National Aeronautics and Space Administration

Simulation and Flight Test Data Collection Review for Supporting Phase 1 Detect and Avoid MOPS

Ames Research Center

**Confesor Santiago: Project Engineer, UAS in the NAS
Separation Assurance/Sense and Avoid Interoperability**

5 May 2016

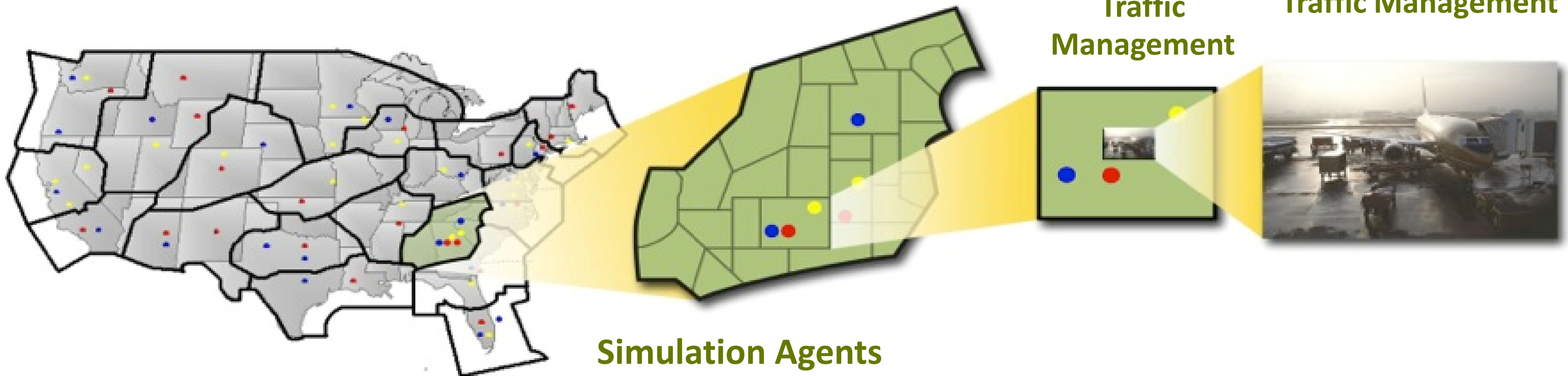
Cleared for public release.

Barriers for Integrating UAS into the NAS

- What's the impact against current traffic in the NAS
  - Encounter rates and geometries?
  - How would UAS interact with existing traffic, i.e. VFR.
- Surveillance requirements?
- Alerting requirements?
- Maneuver guidance?

Capabilities

Airspace Concept Evaluation System (ACES)



Simulation Agents

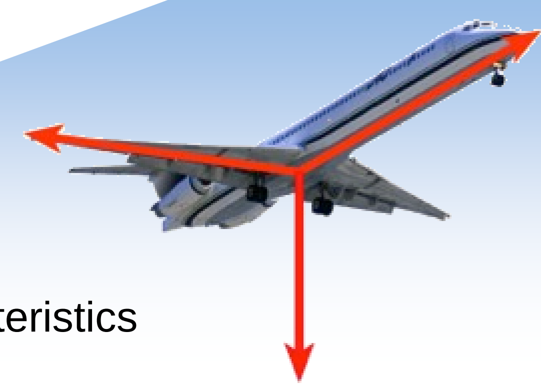
- Air traffic controller decision making
- Traffic flow management models
- Individual aircraft characteristics
- UAS Detect-and-Avoid (DAA) System [JADEM]

NAS-wide Simulation

- Gate-to-gate simulation of ATM operations
- Full flight schedule with flight plans
- Sector and center models with some airspace procedures

4-DOF Trajectory Model

Aerodynamic models of aircraft
Models replicate pilot behavior
User-definable uncertainty characteristics

