https://ntrs.nasa.gov/search.jsp?R=20190002776 2020-03-09T21:52:01+00:00Z

Flight Deck Surface Trajectory-Based Operations (STBO): A Four-Dimensional Trajectory (4DT) Simulation

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https://hsi.arc.nasa.gov/groups/HCSL

Flight Deck Simulation

Flight Deck (B737NG) Simulation:

- Pilot-in-the-Loop Simulation
- Far-Term Concept for Surface Operations
- Human-Centered Systems Lab (HCSL)
- Airport and Terminal Area Simulator (ATAS)

Airport Surface Operations

- Concepts, research efforts, programs, and activities aimed at **improving operations on the airport surface**:
  - Coordinate surface movement to:
    - reduce congestion and excessive queues at departure runways
  - Improve the predictability of surface operations:
    - specifically, takeoff time
  - Reduce the environmental impacts of taxi operations:
    - reduce inefficient stop-and-go-taxi

Surface Trajectory-Based Operations (STBO) Concept:

- Incorporates a time-component into taxi operations

Surface Trajectory-Based Operations

SJSU

Current-Day Surface Operations → **Near-Term w/ Target Times** → **Far-Term with Flight Deck Component** → . . . → **Far-Term Full 4DT Operations**

*Increasing Use of **Time Information** in Surface Trajectory-Based Operations (STBO)*

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term with Flight Deck Component

Far-Term Full 4DT Operations

Flight Deck:

1. Pushback Time

ATC:

1. Manage departure sequence

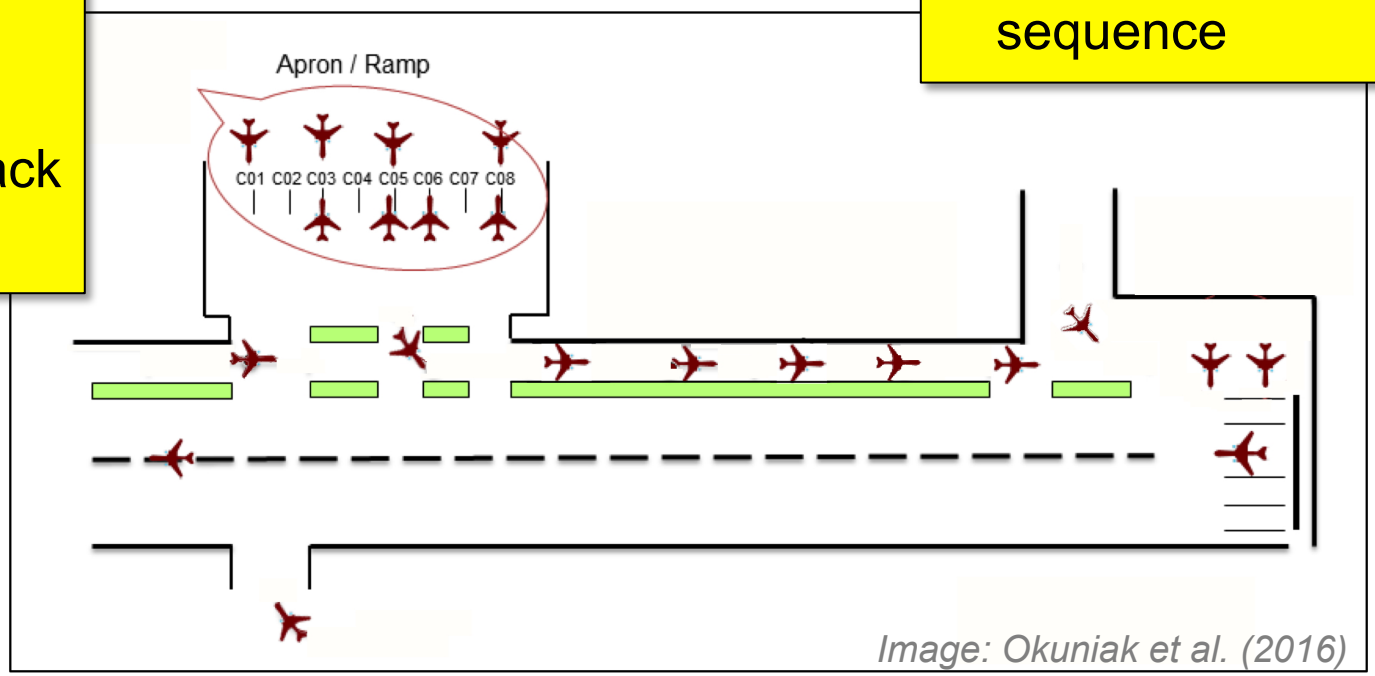

Image: Okuniak et al. (2016)

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term with Flight Deck Component

Far-Term Full 4DT Operations

***Wheels-Up Time**

Flight Deck:

1. Pushback Time
2. Wheels-up Time

No information about:

- taxi duration
- queue size

ATC:

1. Manage to ensure flight meets its assigned wheels-up time

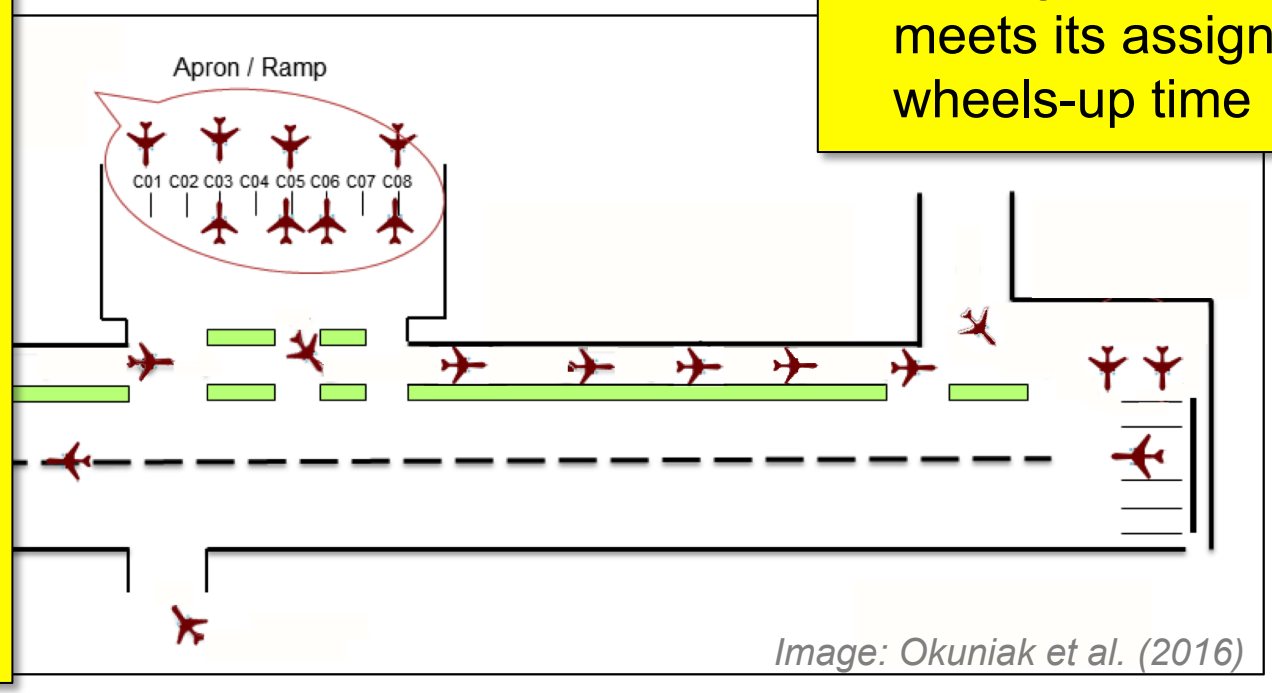

Image: Okuniak et al. (2016)

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term with Flight Deck Component

Far-Term Full 4DT Operations

Controllers provide clearances to meet target times

ATC/Ramp manages with Scheduling/ Decision Support Tools (DSTs):

- Pushback Time (TOBT)
- Airport Movement Area Time (TMAT)
- Target Take-Off Time (TTOT)

Flight Deck:

1. Pushback Time

No information about:

- taxi schedule

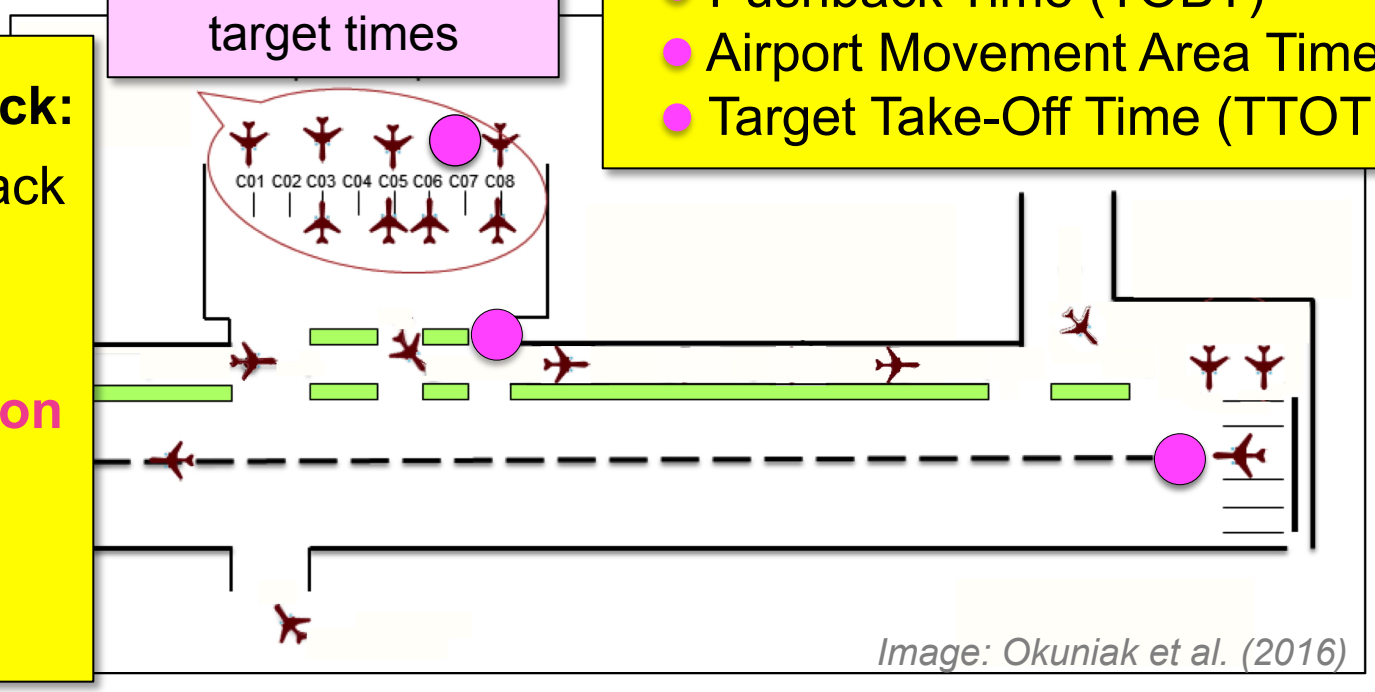

Image: Okuniak et al. (2016)

Example:

ATD2 IADS system to be deployed Charlotte Fall 2017.

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term with Flight Deck Component

Far-Term Full 4DT Operations

Flight Deck: Avionics Display/ Algorithm to support schedule conformance.

- Pushback
- AMA Time
- Takeoff Time
- Merge Points
- Active RWY
- RWY Queue

Flight Deck / ATC Coordination

Times included in Taxi Clr

ATC/Ramp: Scheduling / Decision Support Tools (DSTs):

- Pushback Time (TOBT)
- AMA Time (TMAT)
- Target Take-Off (TTOT)
- Merge, Queue, Active RWY

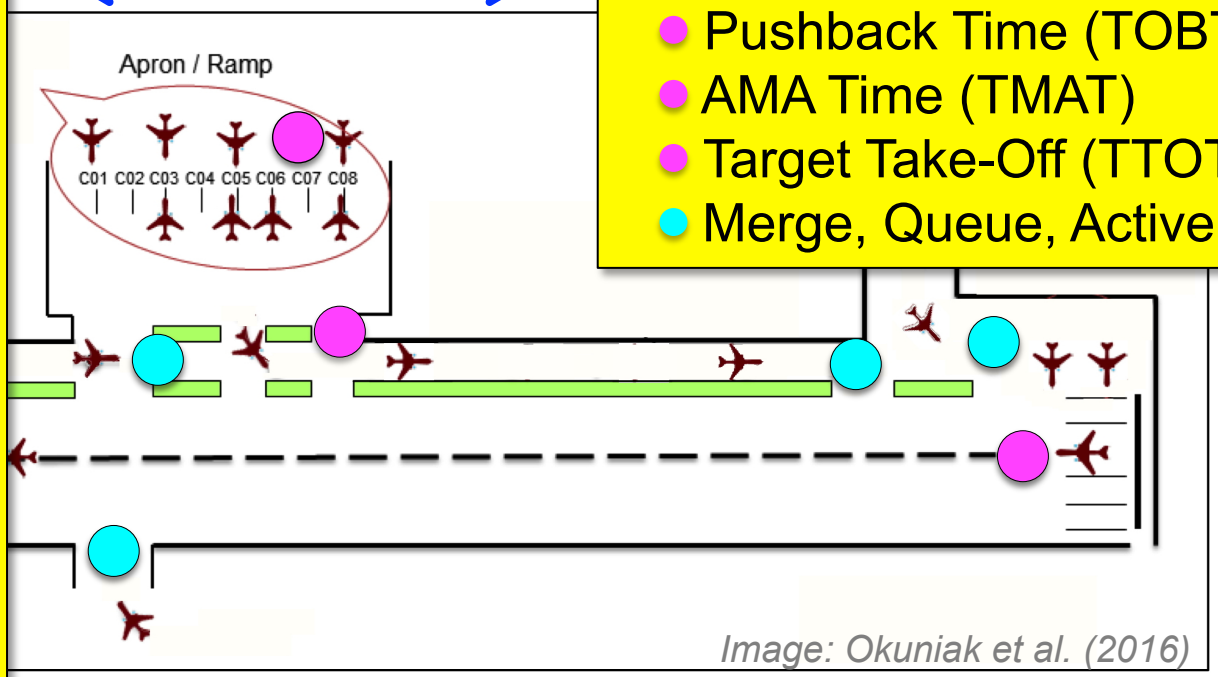

Image: Okuniak et al. (2016)

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term with Flight Deck Component

Far-Term Full 4DT Operations

Flight Deck / ATC Coordination

Times included in Taxi Clr

4DT Operations: ∞ # of time points

ATC:

Surface Management System generates conflict-free 4DT taxi clearances.

Flight Deck: Avionics Display/ Algorithm to support 4DT schedule conformance.

● Expected 4DT Location

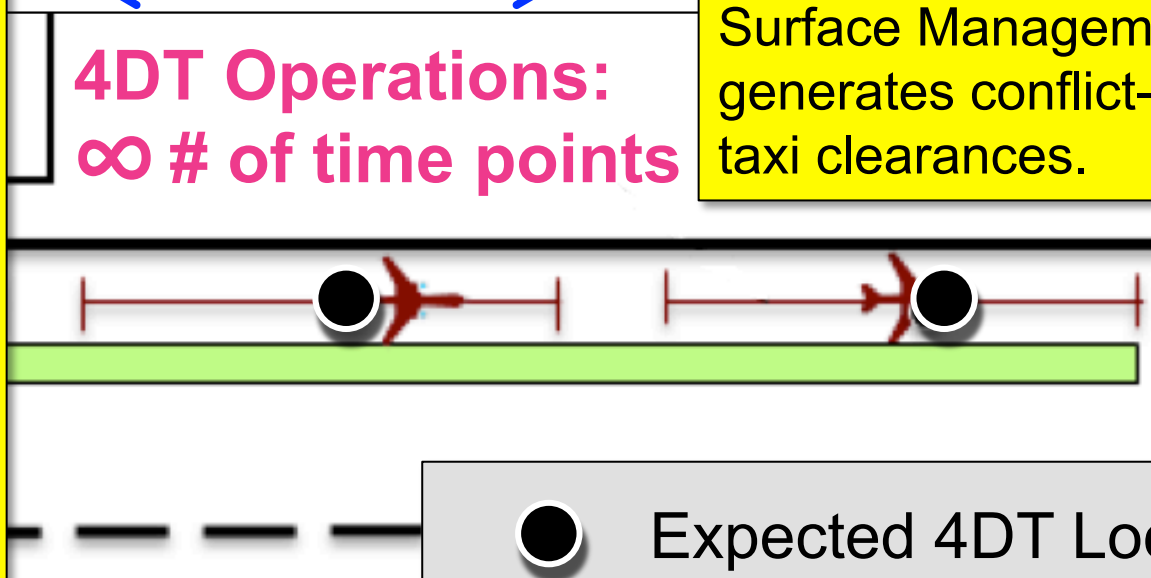

Image: Okuniak et al. (2016)

● Expected 4DT Location

Allowable 4DT Tolerance

Surface Trajectory-Based Operations

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Increasing Use of Time Information in STBO

Current-Day Surface Operations

Near-Term w/ Target Times

Far-Term wit Flight Deck Component

Far-Term Full 4DT Operations

Flight Deck / ATC Coordination

es included in Taxi Clr

ATC:

Surface Management System generates conflict-free 4DT taxi clearances.

ight Deck: Avionics Display/ Algorithm support 4 conformance.

