Flight Deck Surface Trajectory-based Operations (STBO): Results of Piloted Simulations and Implications for Concepts of Operation (ConOps)

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www.nasa.gov
**Problem**

1. Current-day flight deck operations are not able to support:
   - NextGen Arrival - Anticipated throughput generated by NextGen concepts such as M&S, VCSPA, etc.
   - NextGen Departure - Predictability required for NextGen concepts.
   (re: IADS RTT ConOps 4-12-10)

2. Must work ATC concepts in parallel with flight deck concepts or be vulnerable to risk of developing concepts to which pilots cannot comply.
   (i.e., IADS RTT Doc: “OV-6c NEXTGEN 2018 Scenario 07 - Peak Departures v0.1 4-13-2009”)

**Research Needs**

- Develop/assess Surface Traffic Mgmt. Systems / Flight Deck ConOps variants
- Determine technologies/procedures for pilots to conduct NextGen taxi operations
- Assess compliance and pilot workload under NextGen IADS operations
- Define and conduct RTT IADS RTP efforts

**Approach**

**Iterative Pilot-in-the-loop Simulations**

- ConOps Definition / refinement
- Pilot compliance
- Pilot info. requirements
- Pilot acceptance

**Impact**

- ConOps Development
- SMS Algorithm/Parameters Development
- Flight Deck System Requirements
- Robust systems (e.g., off-nominals)

**Progress**

- Multiple simulations
- Defined ConOps options
- Eliminated specific candidate ConOps options
Pilot requirements for Surface Trajectory Based Operations (STBO) clearances

Problem: Integrating Surface Management Optimization (SMO) STBO clearances with flight deck information requirements

Advanced Surface Management Optimization (SMO) Systems and ConOps Must Incorporate Pilot Operating Requirements
- Ability to comply with speed requests
- Variance of route and time conformance
- Conceptual development (e.g., form of taxi clearances - continuous, updates, etc.)
- Pilot/Aircraft non-conformance
- Rerouting

Human Factors Pilot-in-the-loop Studies to Determine Pilot Operating Requirements
- Speed conformance
- Route and time conformance
- Conceptual (ConOps) development
- Pilot workload, Situation awareness (SA)
- Safety impacts due to time pressure

STBO Flight Deck Issues
STBO Concepts
- Progressive taxi/route updates
- Continuous-coupled STBO clearances
- Endpoint-only STBO Clearances (push-back, departure queue)

STBO Taxi Clearance Formats
- Flight Deck speed & time displays
- Bandwidth of error-nulling (i.e., continuous vs. non-continuous checkpoint error)
- ATC STBO Clearance: Speed, Time

Pilot Performance Metrics
- Variance of speed, time-of-arrival error
- SA, workload, safety impacts
NextGen Taxi / Surface Trajectory-Based Operations (STBO)

Surface Trajectory-Based Operations (STBO) inherently different than In-Air TBO
• In-Air: More constrained – due to aircraft inertia, min/max speeds, in-trail separations.
  ➔ More predictable, much more likely to have fully defined trajectories: $X(t), Y(t)$
• Taxi: Not constrained – aircraft start, stop, wait, merge into queues, no min. separation
  ➔ Less predictable, more variants on defining STBO than in-air TBO
NextGen Taxi / Surface Trajectory-Based Operations (STBO)

SARDA: Spot and Runway Departure Advisor

RTT Research Transition Product: "Integrated Surface Management w/Flight Deck"

HCSL

Surface Traffic Management Algorithms

# Constraint Points ($X_t, Y_t$)

1. Spot
2. Rwy Queue
3. Rwy Cross
4. Taxiway Merge
5. Rwy Queue

… All intermediate pts…
… All intersections…
∞. Rwy Queue

FULL STBO
Simulation and Results
Pilot requirements for 4-D taxi clearances

Initial Baseline 4-D Taxi Navigation Study
(Williams, Hooey & Foyle, 2006, Proc. AIAA)