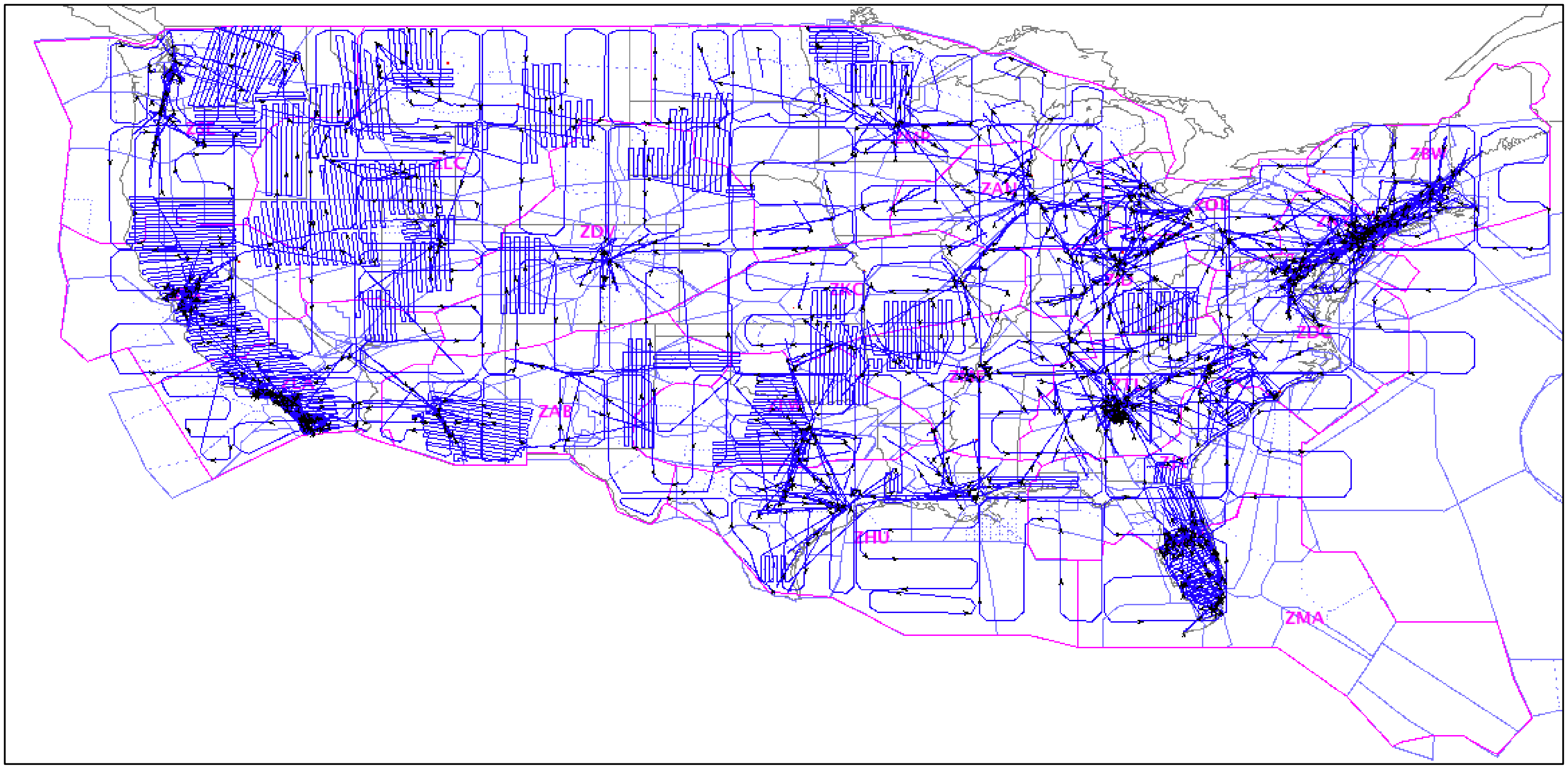


UAS Mission Characteristics

	UAS group	Duration (per flight)	Cruise Speed (knots)	Cruise Alt. (ft)	Flight Pattern
Air Quality Monitoring	Shadow-B	1-4 hrs.	74-89	4k,5k, and 6k ft AGL	Radiator Grid Pattern
Cargo Transport	Cessna 208	varies	137-172	2k-16k	Point to Point
Atmospheric Sampling	Global Hawk	1.5-13 hrs.	151-321	5k-35k ft AGL	Radiator Grid Pattern
On-demand Remote Air Taxi -Cirrus	Cirrus SR22T	varies	153-166	6k-11k	Point to Point
On-demand Remote Air Taxi - Mustang	Cessna Mustang	varies	156-340	9k-20k	Point to Point
Strategic Fire Monitoring	Predator-B	20 hrs.	~209	31k ft MSL	Radiator Grid Pattern
Tactical Fire Monitoring	Shadow-B	1-1.5 hrs.	72-75	3k-7k AGL	Circular Loitering Orbit
Flood Inundation Mapping	Aerosonde	1-4 hrs.	46-51	4k ft AGL	Radiator Grid Pattern Point to Point
Flow Stream Monitoring	Aerosonde	1-4 hrs.	46-51	4k AGL	Radiator Grid Pattern Point to Point
Border Patrol	Predator-B	2-7 hrs.	129-173	4k – 15k AGL	Radiator Grid Pattern