- Expected 4DT Location

4D Operations: ∞ of time points

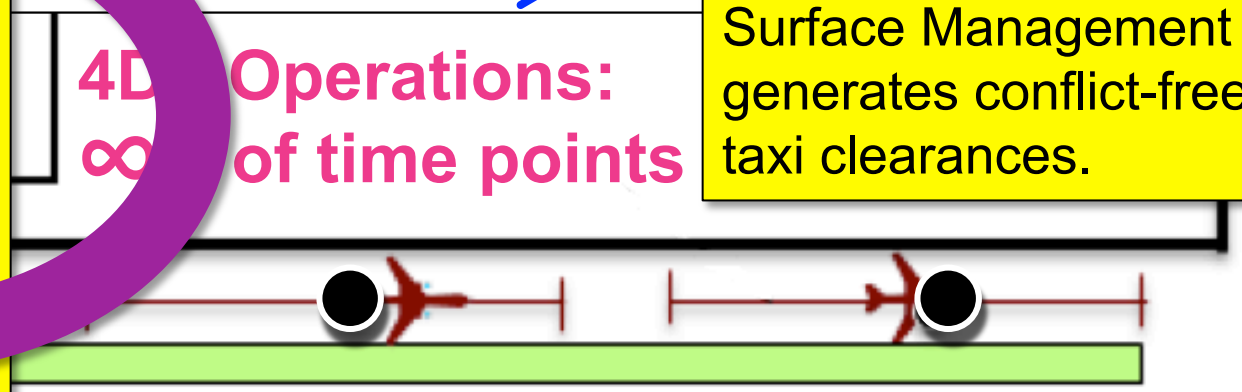

Image: Okuniak et al. (2016)

- Expected 4DT Location
- Allowable 4DT Tolerance

4DT Surface Trajectory-Based Ops

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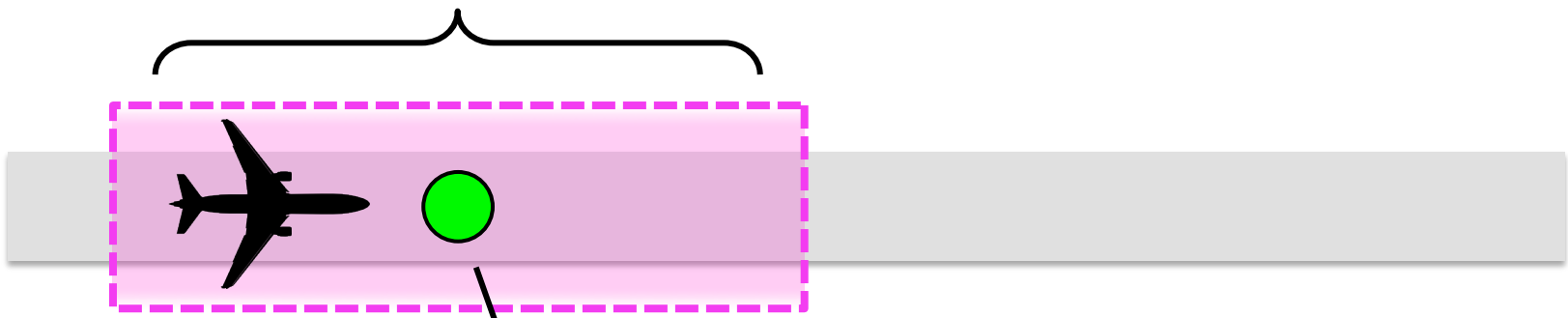
Four-Dimensional Trajectory (4DT) Concept:

- Expected Location (*x, y)* based on 4DT Speed Profile
- At all times, *t,* along the taxi route
- Altitude is fixed on the surface

Hooey, Cheng, & Foyle (2014)
Okuniak, Gerdes, Jakobi, Ludwig, Hooey, Foyle, Jung, & Zhu (2016)

Allowable Tolerance around 4DT Speed Profile



Expected 4DT Location
(*x, y* at all times along the taxi route)

4DT Surface Trajectory-Based Ops

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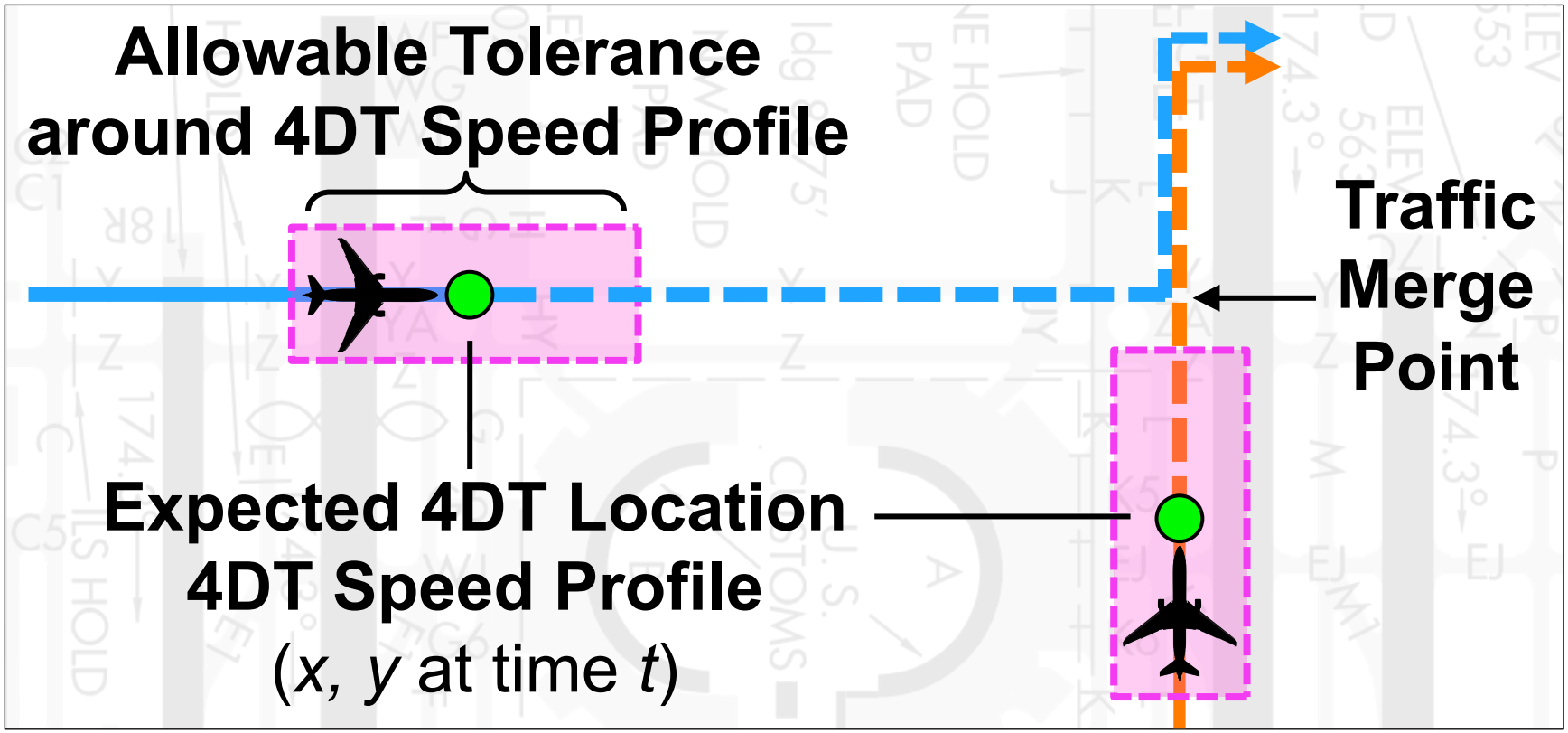
Four-Dimensional Trajectory (4DT) Concept:

- Enables coordination of all surface traffic
- Ensures conflict-free taxi routes
- Goals: Improve efficiency, predictability; reduce fuel burn



4DT Surface Trajectory-Based Ops

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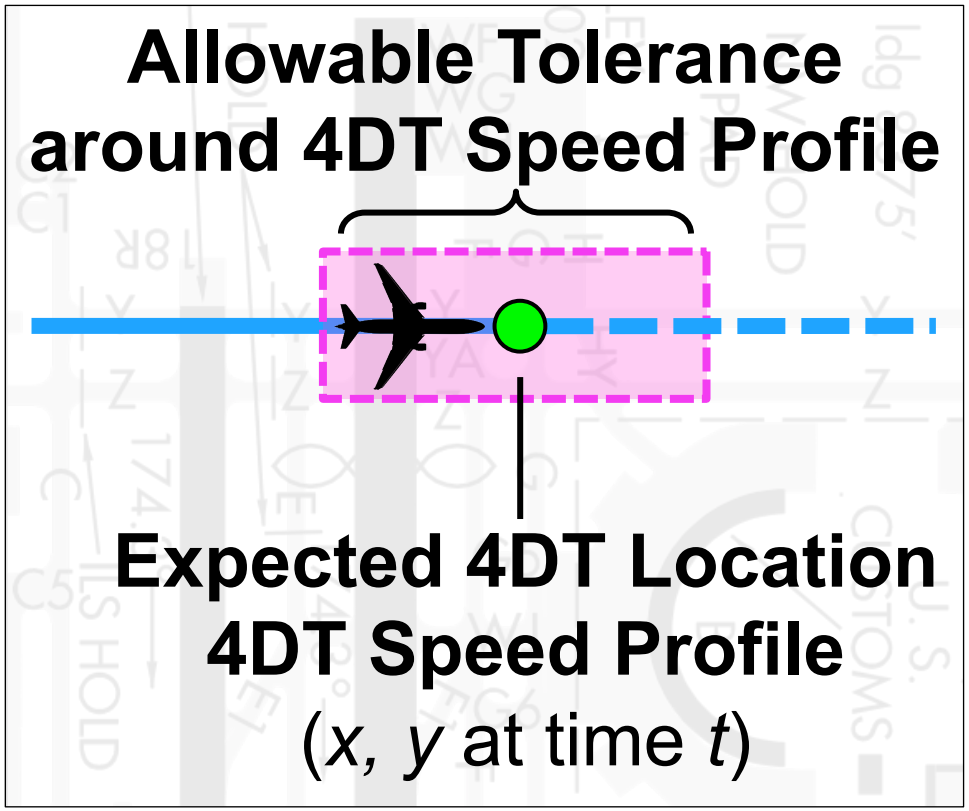
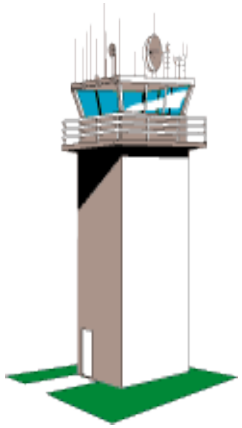
Four-Dimensional Trajectory (4DT) Concept:

- Assumes the use of an ATC surface management system
- Schedules surface traffic, generates a 4DT clearance for each aircraft, monitors conformance, resolves conflicts



Surface Management System

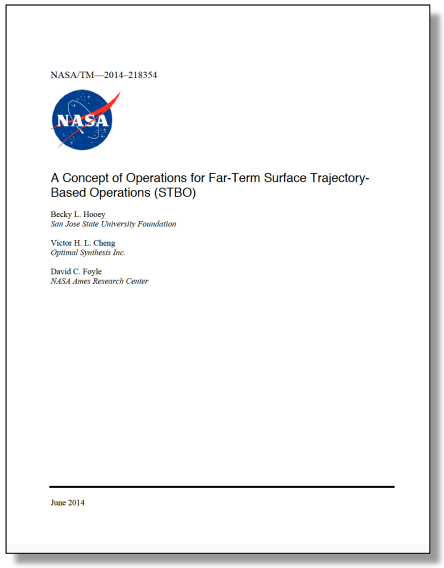


- **German Aerospace Center (DLR)**
  - Research prototype system, *TRACC*

Gerdes & Temme (2012)

4DT Surface Trajectory-Based Ops

4DT Concepts of Operations (ConOps)



NASA/TM—2014–218354

A Concept of Operations for Far-Term Surface Trajectory-Based Operations (STBO)

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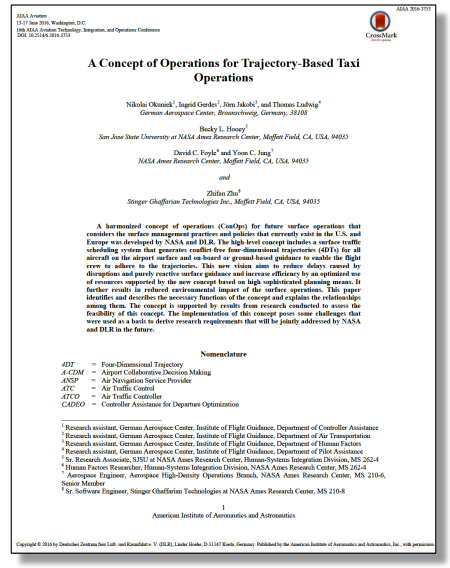
June 2014



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AIAA 2016-3753

A Concept of Operations for Trajectory-Based Taxi Operations

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A harmonized concept of operations (ConOps) for future surface operations that considers the surface management practices and policies that currently exist in the U.S. and Europe was developed by NASA and DLR. The high-level concept includes a surface traffic scheduling system that generates conflict-free four-dimensional trajectories (4DTs) for all aircraft on the airport surface and on-board or ground-based guidance to enable the flight crew to adhere to the trajectories. This new vision aims to reduce delays caused by disruptions and purely reactive surface guidance and increase efficiency by an optimized use of resources supported by the new concept based on high sophisticated planning means. It further results in reduced environmental impact of the surface operations. This paper identifies and describes the necessary functions of the concept and explains the relationships among them. The concept is supported by results from research conducted to assess the feasibility of this concept. The implementation of this concept poses some challenges that were used as a basis to derive research requirements that will be jointly addressed by NASA and DLR in the future.

Nomenclature

4DT = Four-Dimensional Trajectory
A-CDM = Airport Collaborative Decision Making
ANSP = Air Navigation Service Provider
ATC = Air Traffic Control
ATCO = Air Traffic Controller
CADEO = Controller Assistance for Departure Optimization

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Far-Term Surface Trajectory-Based Operations (STBO) ConOps

Hooey, Cheng, & Foyle (2014)

Harmonized U.S. / European Trajectory-Based Taxi Operations ConOps

Okuniak, Gerdes, Jakobi, Ludwig, Hooey, Foyle, Jung, & Zhu (2016) (DLR and NASA)

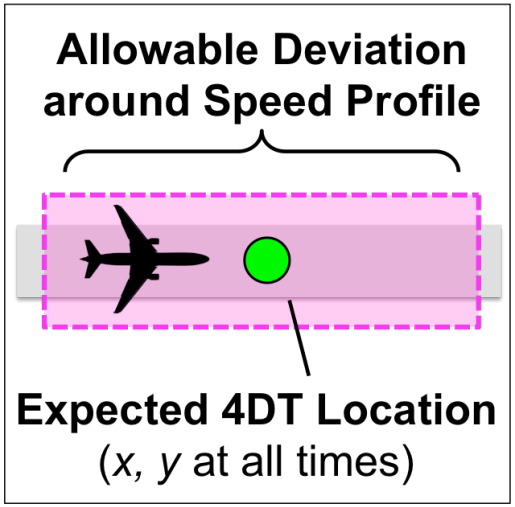
Previous Flight Deck 4DT Study

Supporting 4DT STBO on the Flight Deck:

- Previous pilot-in-the-loop 4DT Flight Deck simulation
- Airport Moving Map (AMM) augmented with 4DT taxi clearance information.