- 18 Current Captains
- Minimal display information (baseline study)
- 4-D Taxi Clearance Formats
  - Speed: Commanded average route speed + Current speed
  - Time: Commanded time to RWY + Elapsed time
  - Both: All
Pilot requirements for 4-D taxi clearances

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  - Speed: Commanded average route speed + Current speed
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  - Both: All
- Results
  - Less error with Both (Time and Speed together) formatted clearances
  - Eyetracking usage - speed used early in route, then switch to using time information
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Simulation and Results
Pilot requirements for 4-D taxi clearances

Initial Baseline 4-D Taxi Navigation Study (Expt #1) *(Williams, Hooey & Foyle, 2006, Proc. AIAA)*
- Less error with Both (Time and Speed together) formatted clearances
- Eyetracking usage - speed used early in route, then switch to using time information

Baseline 4-D Taxi Navigation - Updating/adjusting 4-D taxi clearances study (Expt #2)
- Scenario: ATC Taxi clearance - Segmented ATC clearances w/ "time checkpoints" due to:
  1) changing conditions; or
  2) imperfect aircraft Time of arrival (TOA) compliance at checkpoints
- 17 Current Commercial Transport Captains
- Minimal display information (follow-on to first baseline study)
- 4-D Taxi Clearance Format:
  - Both: Commanded average **SPEED + TIME** to runway crossing (plus current readout)
- 6 experimental trials: 3 w/checkpoints & 3 no checkpoints
- Time checkpoints on EMM (white bars) & auditory tone 75 ft before checkpoint
Pilot requirements for 4-D taxi clearances

**TOA Absolute Error (Left panel).**
- For slower commanded taxi speeds, time checkpoints improve Runway (Time of Arrival) TOA accuracy

**Eye Dwell Time (Right panel).**
- Overall, pilots looked at display information more during checkpoint trials than non-checkpoint trials (24% vs 20% of trial)
- Middle-of-route checkpoints (Segments S2 & S3) --> more visual attention (% Dwell Time) on display
  - Pilots received new updated checkpoint information 4 times as often
  - Visual workload increased
  - Possible traffic awareness issues
# HCSL Completed NextGen Taxi Sims

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Simulation and Results
AP.2.S.09 - "NextGen Time-based Taxi Clearances" Pilot-in-the-loop simulation

**Experiment Goal**
Characterize the distribution of pilots’ Time of Arrival (TOA) performance to inform the development of Surface Traffic Management (STM) algorithms.

**Compare three STM system concepts (# traffic flow points; within-subjects factor):**
1) One single traffic flow point to ensure on-time arrival at the destination runway;
2) Occasional (three) traffic flow points to enable traffic sequencing at important intersections and
3) Frequent (five) traffic flow points to enable dynamic system re-optimizations and very close coordination

**Compare two NextGen Time-based Taxi Ops implementations (Between-subjects factor):**
1) Speed Clearances: Current-day Avionics without Speed Error Nulling
2) Speed & Time (Checkpoint) Clearances: Advanced Avionics with Speed Error Nulling

**Experiment Overview**
16 Pilots (Commercial Transport, CA & FO)
32 departure taxi trials (‘spot’ to runway)
Medium-fidelity simulator; DFW airport
Questionnaires; SME debriefs

- Speed Command
- Time Info (RTA, Elapsed)
- PFD augmented for taxi operations
- Taxi Navigation Display (taxi route, traffic, and traffic flow points)
- Departure clearance datalinked from ATC
- ND shows auto-loaded Tailored Departure Path
- Electronic checklist (encourage realistic cockpit scan; objective workload measure)
Time of Arrival Error

Speed Effect:
- Slow speeds (10 kts): A/C early
- Fast speeds (18, 22 kts): A/C late
- 14 kts (negligible error)

Traffic Flow Point Effect:
- TOA error larger for 1 traffic flow point than for 3 and 5

Next-Gen Implementation Effect:
- TOA Error larger for "no error nulling"
- Reduced spread of TOA Error distribution with "error nulling"