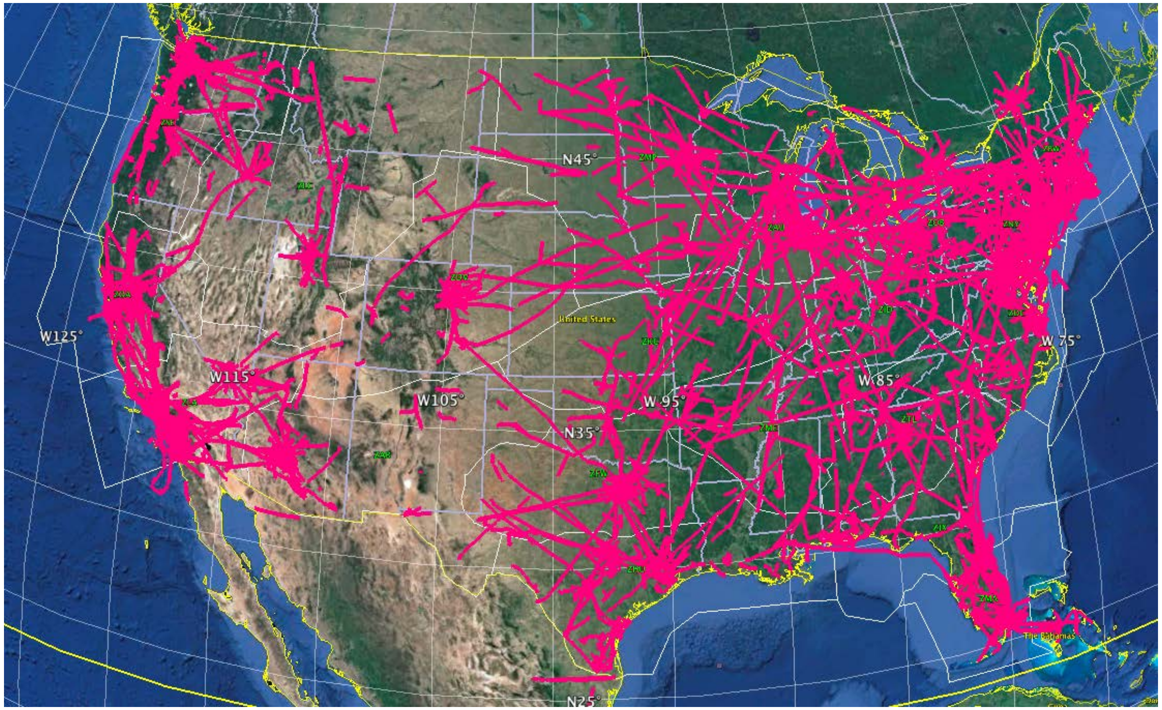
NAS-wide UAS Mission Profile

- A snapshot of mission profiles: UAS tracks in blue



Large Database of Historical Flight Tracks

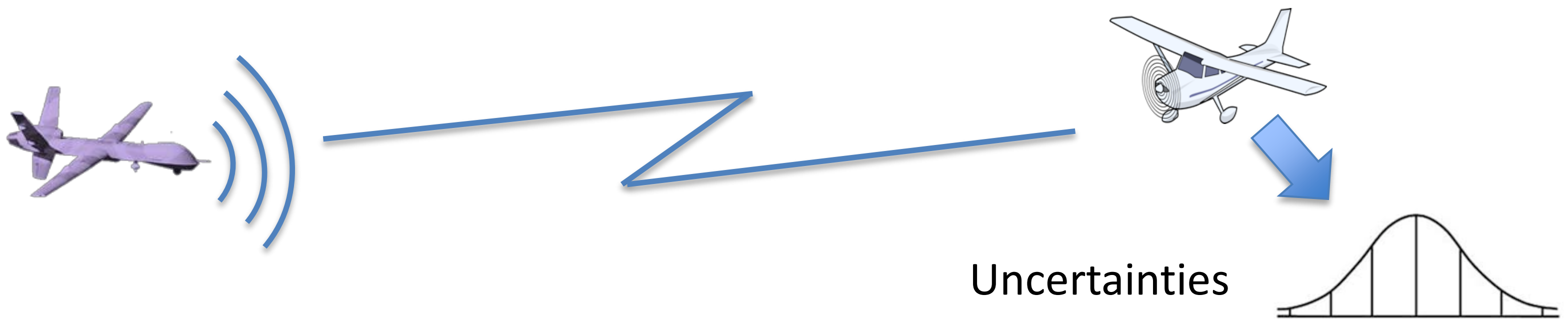
- 3-months database of historical radar data courtesy of RADES (84th Radar Evaluation Squadron)
  - Data contain the radar hits collected from hundreds of radar sites in U.S
  - Developed methodology for associating distinct tracks and classify tracks as IFR or VFR (cooperative and non-cooperative)



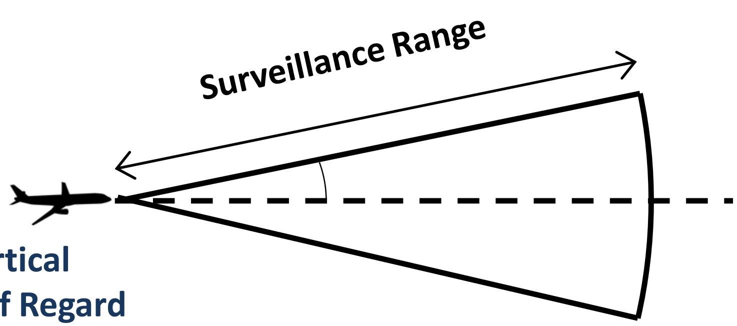
Cooperative VFR Traffic – July 25, 2013

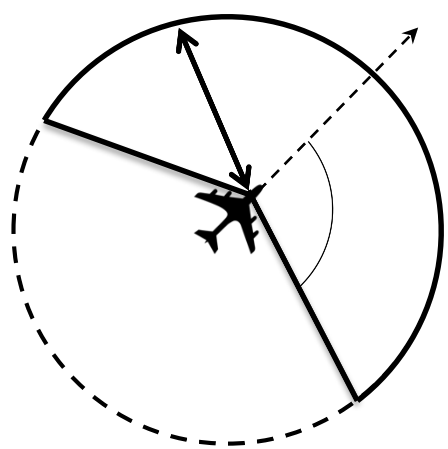
Detect and Avoid Surveillance Models

Surveillance



- Automated Dependent Surveillance – Broadcast (ADS-B)
- Mode S/C Transponder
- Airborne Radar
- Tracker
  Track Association, Filtering, State Estimation