Bakowski, Hooey, Foyle, & Wolter (2015)

4DT Speed Profile and Taxi Routing Information



Flight Deck Display: Airport Moving Map (AMM)

Airport Moving Map (AMM)

Flight Deck Display: Airport Moving Map (AMM)

Airport Moving Map (AMM)

4DT Information on Airport Moving Map (AMM)

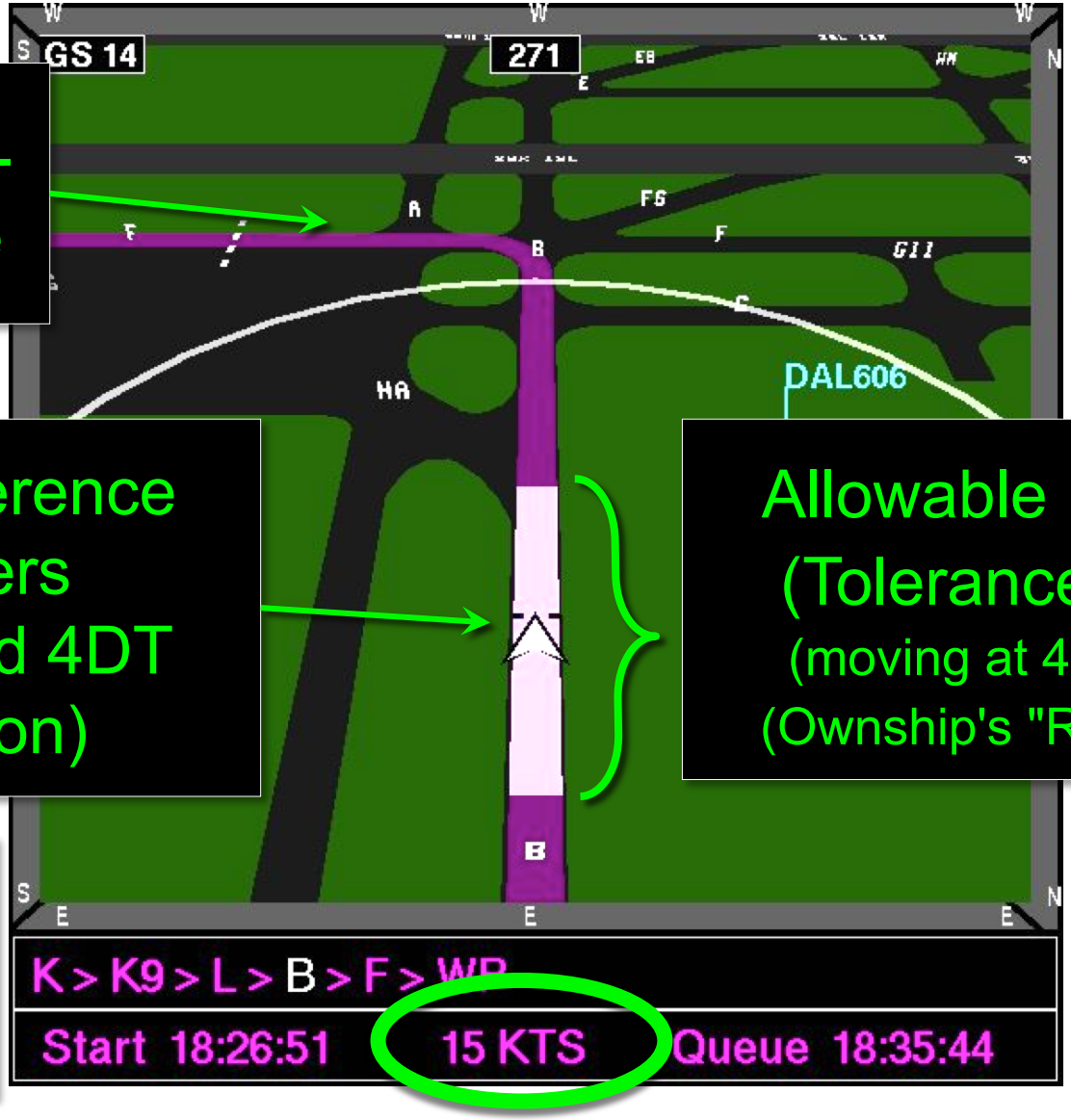
Cleared-to-Taxi Route

4DT Reference Markers (Expected 4DT Location)

Allowable Deviation (Tolerance Bound)
(moving at 4DT Speed)
(Ownship's "Real Estate")

4DT Clearance Speed

4DT Clearance Text



Previous Flight Deck 4DT Study

Previous Pilot-in-the-Loop 4DT Simulation:

– Along-Route Conformance: % Time in Allowable Tolerance

Bakowski, Hooey, Foyle, & Wolter (2015)

Speed-Advisory (No 4DT on AMM)

Verbal Clearance: "Taxi at 14 kts"

4DT +/- 30 sec

4DT Info on AMM

4DT +/- 15 sec

4DT Info on AMM

Previous Flight Deck 4DT Study

SJSU

Previous Pilot-in-the-Loop 4DT Simulation:

– Along-Route Conformance: % Time in Allowable Tolerance

Bakowski, Hooey, Foyle, & Wolter (2015)

Speed-Advisory (No 4DT on AMM)

Along-Route Conformance

+/-15 sec 20%

+/-30 sec 72%

4DT +/- 30 sec

Along-Route Conformance

99%

4DT +/- 15 sec

Along-Route Conformance

99%

Present Flight Deck 4DT Study

Previous Simulation	Present Simulation
One 4DT Display Format	4DT Format Comparison
4DT Straightaway Speed held constant in each trial	4DT Speed Changes Mid-Taxi
4DT Speeds: 14, 15, or 16 kts	Range of Realistic Taxi Speeds: 8 kts – 25 kts
4DT Route Start: Spot	4DT Route Start: at Gate
Time-based Tolerance	Distance-based Tolerance
Dallas/Fort-Worth Airport	Charlotte Douglas Airport
Bakowski, Hooey, Foyle, & Wolter (2015)	*Bakowski, Hooey, & Foyle (2017)*

Airport and Terminal Area Simulator

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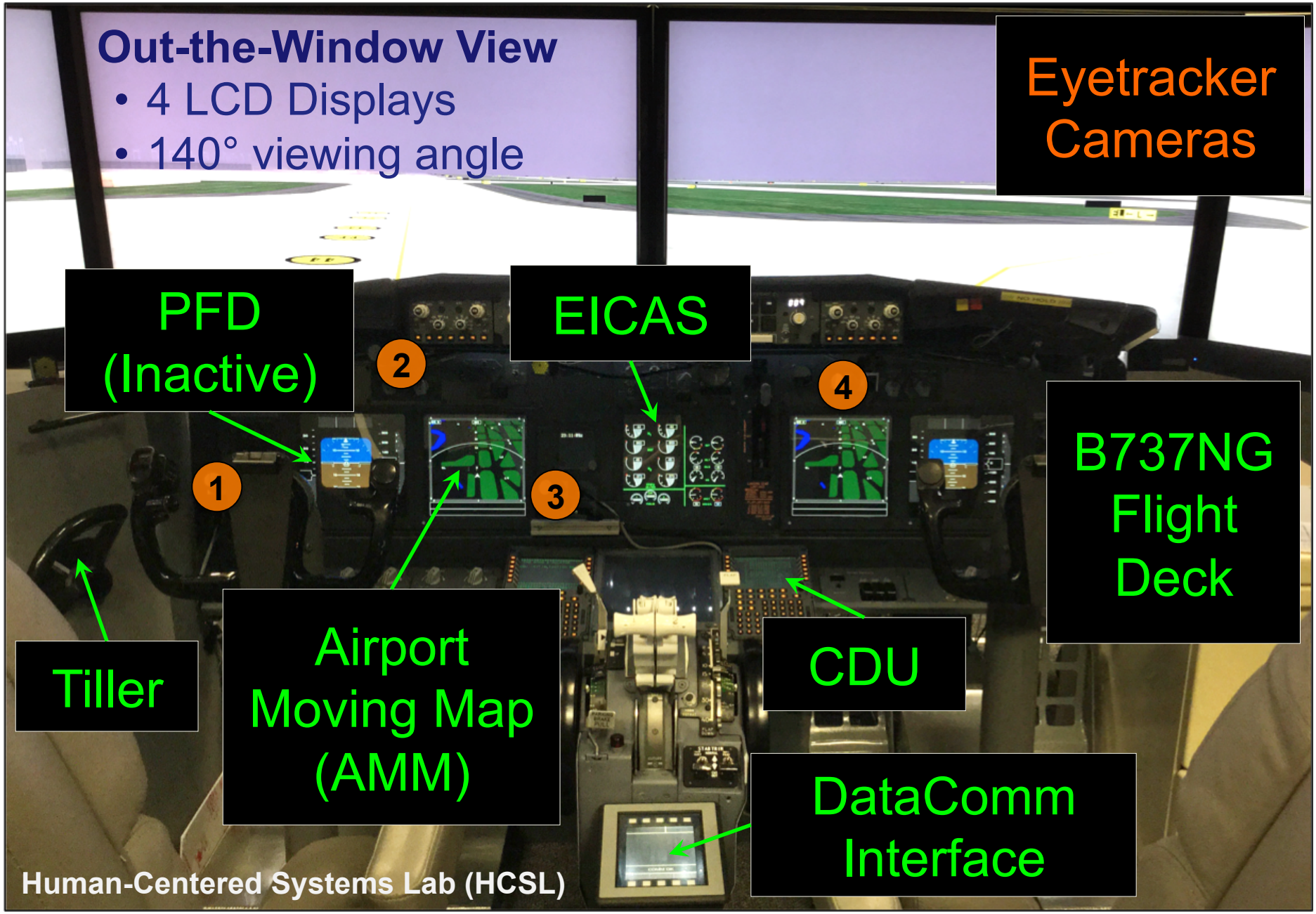
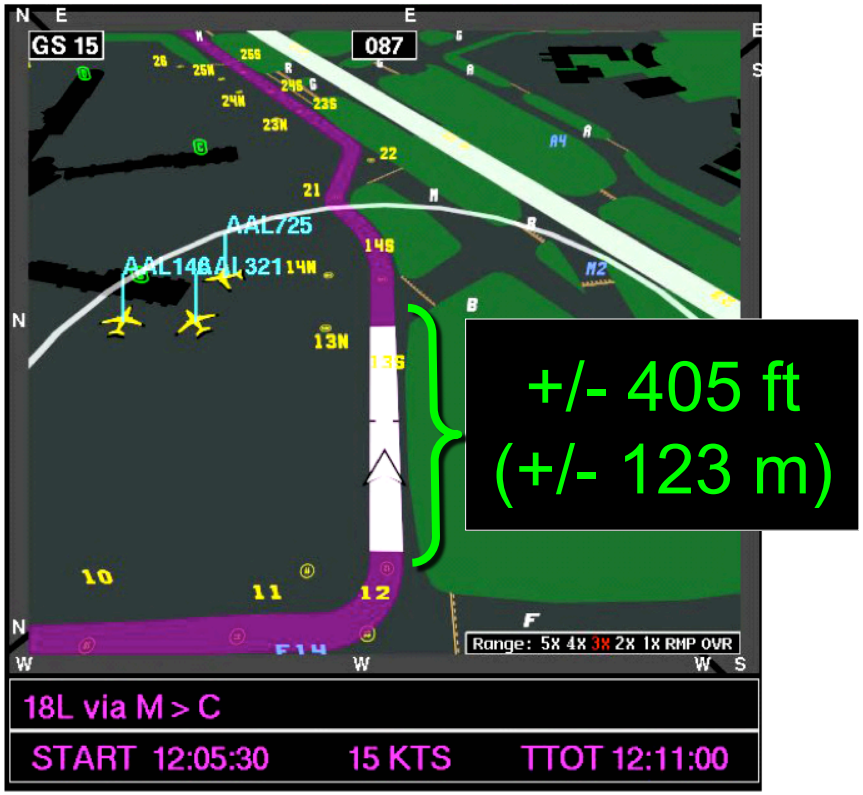


4DT Display Formats

Defined-Conformance Display Format

– Distance-based Tolerance Bands (length constant)

Proposed distance threshold in DLR's TRACC system for conformance monitoring.

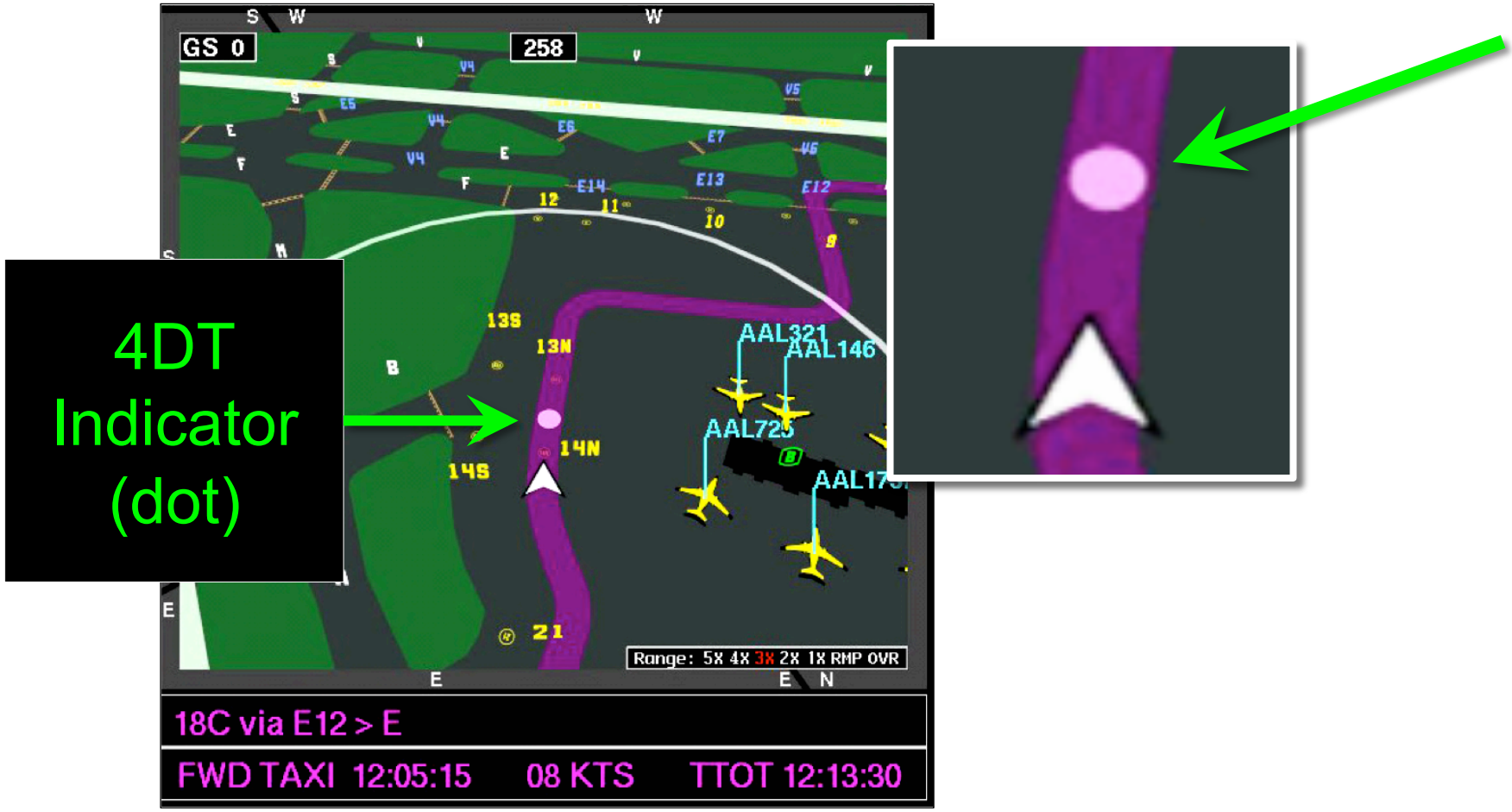


Approximates the length of smaller band from the previous study.

4DT Display Formats

Undefined-Conformance Display Format

- 4DT Indicator: Expected 4DT location (*x, y* at all times, *t*)
- No Allowable Tolerance displayed; Undefined 4DT deviation



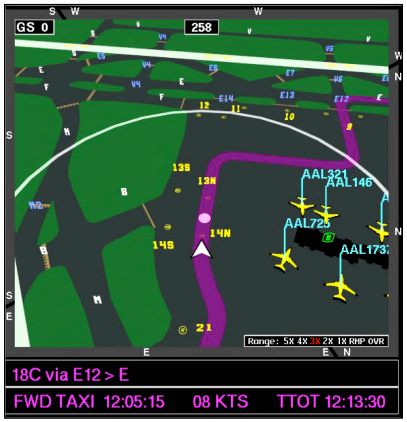
4DT Display Formats

Instructions to Pilots

Defined-Conformance Format

- "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."