Workload
- Error-nulling avionics increased time to verify/accept departure clearance (~ 1 sec for nominal clearance; 12 sec for off-nominal clearance with error)
- 2-3 speed/checkpoint updates recommended by pilots
- 5 updates viewed as too many for:
  - Error nulling: 88%; 7 of 8
  - No Error nulling: 0%; 0 of 6
(p<.001, Performance/workload trade-off)

Structured Interview Results
Safety: "eyes in" vs "eyes out"

NextGen Implementation:
- PFD appropriate and intuitive
- Taxi navigation display should show traffic and taxi hold instructions
- Increased cockpit coordination (i.e., "callouts" for speed & traffic)

Average TOA Error = Actual TOA - Commanded TOA
Positive Error = Aircraft was late / too slow
Negative Error = Aircraft was early / too fast
(plotted with +/- 1 standard error)

Results inform STM Algorithm Development
Departure clearance operations under NextGen surface operations conditions

Compared to “current-day” baseline taxi, Advanced NextGen (error-nulling avionics) had longer latencies to:
- Correctly accept correct clearances
- Correctly reject incorrect clearances

Compared to Limited NextGen (speed commands only), Advanced NextGen (error-nulling avionics) had longer latencies to:
- Correctly reject incorrect clearances

May be indicative of increased workload in Advanced NextGen implementation

Structured Interview Results

- Datalinked direct upload (vs. manual FMS loading): Potential flightdeck workload savings
- "Tailored Departures / Unique Dynamic RNAV/RNP Departures": Clear advantages for system efficiency (re: Wx, winds, traffic) and individual aircraft efficiency (e.g., flight time, fuel savings)
- Need for verification of route (e.g., "NA227-123456"), especially vs. SIDs implementations
- Issues:
  - How does flightdeck "back up" tailored departure routes in case of equipment failure, FMS dumping route, etc. (vs. Current SIDs with hard copy, FULL route information)
  - How does crew do pre-departure route briefing? (vs. Current SIDs with heading based turns, speeds, etc.)
### HCSL Completed NextGen Taxi Sims

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Simulation and Results
ConOps: “ATC Voice Taxi Clearances with Speed Commands”

Pilots: 18 commercial transport Captains (current or recent retirees)
Scenario: DFW Taxi out to take off – Ramp parking spot to runway through take-off roll (up to 80 kts)

Concept Scope

Trajectory-Based Surface Operations
Taxi out operations with:
• ATC voice speed commands
• Pilots required speed range compliance of +/- 1.5 kts
• Pilot acceleration profile control requirement
• Pilot crosscheck of dynamic RNAV routes datalinked to cockpit (waypoints/crossing restrictions)

NextGen Paired Departures
• Closely spaced parallel paired departures - (MITRE/ Lunsford; ICNS 2008, 2009)
• Ownship informed of paired departure via datalink, paired aircraft’s route depicted on Navigation Display
• Time of Arrival (TOA) Error to traffic flow points is improved compared to previous study (40-60 secs TOA error, Foyle et al, 2009) - because of defined aircraft acceleration and speed range requirements ...BUT...

• Workload and safety level were unacceptable

• Likely due to increased requirements of taxi task (Acceleration profile, speed range requirement)
  - 14 of 18 pilots responded that speed conformance range restriction would compromise safety \( p = .018 \)
  - Rated more difficult than current actual taxi operations \( p = .042 \)
  - Eyes-in time 18-24% compared to 8% baseline
  - Responded that they were “frequently” focused on the PFD speed tape when needed to attend to the taxiway

IMPACT
• ConOps of ATC providing taxi clearances with speed (via ATC DST) is not workable
• Need for RTA in taxi clearance; flight deck displays
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• Viewed as *not safe* | • ATC speed clearances will not suffice  
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### Evaluation of Taxi Information Needed: Speed, Time, Both?

- **Findings**
  - Need both Speed (A/C control) and Time (RTA) information to meet RTAs
  - Need FD displays
  - Need RTA in taxi clearance
  - **Customers:** FAA, avionics/EFB mfg.