Detect and Avoid – Pilot Model

Closed-Loop Fast-Time Simulations

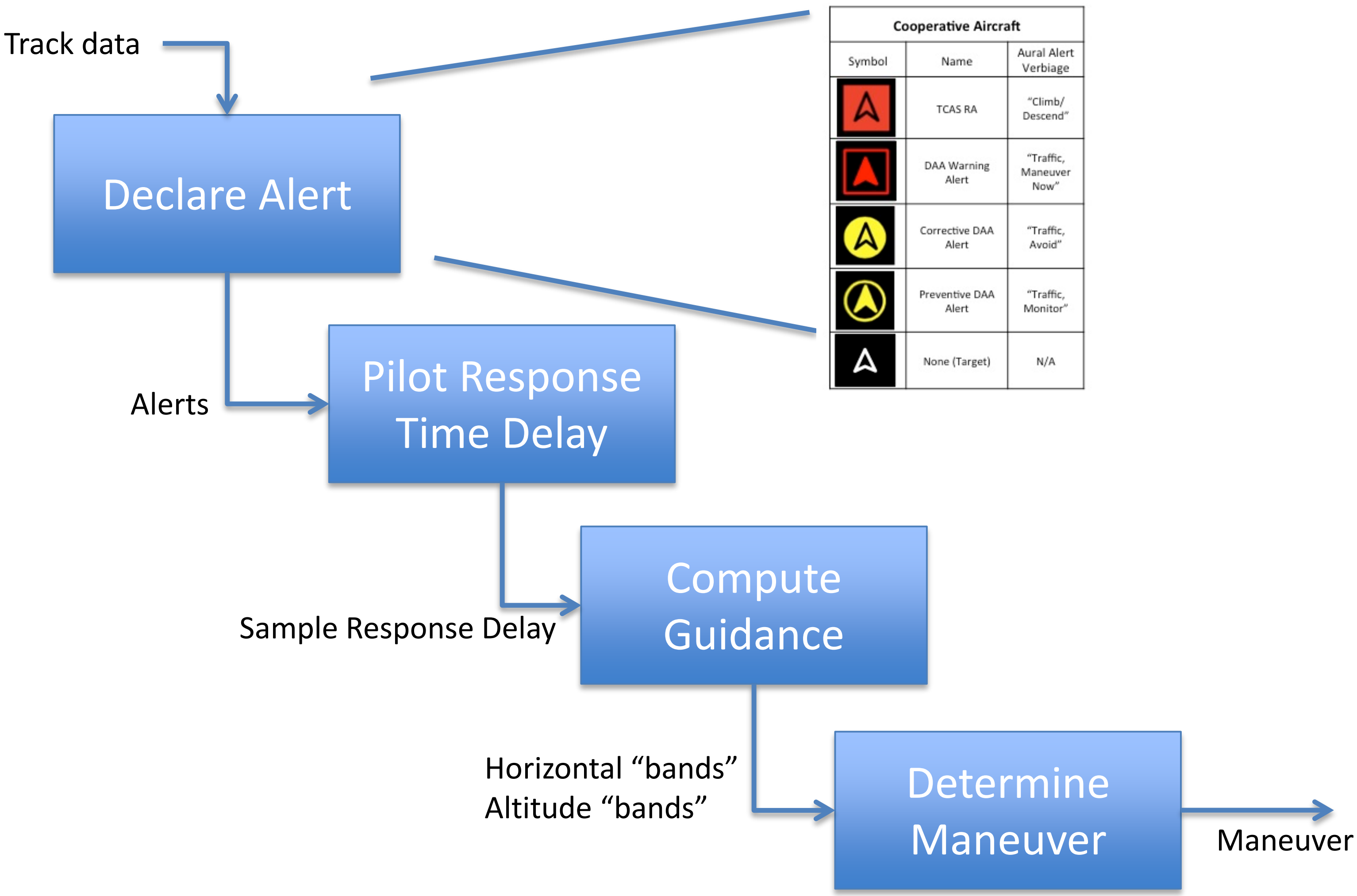
Pilot Model Motivation

- UAS pilot is a key element of a DAA system to determine, coordinate, and execute a final maneuver to avoid losses of well clear.

- Performance of DAA alerting and guidance systems:
  - Depends on how quickly and accurately the UAS pilot responds to DAA alert and executes an avoidance maneuver to remain well clear.

- Need for UAS pilot model in NAS-wide fast-time simulations
  - Establish a preliminary model of UAS pilot response behavior interacting with a DAA system based on human-in-the-loop experiment data.
  - Response time and maneuver selection rules.