Undefined-Conformance Format

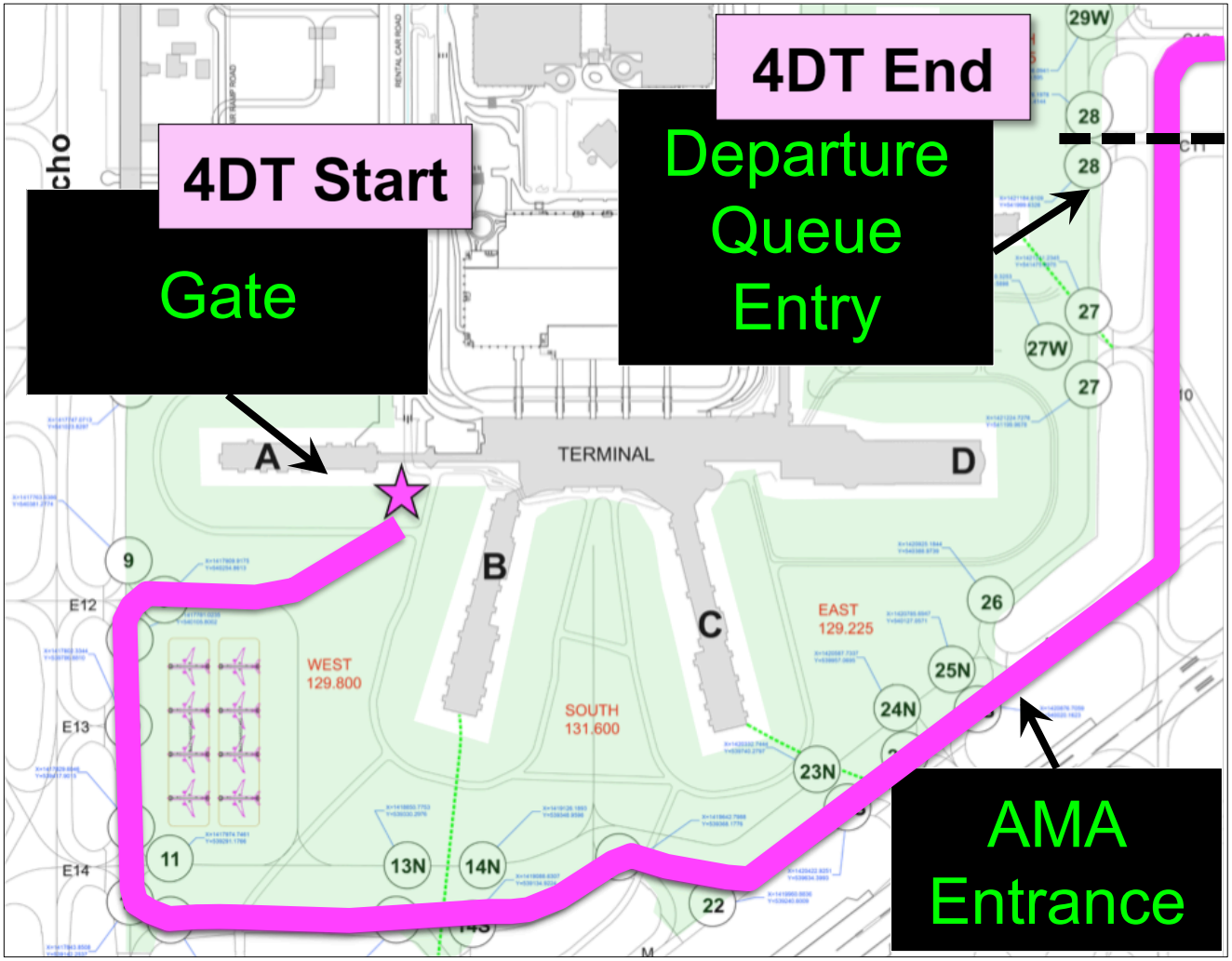


- "You decide how "close is close enough" to taxi to the dot and you can taxi ahead of, or behind, the 4DT dot."
- **Pilots defined conformance as they saw fit.**

4DT Taxi Route

4DT Taxi Clearance

– One continuous clearance from Gate to RWY Queue



Average Taxi Distance: 6,633 ft

Average Trial Duration: 12 min

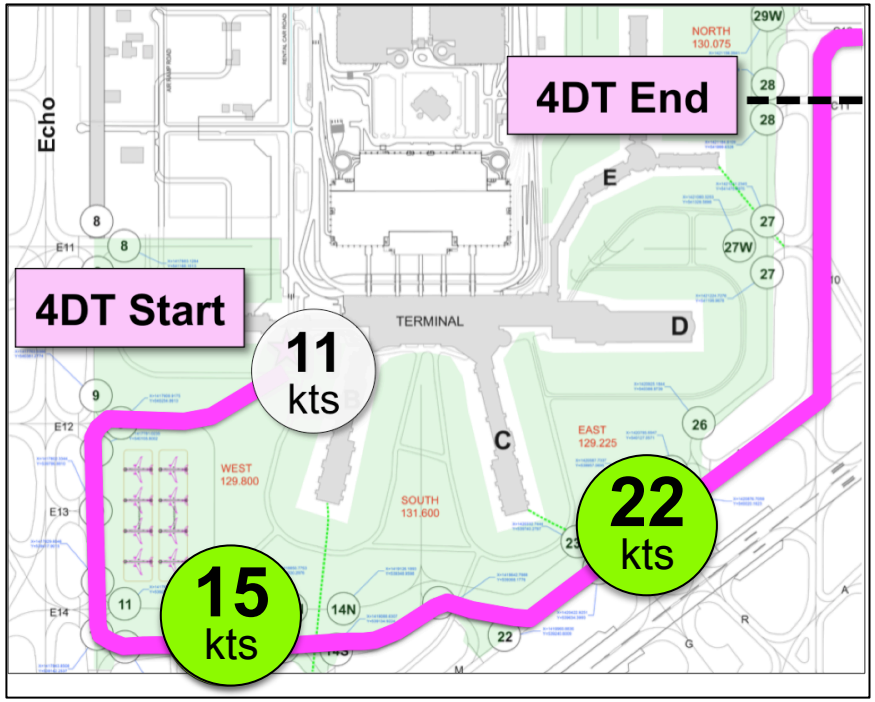
4DT Speed Changes During Taxi

4DT Speed Changes

- Each trial included 2 or 5 4DT Speed Changes during taxi
- Flight deck alerted to speed change by auditory tone

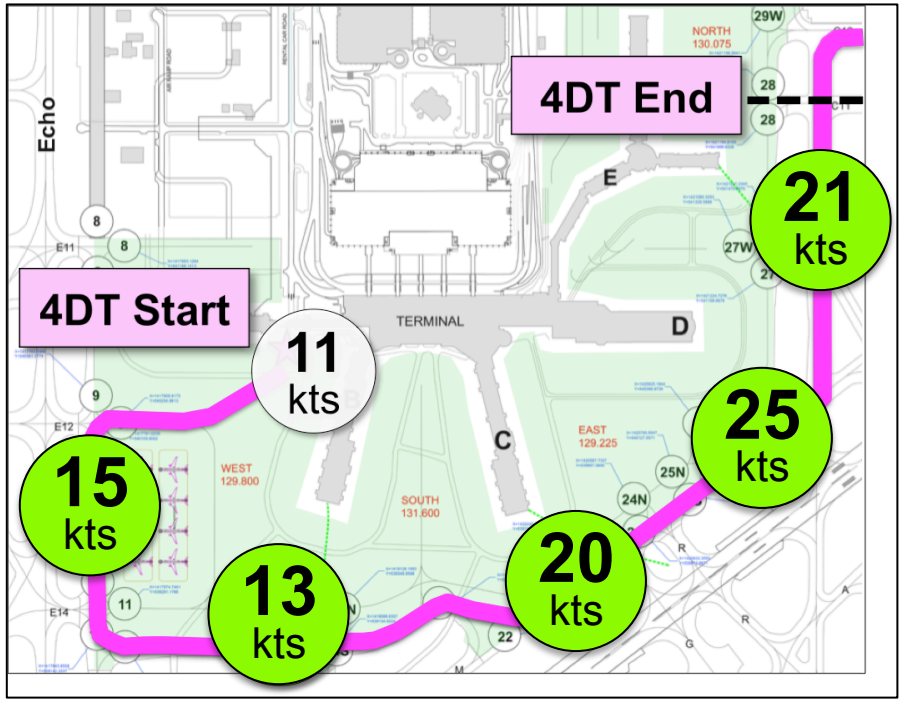
2 Speed Changes

(Segment distance: 1,645 ft – 2,834 ft)



5 Speed Changes

(Segment distance: 887 ft – 1,630 ft)



4DT Taxi Speeds

Range of Realistic Taxi Speeds, 8 kts – 25 kts

- Assigned speeds to taxi segments in such a way as to create 'Slow' and 'Fast' average speed trials.
- Slower speeds used in the Ramp Area than in AMA because of proximity to terminal, other aircraft, and turns.

8 kts | 9 kts | 11 kts | 13 kts | 14 kts | 15 kts | 16 kts | 19 kts | 20 kts | 21 kts | 22 kts | 25 kts

	Ramp	Airport Movement Area (AMA)
'Slow' Avg. Speed	10 kts	16 kts
'Fast' Avg. Speed	13 kts	22 kts

Flight Deck Crew

Pilot Participants

- Assumed the role of Captain in the simulation
- 12 Commercial/Cargo Pilots participated in the simulation:
  - 11 were Captains, one was a First Officer
  - 11 were Current, one was recently retired
  - Average age: 56 years
  - All 12 pilots had taxi experience

A member of the research team assumed the role of the First Officer in the simulation to create 2-person crews:

- First Officer provided navigation and traffic awareness support in a consistent manner to each pilot
- Acknowledged 4DT speed changes, "Speed Change"

Experimental Taxi Scenario

4DT Taxi Clearance

- 4DT Taxi Clearance sent to the Flight Deck via DataComm
- 4DT information propagates into Flight Deck Avionics

4DT Taxi Clr. DataComm

- Taxi Route/RWY
- 4DT Schedule Info

12:01:30 Z FROM KCLT	OPEN

ATS227
RWY 18L
VIA M C

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

COMM OK

UNABLE | STBY | WILCO

Cleared-to-Taxi Route

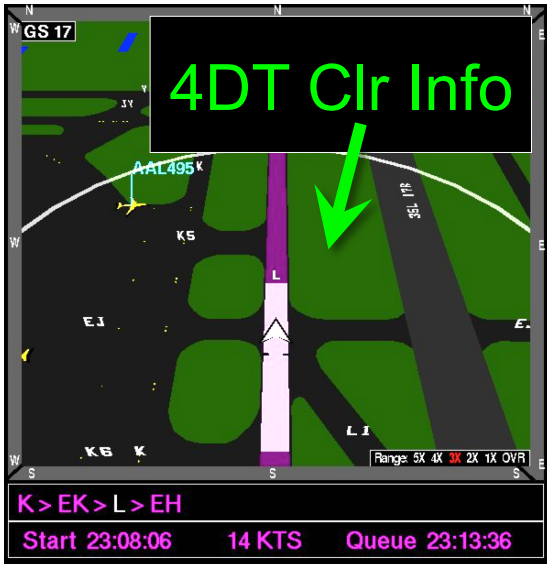
Cleared-to-Taxi Route

4DT Clearance Information

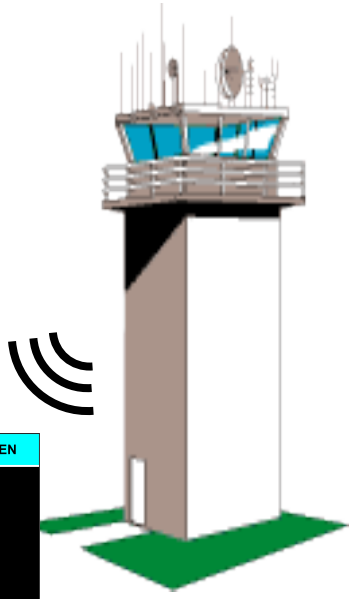
4DT Clearance Info on the Flight Deck

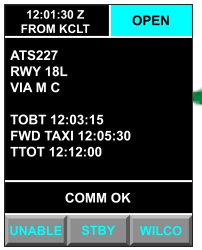
DataComm Enables Flight Deck / ATC Coordination in 4DT Operations

Flight Deck Avionics:
Airport Moving Map



ATC Surface Management System:
Generates conflict-free 4DT taxi clearances





4DT Clearance to Flight Deck via DataComm

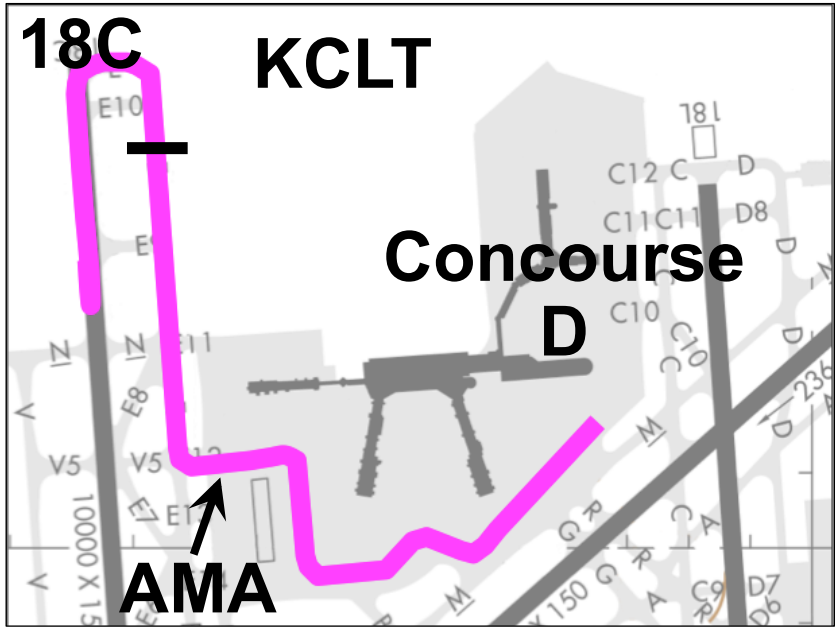
4DT Clearance Loaded into Flight Deck Avionics

Airport Environment

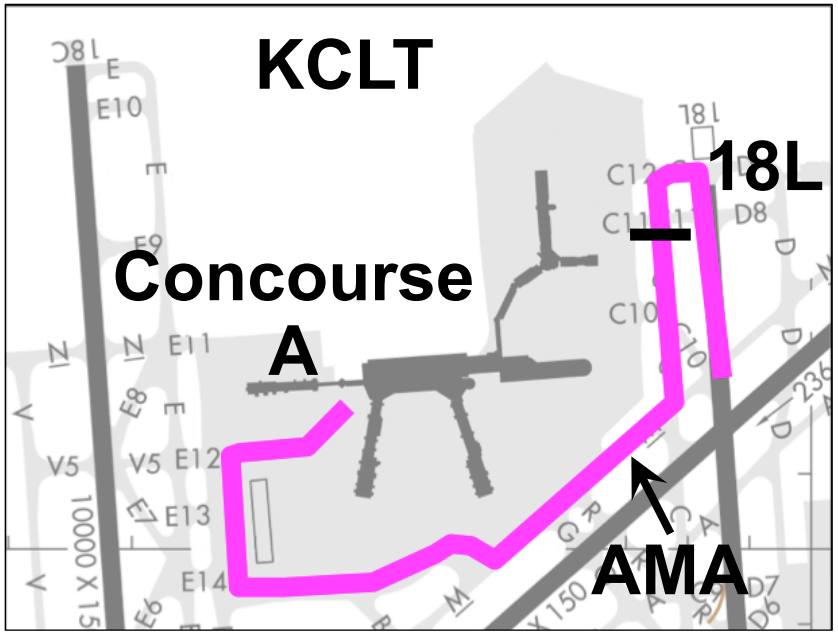
Charlotte Douglas Airport (KCLT)

- Departure taxi-out trials
- Two taxi routes
- 4DT Route extends from Gate to RWY queue
- Traffic in the Ramp Area and at the RWY (did not conflict)

Concourse D to RWY 18C



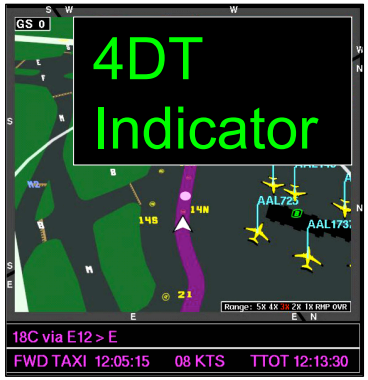
Concourse A to RWY 18L



Taxi Simulation Trials

12 Experimental Trials

- Created by repeating the four Speed Change/Speed trials:
  - **2** Speed Changes / '**Slow**' Average Speed
  - **2** Speed Changes / '**Fast**' Average Speed
  - **5** Speed Changes / '**Slow**' Average Speed
  - **5** Speed Changes / '**Fast**' Average Speed
- In each of the three Display Format conditions:

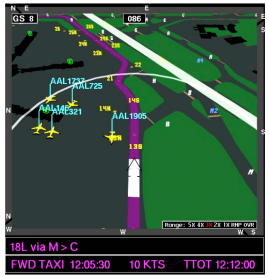


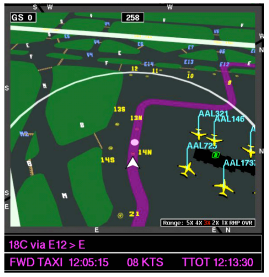
- Display conditions were blocked and counterbalanced
- Practice trial before each Display Format block

