1</strong></td>
<td>Defined Conformance</td>
<td>+/- 50 m</td>
<td>Reference Markers with Tolerance Band</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>4DT</strong></td>
<td>+/- 50 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Condition 2</strong></td>
<td>Defined Conformance</td>
<td>+/- 123 m</td>
<td>Reference Markers with Tolerance Band</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>4DT</strong></td>
<td>+/- 123 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Condition 3</strong></td>
<td>Undefined Conformance</td>
<td>Undefined</td>
<td>Dot (no tolerance indicated)</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>4DT</strong></td>
<td>Undefined Conformance</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Flight Deck 4DT Display Comparison Study (2016)

**Defined-Tolerance Display Format (Distance-Based Band)**

![Diagram showing 4DT display with tolerance bands]

- Defined Tolerance Instructions:
  - You are in compliance with the 4DT clearance when the ownship icon is within the tolerance band.
  - No need to track the 4DT reference markers precisely.
Un**defined**-Tolerance Display Format

- 4DT indicator: Light pink dot.
- Allowable tolerance was undefined.
- Undefined tolerance display format instructions:
  - "You decide how “close is close enough” to taxi to the dot and you can taxi ahead of, or behind, the 4DT dot."
- Pilots defined conformance as they saw fit.
- No need to track the 4DT indicator (dot) precisely.
Flight Deck 4DT Display Comparison Study (2016)

4DT Acceleration/Deceleration Rate
1 kt per sec

Beginning of 4DT Taxi
4DT Speed Changes
14 kt turn in the AMA

Turn Speed = 14 kts in the AMA

Charlotte Douglas Airport

Queue-Entry

AMA Entrance
(one, continuous, clearance Ramp to RWY Queue)

Ramp, Near Terminal

4DT Start

4DT End

RWY 18L
Flight Deck 4DT Display Comparison Study (2016)

4DT Speed Changes
2 or 5 per Trial

4DT Speeds
8 kts – 25 kts
'Slow' or 'Fast' Average Speed

<table>
<thead>
<tr>
<th>Ramp</th>
<th>AMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>10 kts</td>
</tr>
<tr>
<td>Fast</td>
<td>13 kts</td>
</tr>
</tbody>
</table>

Example Trial:
- 5 4DT Speed Changes
- 'Fast' Speed

Ramp, Near Terminal
Queue-Entry
4DT Start
4DT End
RWY 18L

11 kts
13 kts
15 kts
20 kts
21 kts
25 kts

Joint Workshop for DLR – NASA ATM Research Collaboration August 22 – 24, 2017
Flight Deck 4DT Display Comparison Study (2016)

- Charlotte Douglas Airport (KCLT)
- 12 Pilots
- Experimenter First Officer
  - assisted with navigation, DataComm
- 12 experimental trials
  - 3 4DT Display Formats:
    - blocked and counterbalanced
    - practice trial before each block
- Taxi Routing for Aircraft: Creation and Controlling (TRACC) (DLR)
  - prototype surface management system
  - parameters from simulation analysis
  - two or five speed changes
  - +/- 50 m (smaller tolerance band)

- These four trials repeated in each of the three 4DT Display Format conditions.
Flight Deck 4DT Display Comparison Study (2016)

Example Trial
Flight Deck 4DT Display Comparison Study (2016)
Flight Deck 4DT Display Comparison Study (2016)

4DT Start Time

Queue Area

Queue Entry

Taxi CIR

Speed Changes

4DT Clearance Information (cyan until 4DT Start Time)

Ownship at Concourse A

Cleared-to-Taxi Route (Ramp to Queue)

4DT Start Time

12:01:30 Z
FROM KCLT

ATSS27
RWY 18L
VIA M C

TOBT 12:03:15
FWD TAXI 12:05:30
TTOT 12:12:00

COMM OK

UNABLE STBY WILCO

18L via M > C
FWD TAXI 12:05:30 00 KTS
TTOT 12:12:00
Flight Deck 4DT Display Comparison Study (2016)

- At Target Off-Block Time (TOBT)

Queue Area

Queue Entry

Taxi Clr

Speed Changes

Pushback (TOBT)

Ownship at Concourse A

Cleared-to-Taxi Route (Ramp to Queue)

4DT Start Time

4DT Start Time

12:03:15 Z
FROM KCLT

OPEN

COMM OK

UNABLE STBY WILCO

18L via M > C
FWD TAXI 12:05:30 00 KTS TTOT 12:12:00
Flight Deck 4DT Display Comparison Study (2016)

Queue Area
Queue Entry
Taxi Clr
Speed Changes
Pushback (TOBT)
4DT Start Time
Cleared-to-Taxi Route
Ownship
4DT Tolerance Band (or dot)
Concourse A