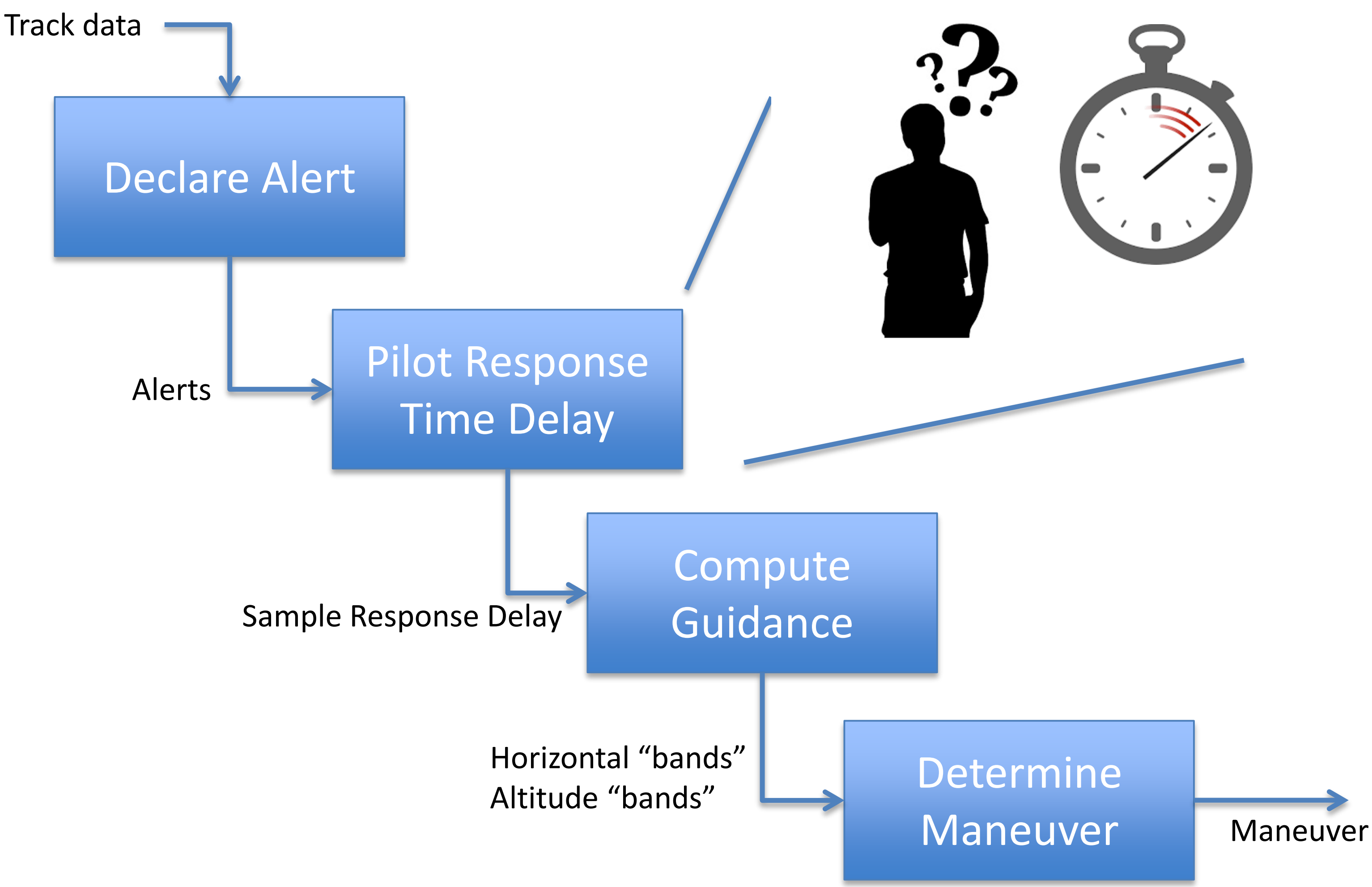
Pilot Model: Alert Declared



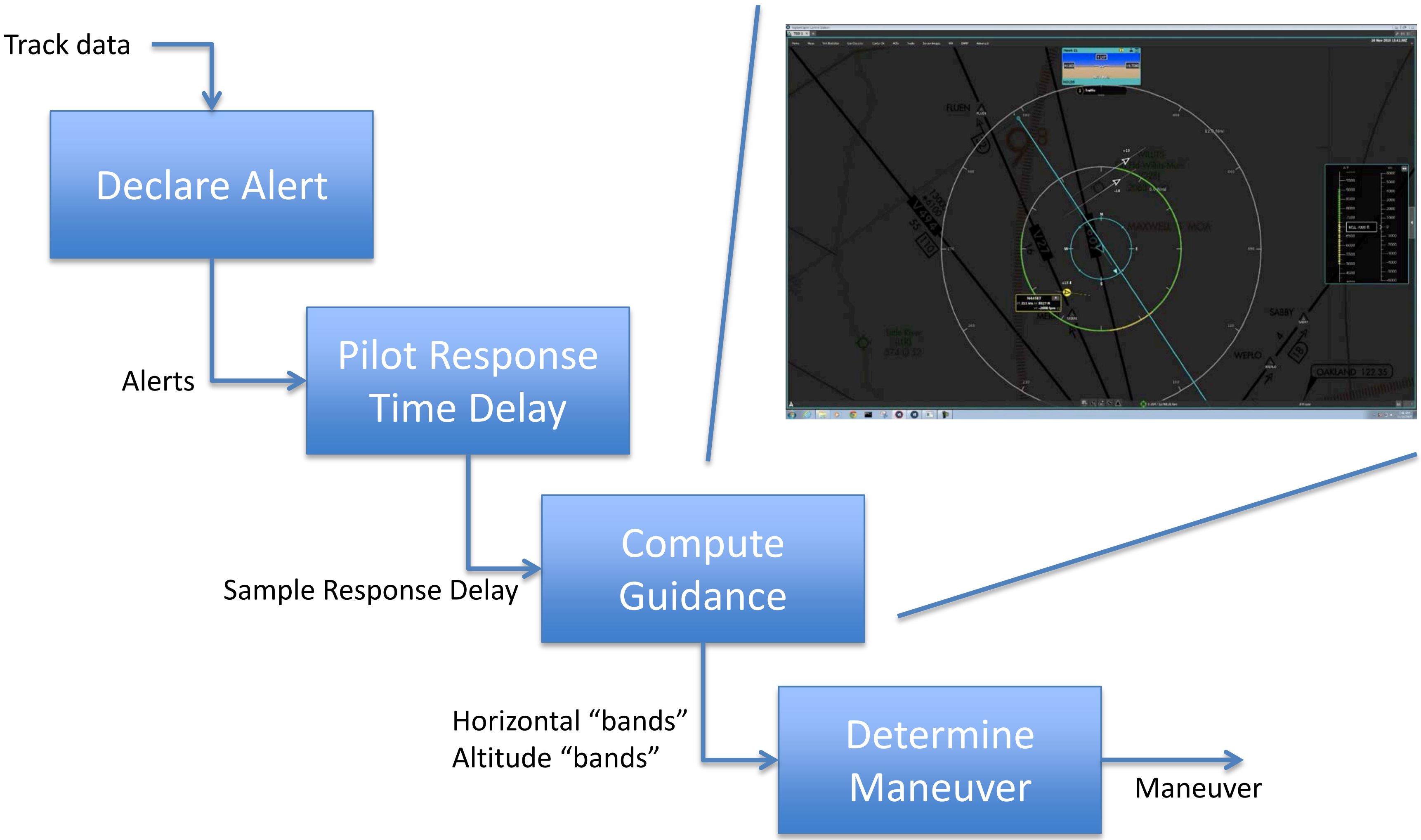
Cooperative Aircraft		
Symbol	Name	Aural Alert Verbiage
	TCAS RA	“Climb/ Descend”
	DAA Warning Alert	“Traffic, Maneuver Now”
	Corrective DAA Alert	“Traffic, Avoid”