Present Study

Taxi Simulation Variables

- 4DT Display Formats
  - Defined Tolerance +/- 164 ft (+/- 50 m)
  - Defined Tolerance +/- 405 ft (+/- 123 m)
  - Undefined Tolerance (dot)
- 4DT Speed Changes (2 or 5 per trial)
- 4DT Speeds (8 kts – 25 kts) ('Slow' or 'Fast')





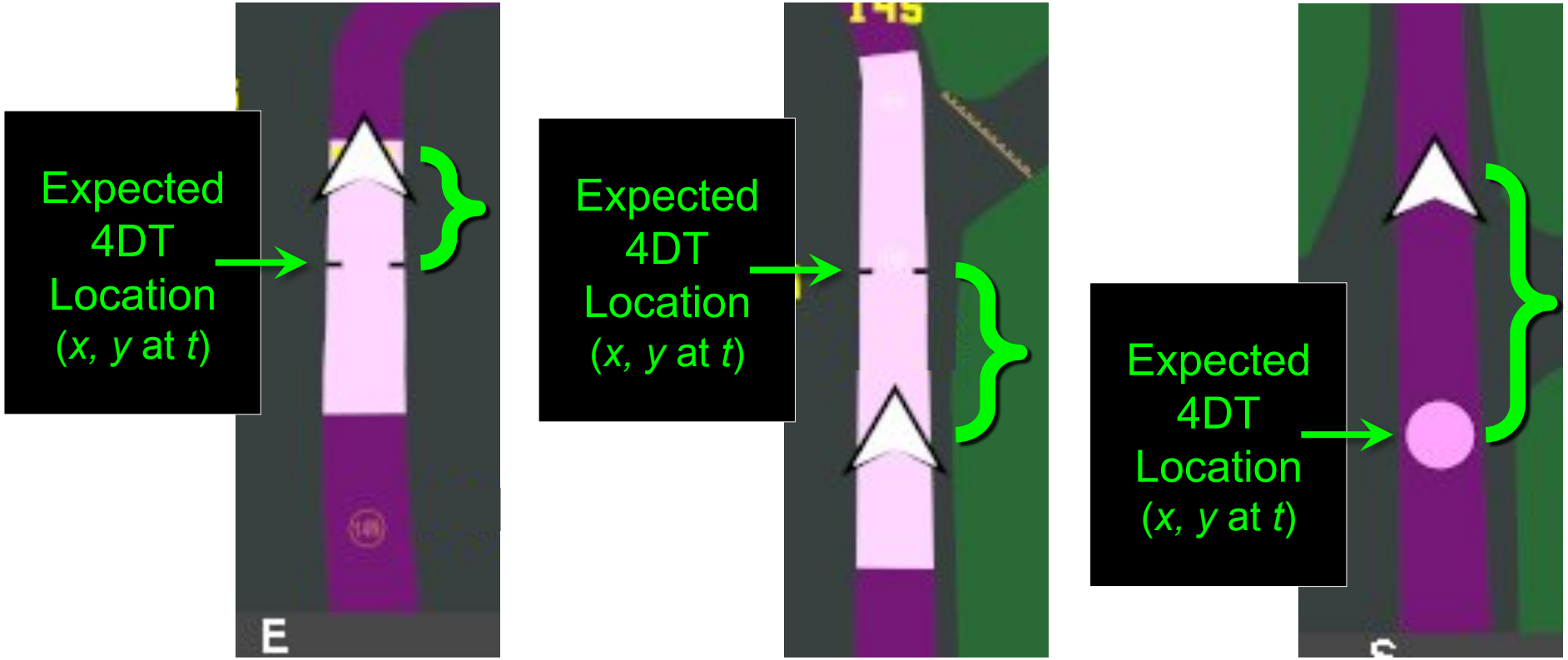
Results

- Conformance to the 4DT Clearance
  - Distance between Ownship and Expected 4DT Location
  - Percent Time Ownship within a Distance Range
- Eyes-Out Time (eye-tracker data)
- Pilot ratings of eyes-out time, safety, and workload

Results

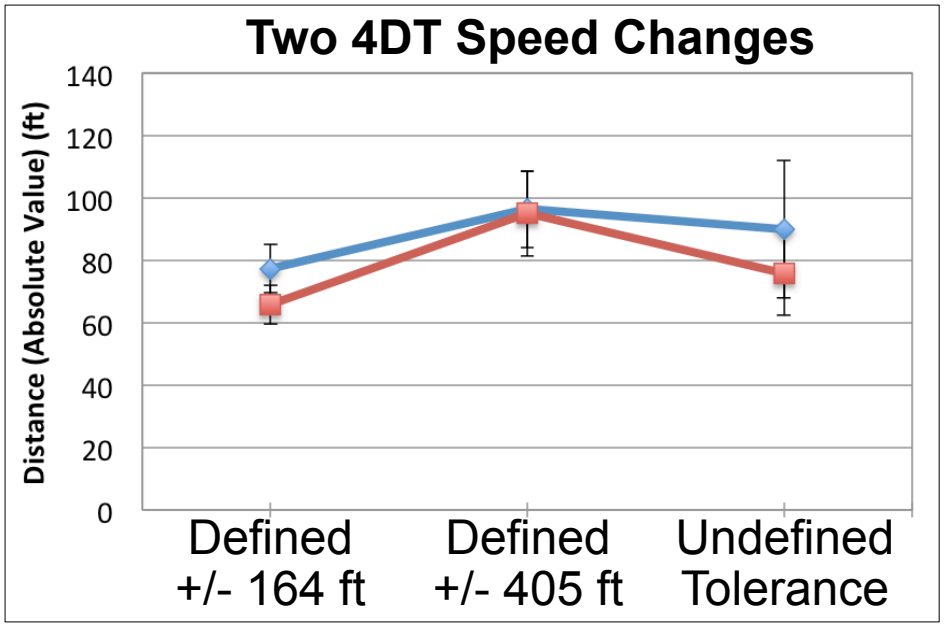
Distance (Absolute Value) from 4DT Indicator

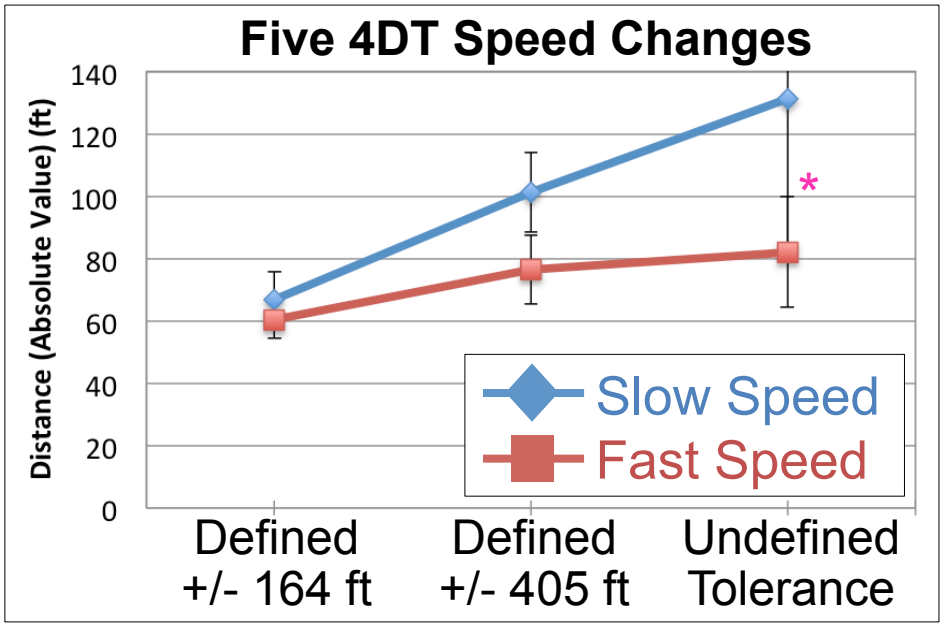
- Distance between Ownship and Expected 4DT Location
- Distance from 4DT Location recorded during taxi (20 hz)
- Absolute Value: Ownship in front of or behind 4DT location



Results

Distance (Absolute Value) between Ownship and Expected 4DT Location





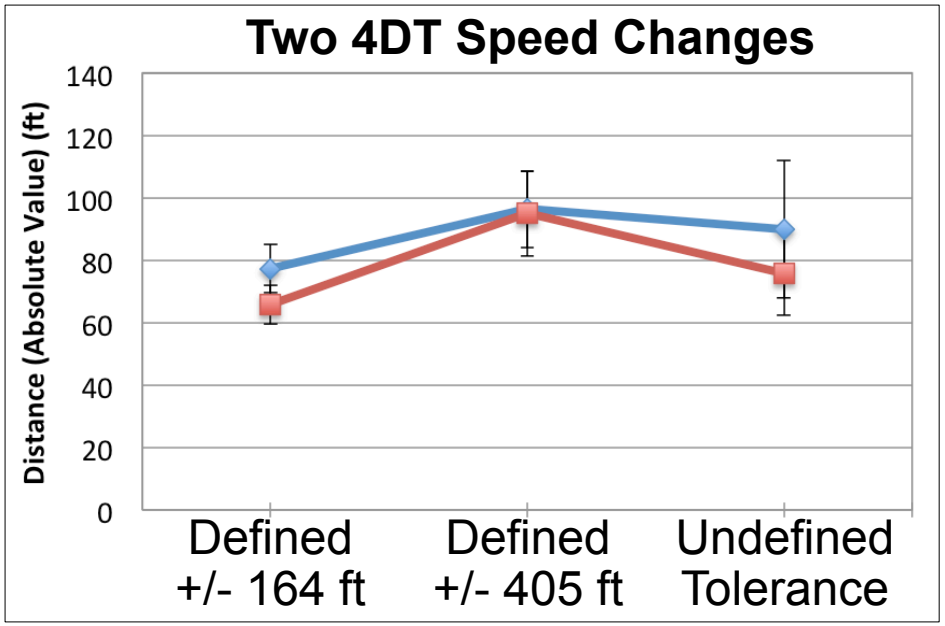
3 (4DT display format) by 2 (4DT speed) by 2 (4DT speed changes) repeated-measures ANOVA:
4DT speed by number of 4DT speed changes interaction, $F(1,11) = 5.13$, $p < .05$*

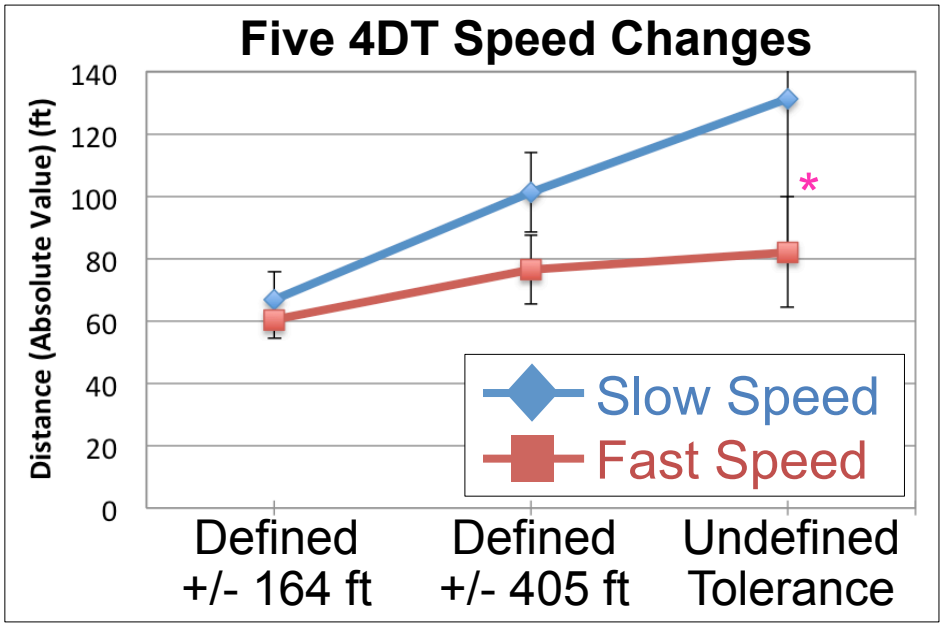
Pilots taxied a greater distance from the expected 4DT location:

- In the +/- 405 ft Defined-Tolerance Condition (92.2 ft) than in +/- 164 ft (67.5 ft).
  - However, in both conditions, pilots taxi well-within the defined-conformance bounds.
- In the 'slow' avg. speed condition (93.8 ft) than in 'fast' avg. speed (75.9 ft).
  - Pilots indicated that it may be challenging to maintain slower speeds (8 or 9 kts) and may require more control inputs (e.g., braking). Pilots use their brakes sparingly during taxi.
- In the 5 4DT speed change condition (86.3 ft) than with 2 changes (83.3 ft).
  - Considerations for the frequency, and magnitude of, 4DT speed changes in 4DT operations.

Results

Distance (Absolute Value) between Ownship and Expected 4DT Location





3 (4DT display format) by 2 (4DT speed) by 2 (4DT speed changes) repeated-measures ANOVA:
4DT speed by number of 4DT speed changes interaction, $F(1,11) = 5.13$, $p < .05$*

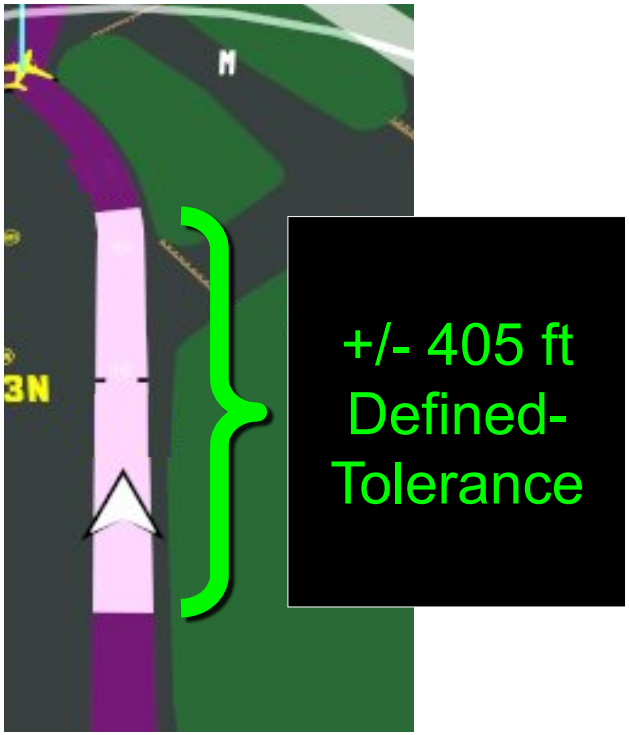
Pilots taxied a greater distance from the expected 4DT location:

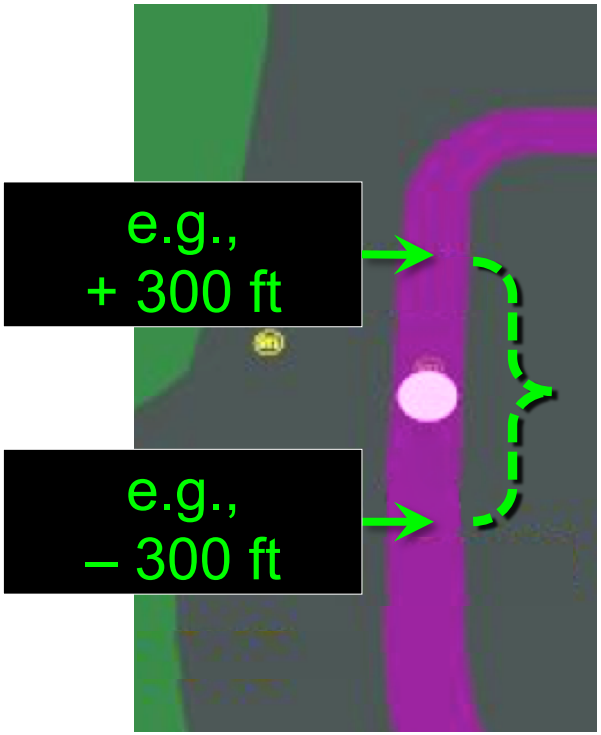
- Average distance in the +/- 405 ft and Undefined (dot) are similar.
  - However, the *range* of distances was larger in the Undefined-Tolerance Format (taxi strategy).
  - The Undefined-Tolerance (dot) Display Format allowed pilots to interpret ‘conformance’ and employ different taxi strategies.
  - One pilot maintained a distance well ahead of the 4DT indicator in the 'slow' average speed/five-speed change trial to ensure precise arrival at the queue.*