- **ConOps Implications**
  - Defined SMO algorithm parameters: Speed, Distance, # constraint pts
  - Initial FD display requirements
  - **Customers:** FAA, avionics/EFB mfg., SMO Developers

### Evaluation of Intermediate Checkpoints with Speed + Time

- **Findings**
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- **Findings**
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- **Findings**
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### Conclusion: What do we know re: ConOps?

1. Surface Traffic Management System ← Sim data (TOA error, variability) of taxi speed, route length, # constraint points
2. ATC Clearance: Recommend 1 ≤ # intersection constraint points ≤ 4
3. ATC Clearance: Time (RTAs) necessary but not sufficient
4. ATC Clearance/Flight Deck: Taxi clearances with speed not safe/workable with current-day flight deck
5. Flight Deck: Need flight-deck display (avionics/EFB) capability

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Next Steps: HCSL NextGen Taxi Sims

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**Overall Research Objectives**
Expand ConOps to address:
- Flight Deck Avionics/EFBs
- Traffic management

**Specific Plan**
- FY11 Simulations
  Sim #1 – Timing/format parameters for Data Comm vs. Voice trades for taxi re-routing
  Sim #2 - Initial look at RTT RTP “Integrated Surface Management w/ Flight Deck”
    a) Evaluate Flight Deck Display concepts x Traffic Flow concepts
    b) Increase scenario complexity (traffic conditions, ATC-revised Rwy RTAs)
- FY12 sims – Advanced flight deck concepts to enable SMO re-optimizations
- FY13 – SMS / Flight Deck Integration sims
  a) Evaluate Flight Deck concept elements (# Constraint Points + Flightdeck + Traffic) defined in previous sims with actual SMS algorithms (informed by sims)
- FY14-15 sims – Develop RTT RTP “Integrated Surface Management w/ Flight Deck”
Research Approach

Human-centered design and evaluation process
(from Foyle & Hooey, 2008)

NextGen Pilot Taxi Operations
HITL Research Approach

Off-nominal Methodology Papers:
Flight Deck Surface Trajectory-based Operations (STBO): Results of Piloted Simulations and Implications for Concepts of Operation (ConOps)

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Research Focus: Pilot requirements for Surface Trajectory Based Operations (STBO) clearances

Objective
STBO to enable NextGen flight deck operations to support:
• NextGen Arrival - Anticipated throughput generated by NextGen concepts such as M&S, VCSPA, etc.
• NextGen Departure - Predictability required for NextGen concepts (e.g., Rwy; Merge; Flow)  
  (ref: IADS RTT ConOps 4-12-10)

Must work ATC concepts in parallel with flight deck concepts
• Otherwise, vulnerability to risk of developing concepts to which pilots cannot comply
  (ref: IADS RTT Doc: “OV-6c NEXTGEN 2018 Scenario07 / Peak Departures v0.1 4-13-2009”)

Goals:
• Integrate Surface Traffic Management (STM) systems’ STBO clearances with flight deck information requirements
• Define parameters for flight deck and STM system
• Determine ConOps for STBO
NextGen Taxi /
Surface Trajectory-Based Operations (STBO)

SARDA: Spot and Runway Departure Advisor

RTT Research
Transition Product:
“Integrated Surface Management w/Flight Deck”

Surface Traffic Management Algorithms

# Constraint Points \((X_t, Y_t)\)

1. Spot
2. Rwy Queue
3. Rwy Queue
4. Rwy Queue
5. Rwy Queue

∞

1. Spot
2. Rwy Cross
3. Taxiway Merge
4. Rwy Queue
∞. Rwy Queue

∞

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2. Rwy Cross
3. Taxiway Merge
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2. Rwy Queue
3. Rwy Queue
4. Rwy Queue
∞. Rwy Queue

“FULL” STBO
Flight Deck Simulations and Results
Experiment 1: Commanded Speed – Without Speed Profiles or Conformance