	Preventive DAA Alert	“Traffic, Monitor”
	None (Target)	N/A

Pilot Model: Simulated Action Response Delay

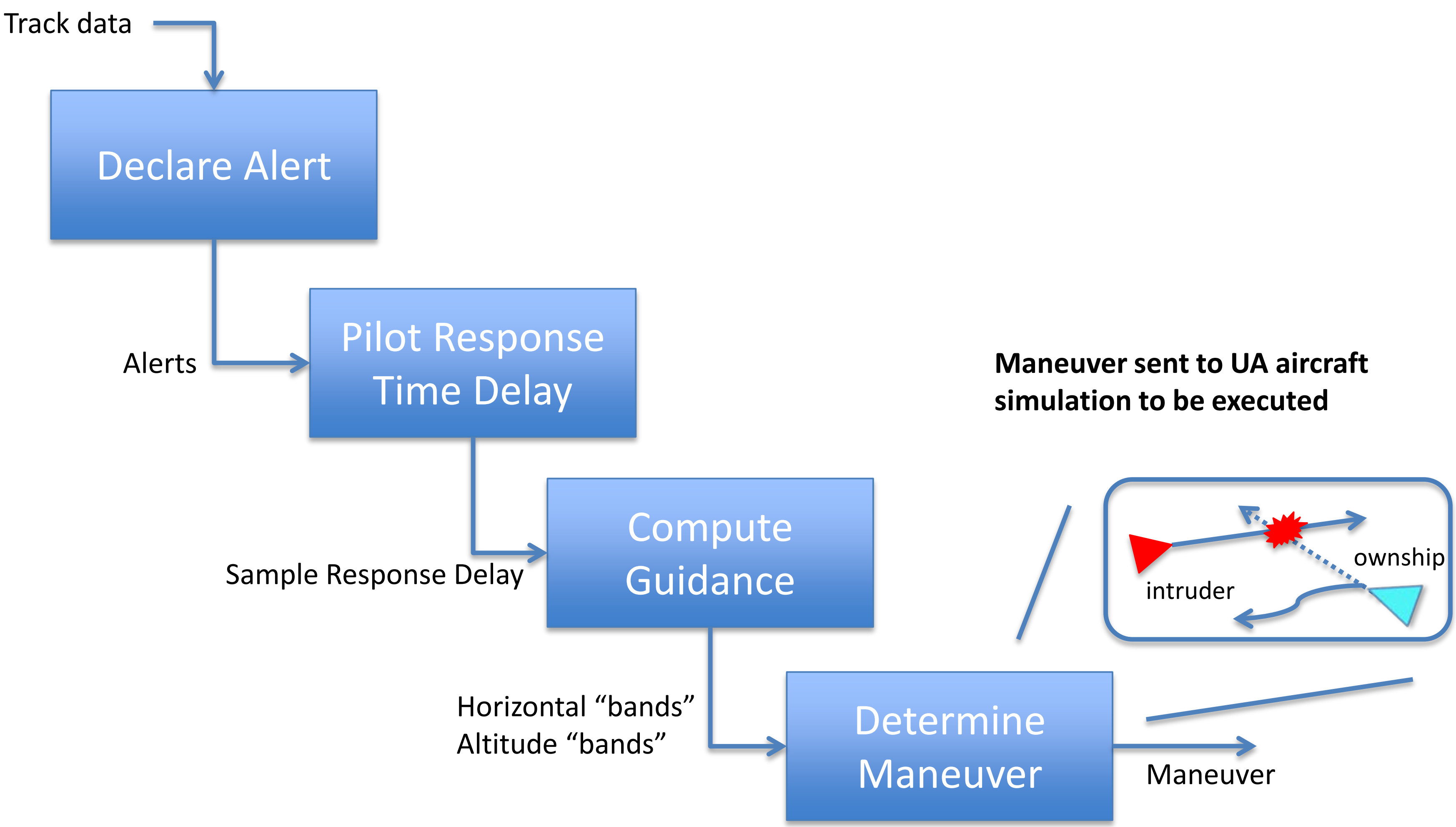
Response time distributions informed by pilot measure response in human-in-the-loop experiments