Results

Percent Time Ownship in a Distance Range

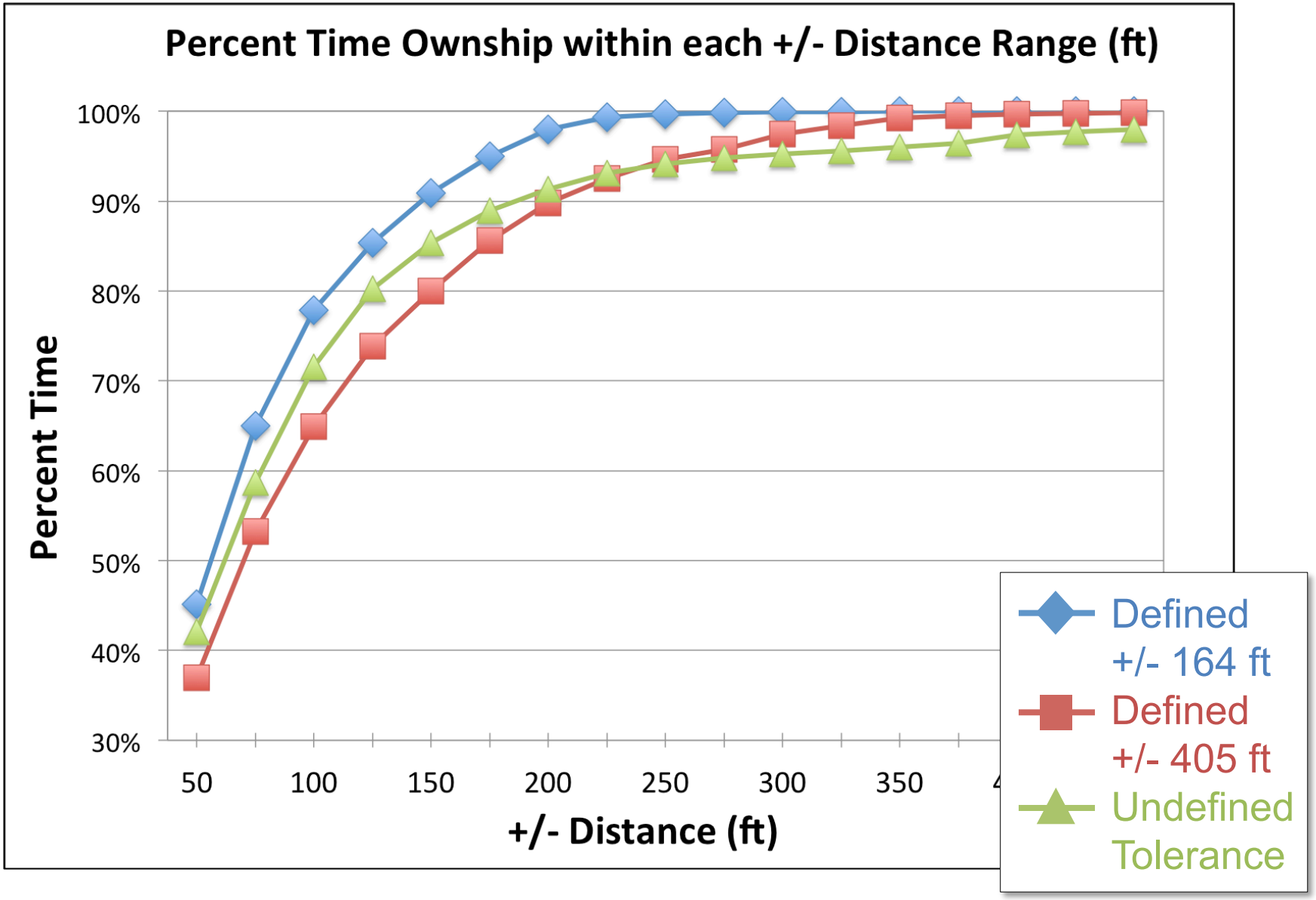
- Percentage of total route time the ownship taxied within:
  - A tolerance bound in the Defined-Tolerance Display condition, or
  - A given distance range (+/- x ft) around the expected 4DT location





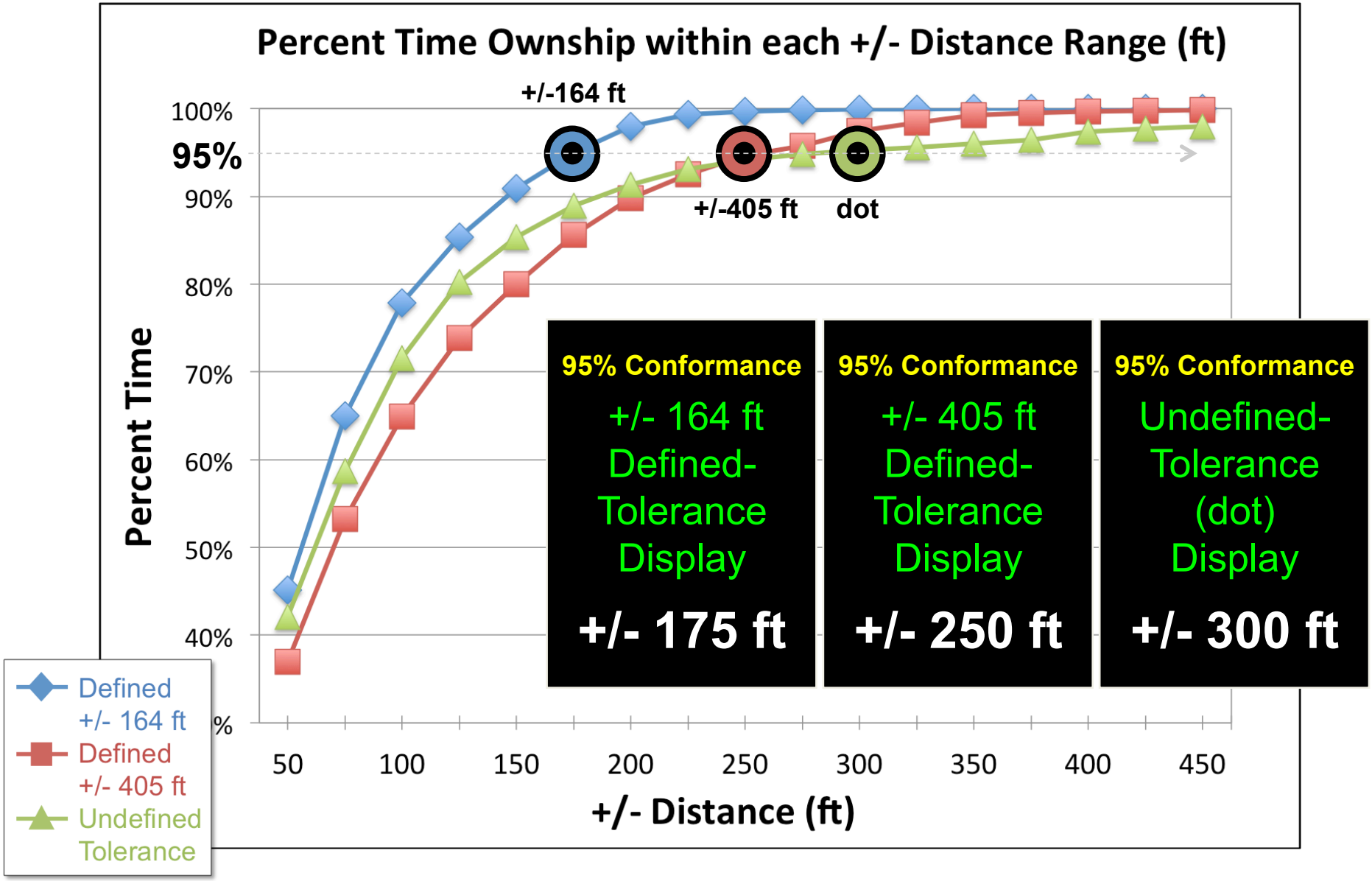
Results

Percent Time the Ownship was in a given Distance Range



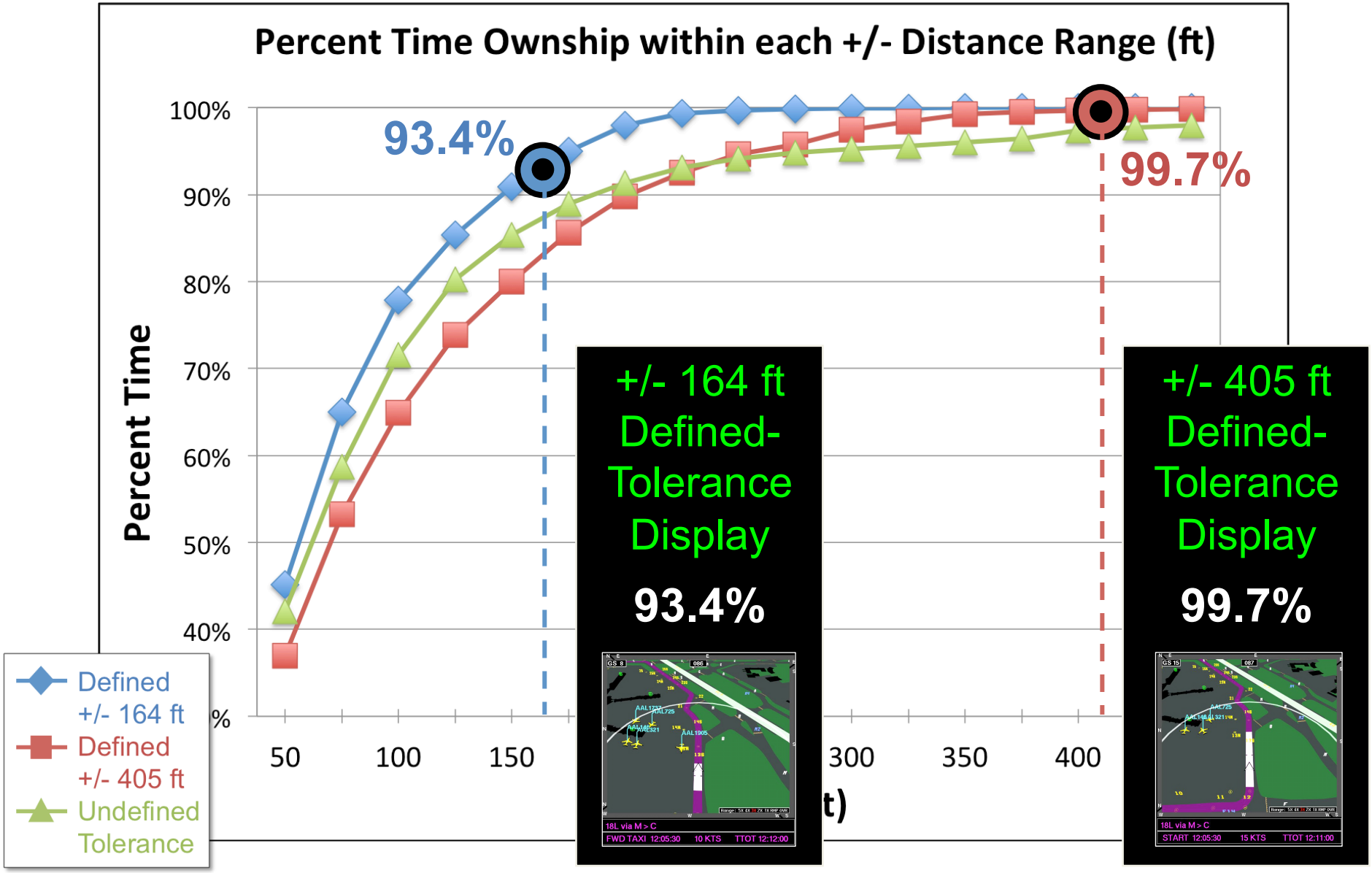
Results

95% Conformance: Distance Range in which Pilots Taxied 95% of Route



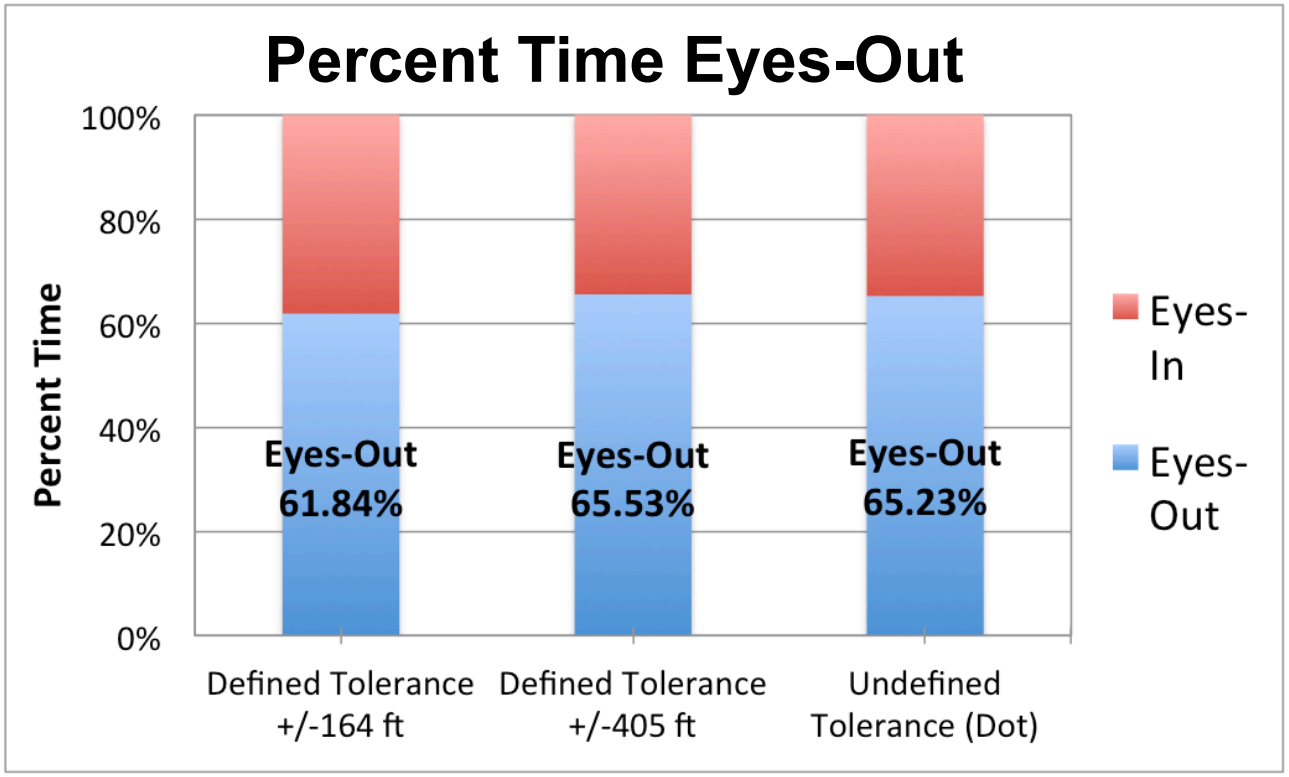
Results

Conformance in the Defined-Tolerance Band Conditions



Eyes-Out Time

Time spent scanning Out-the-Window (OTW) during taxi



3 (4DT display format) by 2 (4DT speed) by 2 (4DT speed changes) repeated-measures ANOVA:
Main effect of 4DT Display Format $F(2,16) = 3.17$, $p = .069$; Main effect of 4DT Speed Changes $F(1,8) = 5.24$, $p = .051$

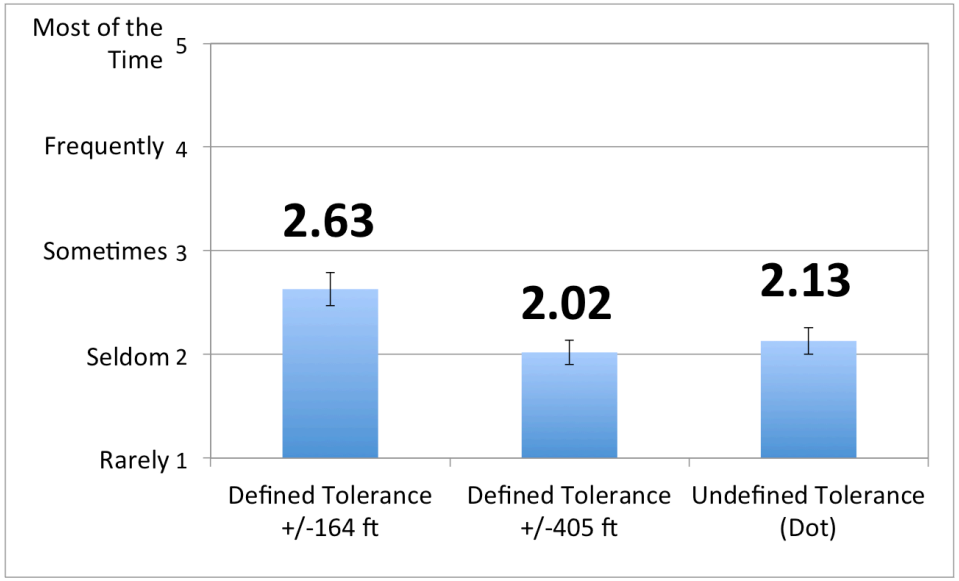
Less Time Scanning OTW:

- In the smaller +/- 163 ft Defined-Conformance Condition (61.8%).
- In the five-speed change condition (63.1%) vs. two changes (65.3%).