**Objective:** “Minimum Flight Deck Equipage”
ConOps Evaluation
1) ATC provides ‘A/C required speed’ in taxi clearance (either automated or ATC Decision Support Tool)
2) Pilots not required to follow specific acceleration/deceleration speed profiles (only “be aggressive”)

- 8 Current or recently retired pilots: 6 CAs; 2 FOs
- STBO Taxi Clearances – manipulated:
  - **Speed:** Taxi clearance included required speed
  - **# Intermediate Time Constraint Points**

**Results**
- More RTA error with 1 time constraint point
- Less RTA error with 3 or 5 time constraint points
- Slower required speeds → early arrival; Faster required speeds → late arrival

Foyle, Hooey, Kunkle, Schwirzke & Bakowski, 2009, ICNS
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Findings

ConOps Implications
- Defined STM STBO algorithm parameters: Speed, Distance, # Time constraint points
- Intermediate taxi time constraint points useful (meeting RTAs, traffic flow)
- ATC taxi clearances with speed alone may not suffice

Customers:
FAA, avionics/EFB mfg., STM STBO Developers

Foyle, Hooey, Kunkle, Schwirzke & Bakowski, 2009, ICNS
Experiment 2: Commanded Speed – With Speed Profiles/Conformance Range

**Objective:** “Minimum Flight Deck Equipage”
ConOps Evaluation
1) ATC provides ‘A/C required speed’ in taxi clearance (either automated or ATC Decision Support Tool)
2) Pilots required to follow specific acceleration/deceleration speed profiles (2 kts/sec accel./decel.)
3) Investigated speed conformance tolerance

- 18 Current/recently retired pilots: 13 CAs; 5 FOs
- STBO Taxi Clearances – manipulated:
  - **Speed:** Taxi clearance included required speed
  - **# Intermediate Time Constraint Points**
  - **Speed Conformance Range:**
    - Undefined (tested first) / Defined (+/- 1.5 kts); Current-Day Baseline

- Results
  - Improved RTA error (because of defined aircraft acceleration and speed range requirements **BUT**…
  - Visual workload and safety level were **unacceptable**

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Bakowski, Foyle, Kunkle, Hooey & Jordan, 2011, ISAP
Objective: “Minimum Flight Deck Equipage”

ConOps Evaluation
1) ATC provides ‘A/C required speed’ in taxi clearance (either automated or ATC Decision Support Tool)
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Results
- Improved RTA error (because of defined aircraft acceleration and speed range requirements)
  BUT...
- Visual workload and safety level were unacceptable

Findings
ATC taxi clearances with speed:
- Poor RTA conformance without speed accel./decel. profiles
- Good RTA conformance with speed accel./decel. profiles, but
  - with 2-3x “eyes-in” time
  - viewed as not safe

ConOps Implications
- ATC speed clearances alone will not suffice
  → Need for flight deck display/algorithm

Customers:
FAA, RTT

Bakowski, Foyle, Kunkle, Hooey & Jordan, 2011, ISAP
**Objective:** “Flight Deck Equipage” ConOps Evaluation

1) ATC provides taxi clearance with RTA
2) Flight deck equipage (Avionics or EFB, electronic flight bag)

- 8 Current or recently retired pilots: 7 CAs; 1 FO
- Displays (PFD; Taxi Nav. Display, TND)
  - **PFD:** RTA time-to-go; Elapsed time; Algorithm: Speed required to meet RTA (Enables *strategic* usage)
  - **TND:** Route; Time constraint point
- STBO Taxi Clearances – manipulated:
  - Speed
  - # Intermediate Time Constraint Points
- Results
  - Display/algorithm with speed recalculation → good RTA conformance

---

Foyle, Hooey, Kunkle, Schwirzke & Bakowski, 2009, ICNS
Objective: “Flight Deck Equipage” ConOps Evaluation

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  - TND: Route; Time constraint point

- STBO Taxi Clearances – manipulated:
  - Speed
  - # Intermediate Time Constraint Points

Results
- Display/algorithm with speed recalculation \( \rightarrow \) good RTA conformance

Findings

- Flight deck algorithm: Speed recalculation \( \rightarrow \) good RTA conformance

ConOps Implications

- Defined STM STBO algorithm parameters: Speed, Distance, # Time constraint points
- Initial flight deck requirements for STBO ConOps

Customers:
- FAA, avionics/EFB mfg., STM STBO Developers
Cross-Studies: Usage/Safety Implications

“How often did you find yourself focusing on the PFD Speed or Time display, when you should have been paying attention to the external taxiway environment?”