Pilot Model: Compute Maneuver Guidance Options



Pilot Model: Determine Maneuver to Remain Well Clear



Pilot Model Logic

Pilot Model State Diagram Flow

Monitoring

Pilot Model State Diagram Flow

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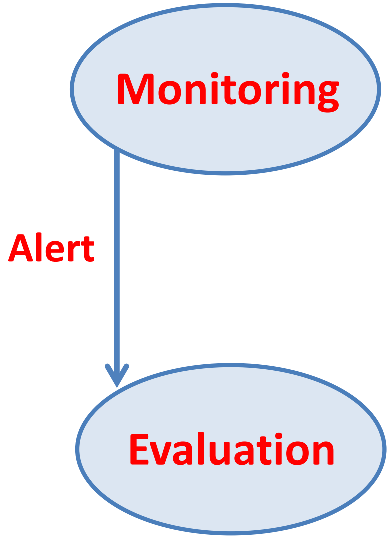

Pilot Model State Diagram Flow

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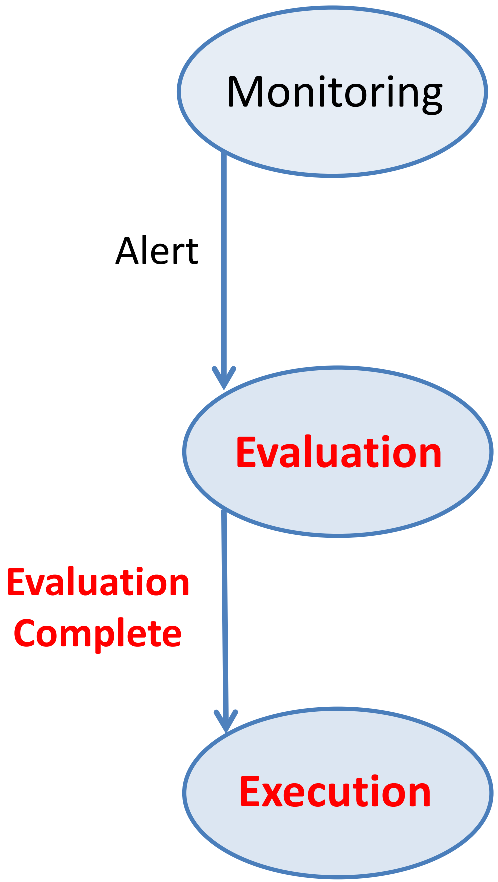
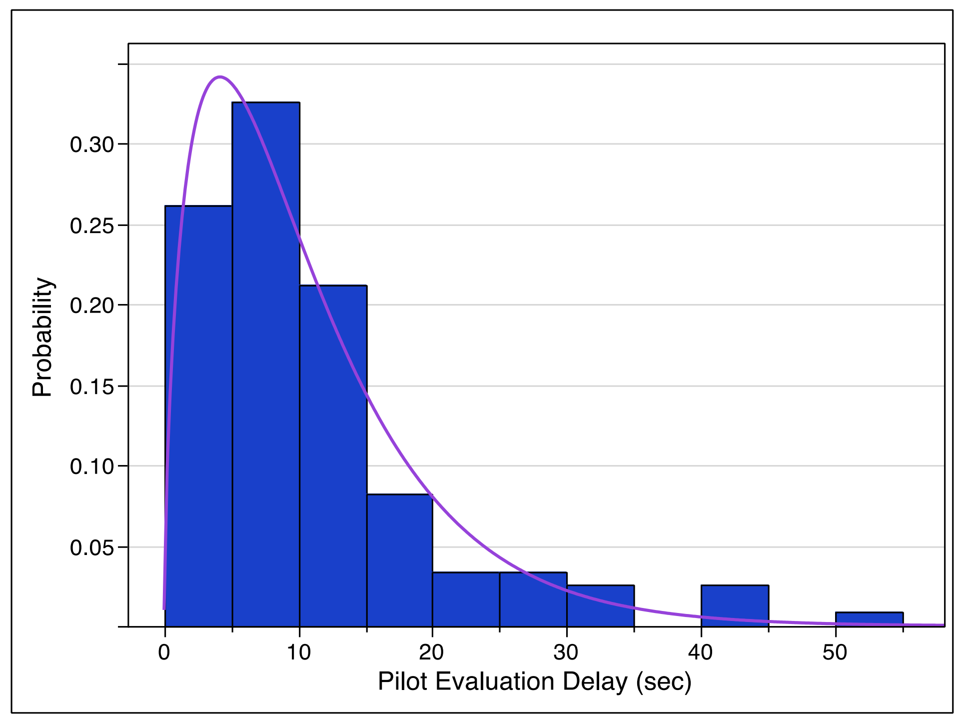