Joint Workshop for DLR – NASA ATM Research Collaboration August 22 – 24, 2017
Flight Deck 4DT Display Comparison Study (2016)
Flight Deck 4DT Display Comparison Study (2016)

- **4DT Start Time** (defined by the 4DT speed profile).
- **Auditory Chime and 4DT information** turns magenta.
- **Pilot begins to taxi.**
- **4DT tolerance band** (or dot) accelerates from 0 kts to 11 kts at 1 kt per sec.
Flight Deck 4DT Display Comparison Study (2016)

- 4DT speed changes were accompanied by an auditory tone.
- AMM text display updated.
- First Officer: "Speed Change".
- Two or five speed changes per trial.
- At predetermined locations.

4DT Tolerance Band (or dot)

Queue Area

Queue Entry

Taxi Clr

Speed Changes

4DT Start Time

Pushback (TOBT)

Ownship

Current 4DT Speed
Flight Deck 4DT Display Comparison Study (2016)

- End of 4DT taxi route at the queue-entry point.
- Upon reaching the queue entry, the tolerance band disappeared.
• Pilot enters the queue area at a safe speed and lines up behind any aircraft at the runway hold line.
Flight Deck 4DT Display Comparison Study (2016)

Percent Time Ownership within each +/- Distance Range (ft)

- +/- 164 ft (+/- 50 m)
  Band: 93.37%

- +/- 405 ft (+/- 123 m)
  Band: 99.71%
Flight Deck 4DT Display Comparison Study (2016)

Percent Time Ownship within each +/- Distance Range (ft)

+/- 123 m 4DT Defined Tolerance
 AMM augmented with graphical representation of defined allowable 4DT deviation

+/- 164 ft ( +/- 50 m)
 Band: 93.37%

+/- 405 ft ( +/- 123 m)
 Band: 99.71%
Flight Deck 4DT Display Comparison Study (2016)

**+/– 50 m 4DT Defined Tolerance**

AMM augmented with graphical representation of **defined** allowable 4DT deviation

**+/– 123 m 4DT Defined Tolerance**

AMM augmented with graphical representation of **defined** allowable 4DT deviation
Distance between the ownship and the expected 4DT location.

Expected 4DT Location

Distance between the ownship and the expected 4DT location.

Expected 4DT Location
Pilots spent more time taxiing closer to the expected 4DT location in this condition than in either the larger or undefined-tolerance conditions.
Pilots spent more time taxiing closer to the expected 4DT location in this condition than in either the larger or undefined-tolerance conditions.
Backup Slides
Flight Deck 4DT Proof-of-Concept Study (2014)

DataComm Touchscreen Interface Display

🎵 DataComm Accompanied by Auditory Chime

Call Sign
RWY
Taxi Route

4DT Schedule Information

Touchscreen Response Buttons
(First Officer)
Out-the-Window (Ramp Departure Spots) at DFW
Flight Deck 4DT Proof-of-Concept Study (2014)

Queue Entry
4DT Indicator disappears.

Queue Area
Aircraft continues taxiing to RWY hold line.

4DT Start Time
4DT Indicator begins to move. Pilot enters the AMA and begins taxi.

Taxi Clearance
At the spot, the flight deck receives the Taxi Clearance, via DataComm.

Pushback
Verbal clearance to pushback and taxi to Ramp Spot.
Flight Deck 4DT Proof-of-Concept Study (2014)

- Time of Arrival (TOA) variability at the queue-entry point (seconds).
- The TOA range was reduced by providing pilots a verbal speed in the Speed-Advisory condition, and further reduced in the two 4DT conditions.

Arrival Time at Runway Queue (sec)

<table>
<thead>
<tr>
<th></th>
<th>Current-Day Equipage</th>
<th>Speed Advisory</th>
<th>4DT +/-30 sec</th>
<th>4DT +/-15 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>300 s</td>
<td>349 s</td>
<td>325 s</td>
<td>327 s</td>
</tr>
<tr>
<td>Range</td>
<td>192 s</td>
<td>46 s</td>
<td>27 s</td>
<td>17 s</td>
</tr>
</tbody>
</table>

331 sec
Expected TOA at the Queue entrance, according to the Speed Profile.

Box and Whisker plots for the West1/15kts and West2/16kts routes followed a similar pattern.
Pilots spent more time taxiing closer to the expected 4DT location in this condition than in either the larger or undefined-tolerance conditions.

Legend:
- **Defined Tolerance**
  - +/- 164 ft ( +/- 50 m)
  - Band: 93.37%
- **Defined Tolerance**
  - +/- 405 ft ( +/- 123 m)
  - Band: 99.71%
- **Dot**