Pilot Assessment of Eyes-In Time

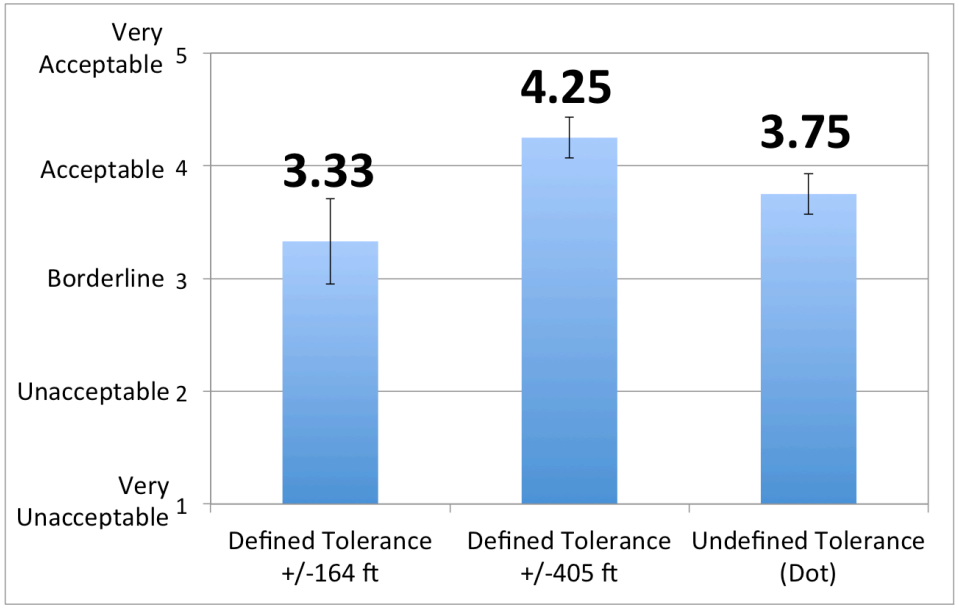
Eyes-In Time Frequency

During this trial, how often did you find yourself focusing on the speed and/or time displays when you should have been paying attention to the external taxiway environment?



Eyes-In Time Acceptability

Rate the acceptability of the eyes-in time required for each 4DT display format.



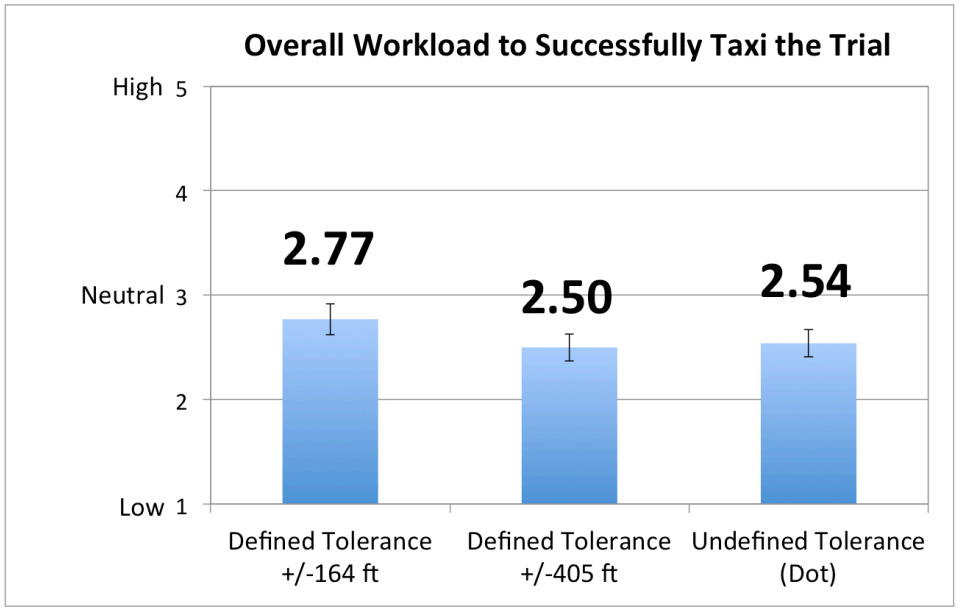
*Pilots rated the +/- 405 ft band as more acceptable than +/- 164 ft band.

Workload / Safety (Subjective Ratings)

SJSU

Workload

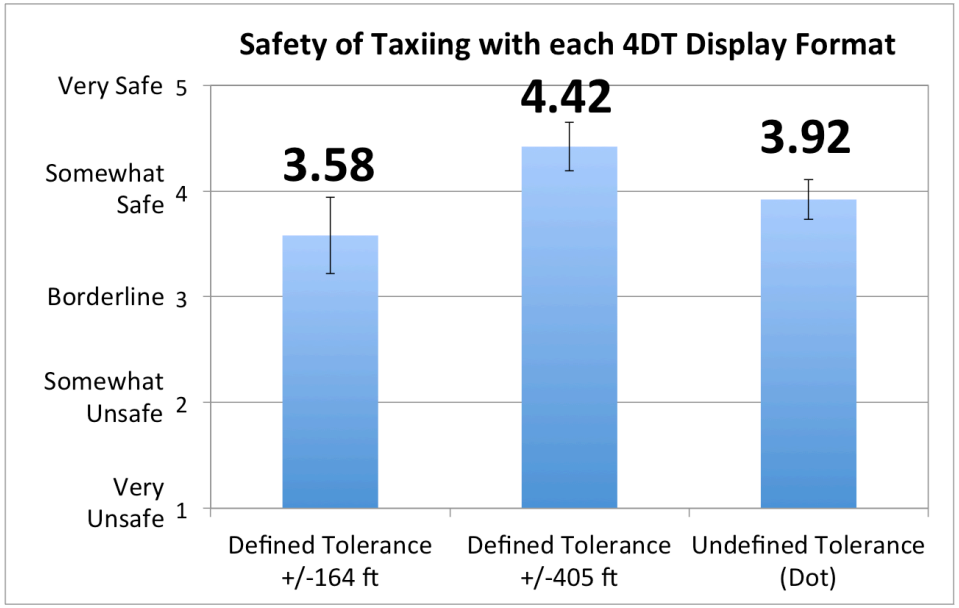
Overall workload required to successfully taxi each trial.



*Pilots perceived workload to be higher with the +/- 164 ft band than with the +/- 405 ft band or the dot.

Safety

Rate the safety of taxiing with each of the 4DT display formats.



*Pilots perceived safety to be higher with the +/- 405 ft band than with the +/- 164 ft band or the dot.

Results

Summary:

- The **larger +/- 405 ft Defined-Tolerance display** afforded several positive findings:
  - 4DT Conformance was higher than the smaller band.
  - More "**eyes out-the-window**" time than the smaller +/- 164 ft Defined-Tolerance band.
  - The "eyes-in" time associated with the larger Defined-Tolerance band was rated as **more acceptable** than the smaller Defined-Tolerance band.
  - Pilots also rated taxiing with the larger Defined-Tolerance band as **safer** than the smaller Defined-Tolerance Band.

Results

Summary:

- Considerations for Pilots / Aircraft in 4DT Operations:
  - Frequency and magnitude of 4DT speed changes.
  - Pilots indicated that it may be challenging to maintain **slower speeds** (e.g., 8 or 9 kts) in an actual aircraft, and may require more control inputs (e.g., braking) to do so.
  - Pilots reported that they would be unlikely to maintain **faster taxi speeds** (e.g., 21–25 kts) while approaching a turn or the departure queue area, and therefore would increase brake use.
  - Might managing **safety concerns** on the flight deck (e.g., hot brakes) make pilots less responsive to 4DT speed changes (braking / throttling)?

Future Research

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Flight Deck / ATC Communications

- Rejecting a 4DT clearance (before, or during, taxi)
- Renegotiating a 4DT clearance with ATC
- DataComm vs. voice communication

Mixed-Equipage

Weather, Low-Visibility

Traffic

- How to communicate an aircraft's intent? "Is that guy going to stop?"
- How to display another aircraft's 4DT?

Contaminated Taxiways

4DT Conformance

- How is non-conformance defined?
- What will the system do in the event of non-conformance?

4DT Revisions

- How much notice does the Flight Deck need for speed or taxi route revisions?
- How long does it take for the Flight Deck to make a speed or taxi route change?

Aircraft Safety Considerations (e.g., hot brakes)

- Slower / fast taxi speeds
- Airport geometry

Flight Deck Off Nominals

- Mechanical issue
- Passenger stands-up during taxi
- Final weights are late; fix changes

Flight Deck Surface Trajectory-Based Operations (STBO): A Four-Dimensional Trajectory (4DT) Simulation

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NASA Ames Research Center

David C. Foyle, Ph.D.
NASA Ames Research Center

SJSU SAN JOSÉ STATE UNIVERSITY

Human-Centered Systems Lab
https://hsi.arc.nasa.gov/groups/HCSL

Future Research

Bakowski, D. L., Hooey, B. L., Foyle, D. C., & Wolter, C. A. (2015). NextGen Surface Trajectory-Based Operations (STBO): Evaluating Conformance to 4-Dimensional Trajectories (4DT). In T. Ahram et al. (Eds.), *6th International Conference on Applied Human Factors and Ergonomics (AHFE 2015) and the Affiliated Conferences, Procedia Manufacturing Vol. 3,* (pp. 2458–2565). Elsevier Procedia.
https://hsi.arc.nasa.gov/groups/HCSL/publications/AHFE15_Bakowski_Hooey_Foyle_Wolter.pdf

Gerdes, I. & Temme, A. (2012). Taxi routing for aircraft: Creation and Controlling – Ground movements with time constraints. *Second SESAR Innovation Days, November 27–29, 2012.*
https://www.sesarju.eu/sites/default/files/SID_2012-05.pdf

Hooey, B. L., Cheng, V. H. L., Foyle, D. C. (2014). *A concept of operations for far-term Surface Trajectory-Based Operations (STBO).* (NASA TM–2014–218354). Moffett Field, CA: NASA ARC.
https://hsi.arc.nasa.gov/groups/HCSL/publications/STBO%20ConOps_TM_2014_218354.pdf

Okuniek, N., Gerdes, I., Jakobi, J., Ludwig, T., Hooey, B. L., Foyle, D. C., Jung, Y. C., & Zhu, Z. (2016). A concept of operations for trajectory-based taxi operations. *Proceedings of the 16th AIAA Aviation Technology, Integration, and Operations Conference, Paper AIAA-2016-3753, Washington, DC, June 13–17, 2016.*
https://hsi.arc.nasa.gov/groups/HCSL/publications/AIAA_ATIO_2016_NASA_DLR_4DT_ConOps.pdf

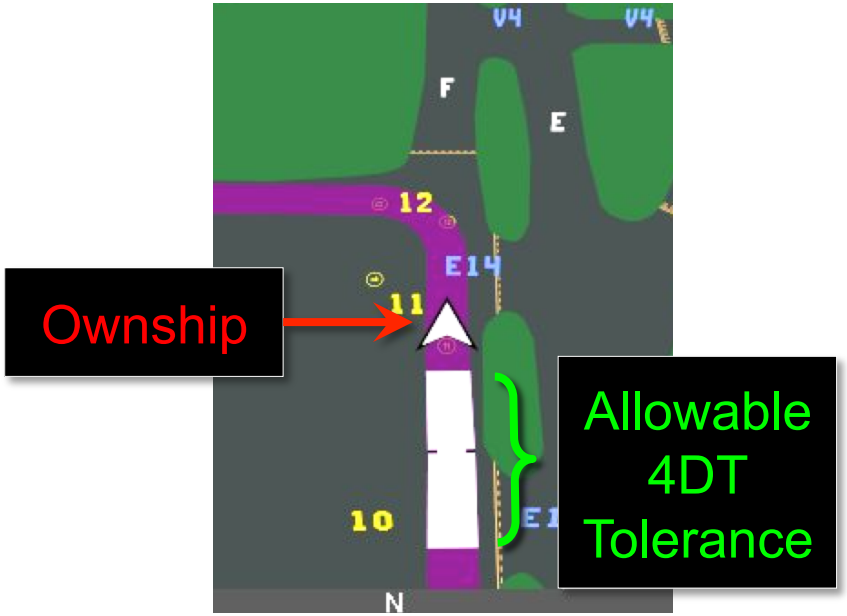
Additional Slides

Conformance to the 4DT

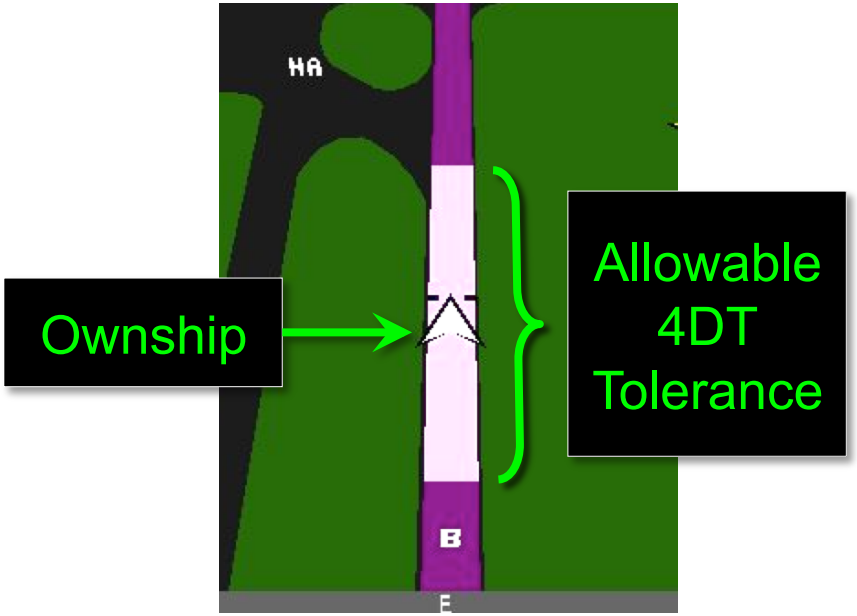
Definition of Conformance to the 4DT:

– Ownship icon is within the Allowable Tolerance Band

Ownship Out of Conformance with 4DT



Ownship In Conformance with 4DT



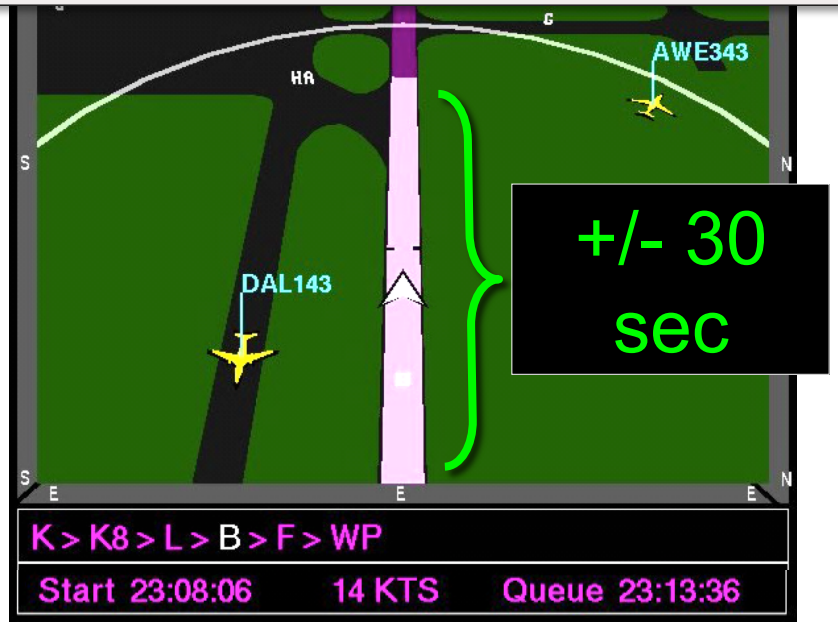
Previous Flight Deck 4DT Study

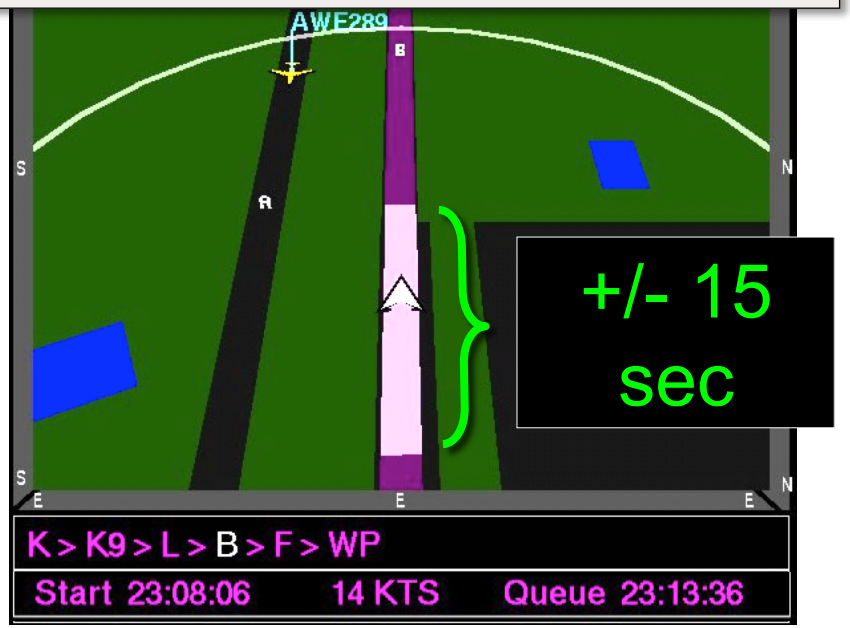
SJSU

Previous Pilot-in-the-Loop 4DT Simulation:

- Taxied on the surface of Dallas/Fort Worth (DFW) Airport
- 4DT Speeds: 14, 15, 16 kts *Bakowski, Hooey, Foyle, & Wolter (2015)*

15 kts	×	+/- 30 sec	=	+/- 760 ft (+/- 232 m)
4DT Straightaway Speed (kts --> ft per sec)		Allowable *Time* Deviation		Distance (Length) of Allowable Tolerance Band

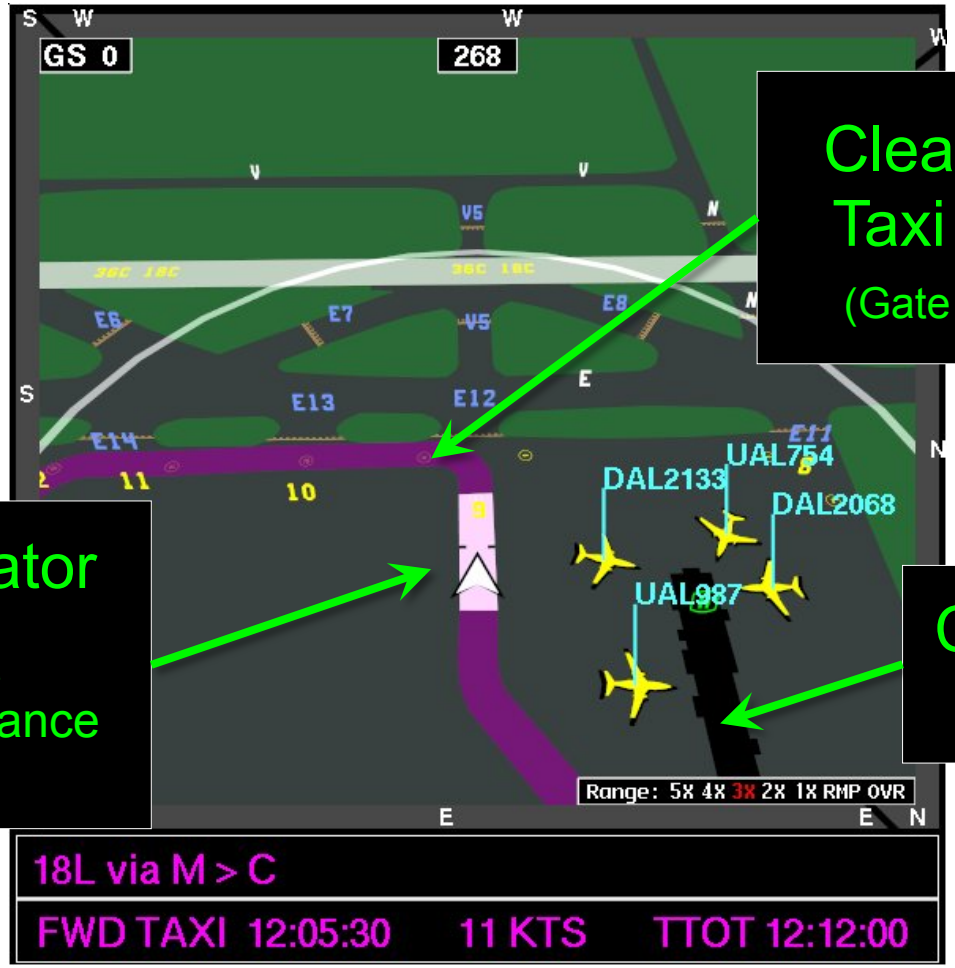




Experimental Taxi Scenario

4DT Start Time

- Accompanied by an auditory chime on the flight deck
- 4DT Indicator begins to accelerate



Cleared-to-Taxi Route

(Gate to RWY)

4DT Indicator

+/- 164 ft Defined-Tolerance Band

Concourse A

Experimental Taxi Scenario

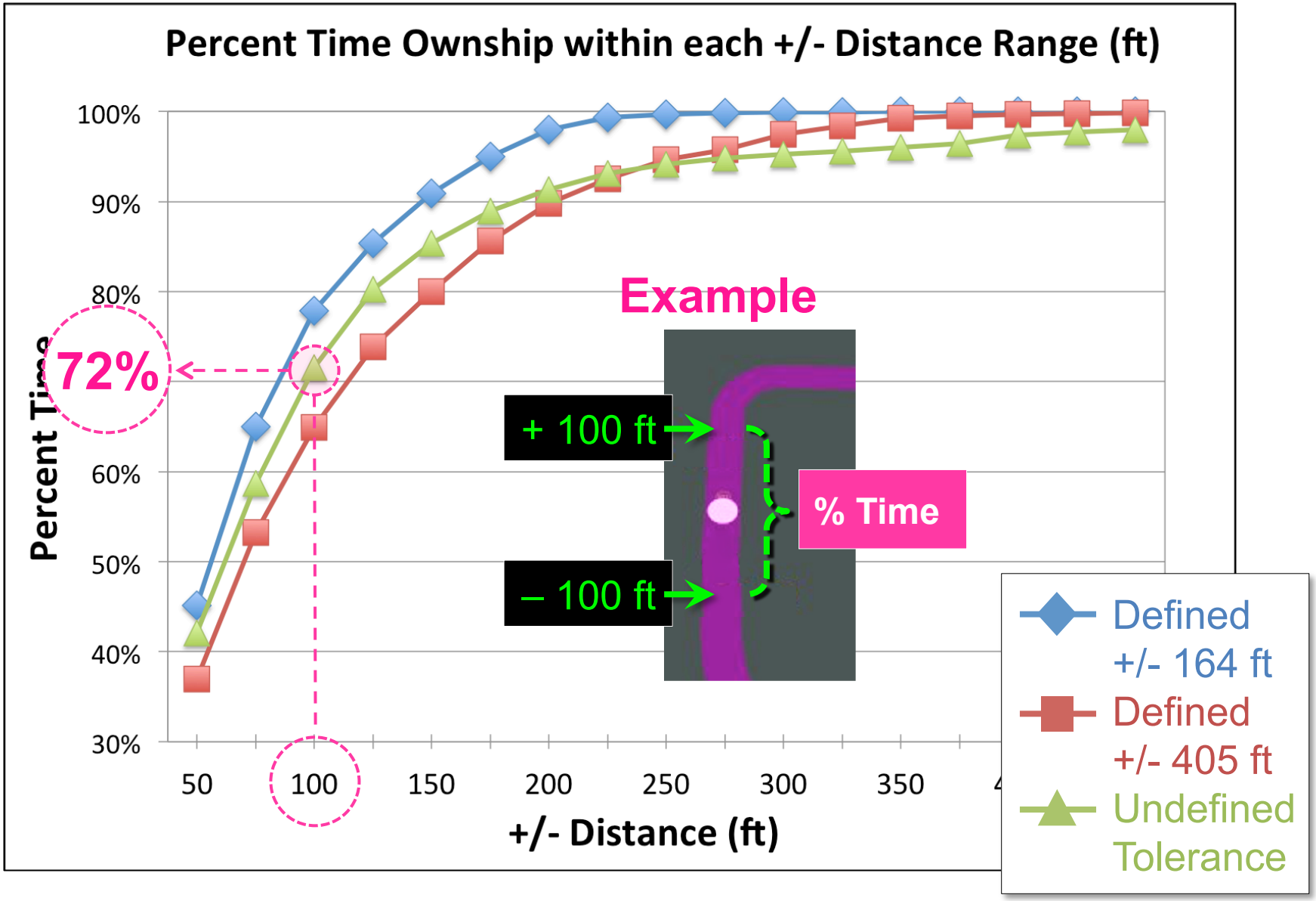
4DT Speed Changes

- Predetermined locations along the taxi route (speed profile)
- Two or five speed changes per trial

- Accompanied by an auditory tone on the flight deck
- AMM text display updated
- First Officer acknowledged, "Speed Change"
- Accel / Decel Rate = 1 kt/sec

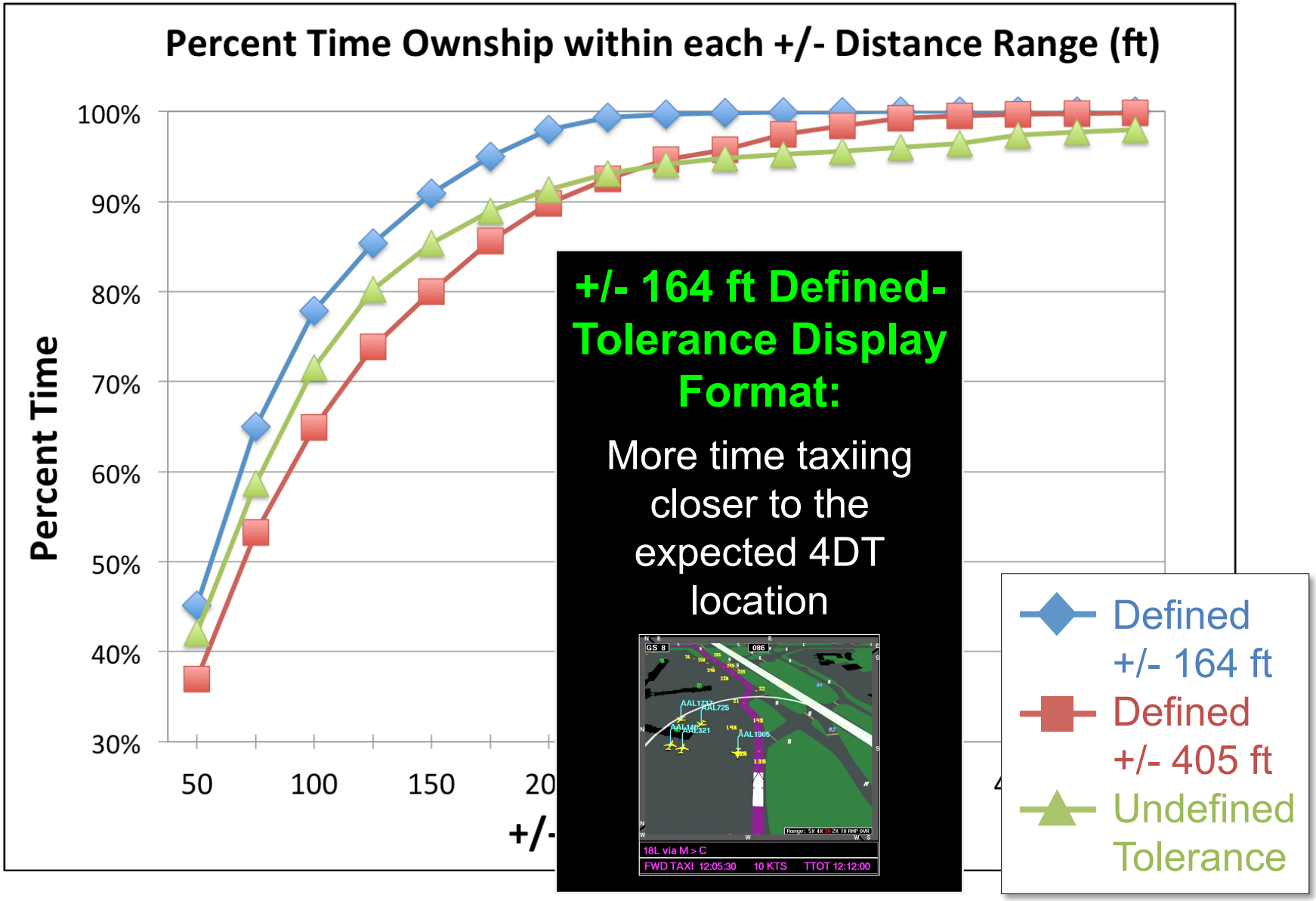
Results

Percent Time the Ownship was in a given Distance Range



Results

Percent Time the Ownship was in a given Distance Range

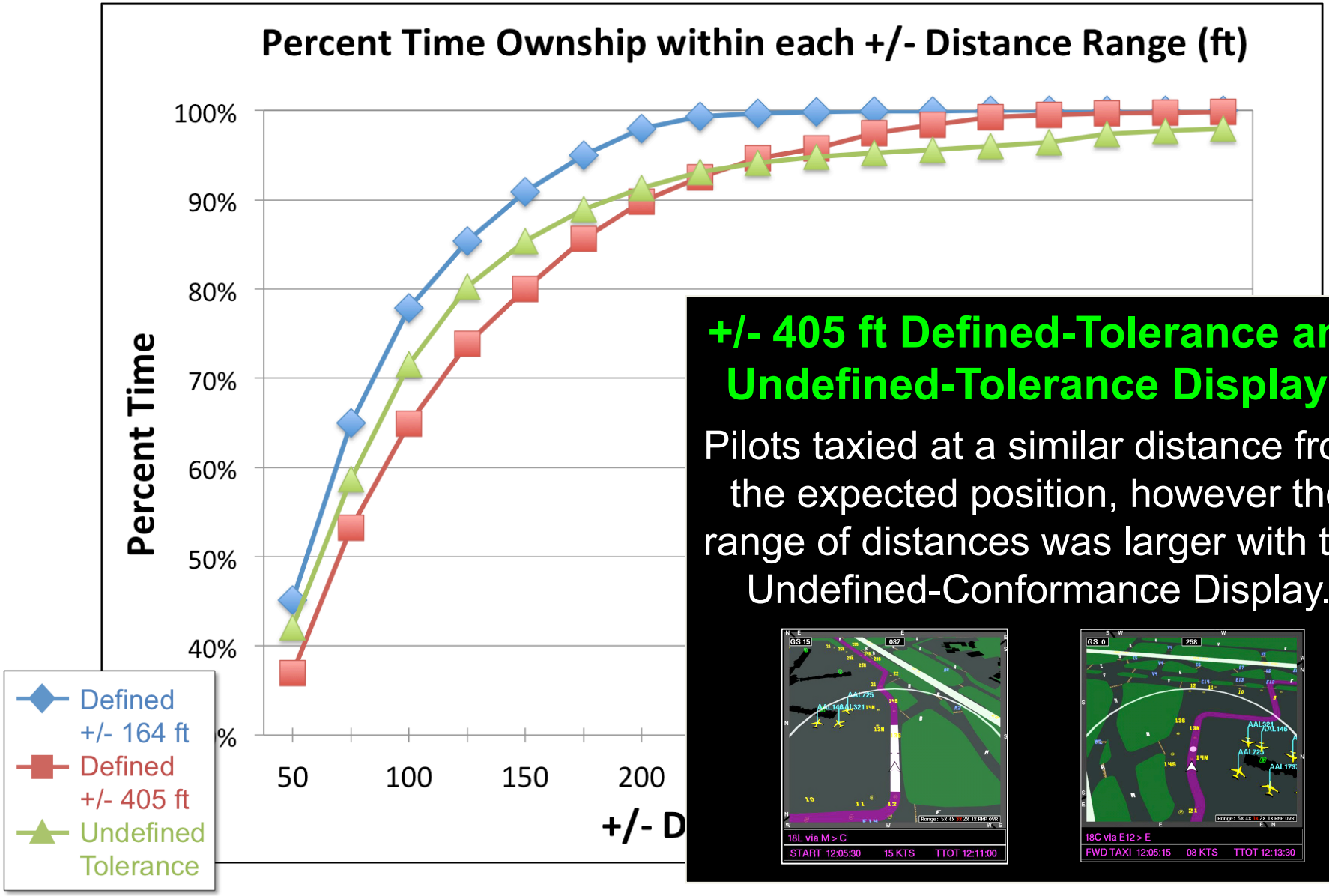


+/- 164 ft Defined-Tolerance Display Format:

More time taxiing closer to the expected 4DT location

Results

Percent Time the Ownship was in a given Distance Range



+/- 405 ft Defined-Tolerance and Undefined-Tolerance Displays

Pilots taxied at a similar distance from the expected position, however the range of distances was larger with the Undefined-Conformance Display.