Exp.1: Speed – No accel./decel. profile
- Eyetracking: 2.4 – 3.3 times baseline
- “Unsafe”: 14/18 pilots

Exp.2: Speed – With accel./decel. profile, Undefined Conformance
- Eyetracking: 2.4 – 3.3 times baseline
- “Unsafe”: 14/18 pilots

Exp.3: Display/Algorithm

Current-Day Baseline

Mean Abs. RTA Error (sec)

(1 Time-Constraint Point)
## Summary / Overall ConOps Implications

<table>
<thead>
<tr>
<th>Summary Findings</th>
<th>ConOps Implications</th>
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<tbody>
<tr>
<td>• STBO clearances with speed are not viable solution</td>
<td>• Requirement for <em>human-centered</em> flight deck display/algorithm for STBO</td>
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</tbody>
</table>
| • Taxiing Captain cannot “tightly control/track” speed, navigate, and maintain separation | **Customers:**
| • Only flight deck algorithm/display condition → Good RTA conformance AND appropriate visual workload / safety | FAA, avionics/EFB mfg., STM STBO Developers |

*Caveat:* Flight deck algorithm/display -- Needs to allow “strategic operation”, not “tight control/tracking”

### Next Steps:
- STBO human-centered flight deck displays
- Operational issues: Datalink coordination between STM system and flight deck
  - Integration with SARDA (Spot and Runway Departure Advisor)

*Human-centered designed systems (Foyle, 2009):*
- Are intuitive and “natural”
- Have readily accessible information
- Support human capabilities (e.g., perceptual processing)
- Mitigate human limitations (e.g., memory)
- Have features supported by “human factors design principles trace”
- Enable appropriate task usage strategies
Backup Slides
Objective: Initial Baseline 4-D Taxi Navigation Study
- 18 Current Captains
- Minimal display information (baseline study)
- STBO Taxi Clearance Formats
  - **Speed:** Commanded average route speed + Current speed
  - **Time:** Commanded time to RWY + Elapsed time
  - **Both:** All
- Results
  - Less RTA error with Both Time and Speed clearances
  - More RTA error with longer routes
  - Slower speeds → early arrival; Faster speeds → late arrival
  - Eyetracking usage - speed used early in route, then switch to using time information

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**Preliminary Experiment:** Pilot information requirements for STBO taxi clearances

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**Williams, Hooey & Foyle, 2006, Proc. AIAA**

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**Speed/Time Format (in green)**

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**RTA Error (sec)**

- **Required Speed (kts)**
  - 10
  - 14
  - 18
  - 22

- **RTA Error (ft)**
  - 3,000 ft
  - 6,000 ft
  - 12,000 ft
**Objective:** Initial Baseline 4-D Taxi Navigation Study

- 18 Current Captains
- Minimal display information (baseline study)
- STBO Taxi Clearance Formats
  - **Speed:** Commanded average route speed + Current speed
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**Results**

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- Eyetracking usage - speed used early in route, then switch to time

---

**Findings**

To accurately meet RTAs:
- Need both Speed (A/C control) and Time (RTA) information

**ConOps Implications**

- Need Flight Deck displays
- Need RTA in ATC taxi clearance

**Customers:**

FAA, avionics/EFB mfg.
Cross-Studies: Usage/Safety Implications

“How often did you find yourself focusing on the PFD Speed or Time display, when you should have been paying attention to the external taxiway environment?”