Corrective Alerts (w/ ATC coord.)

Mean: 10.59 sec Median: 8 sec



*Part-Task 5 Human-in-the-loop Experiment

Pilot Model State Diagram Flow

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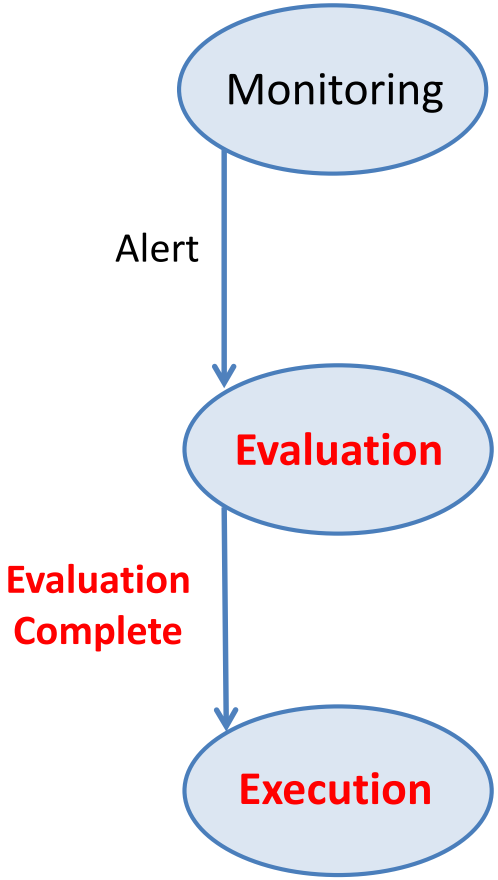
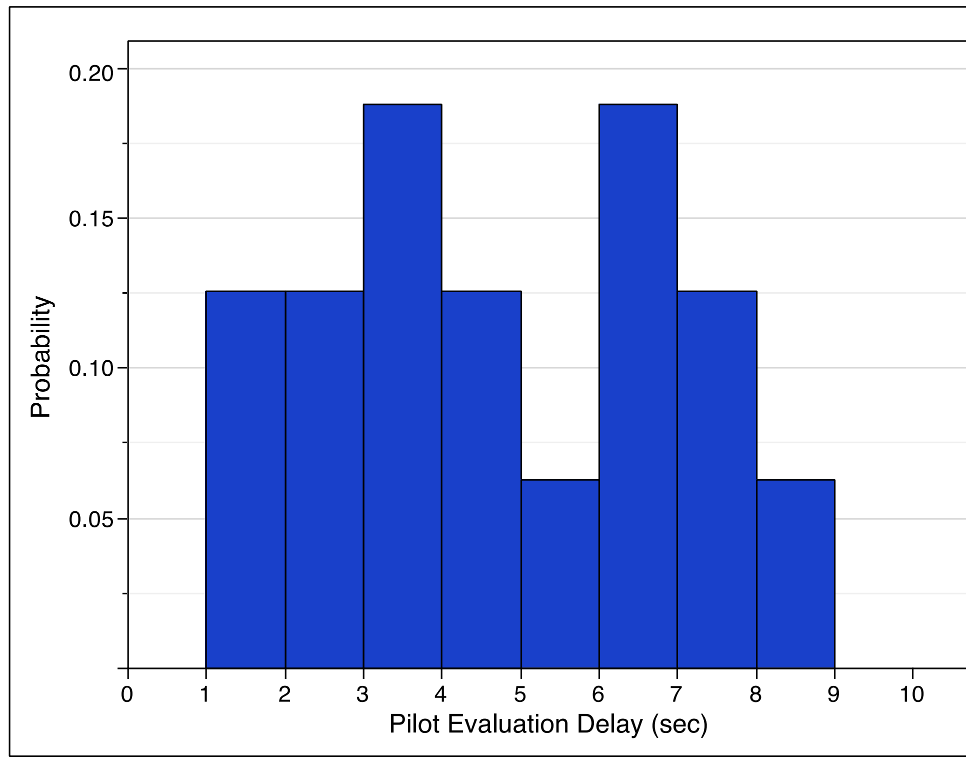


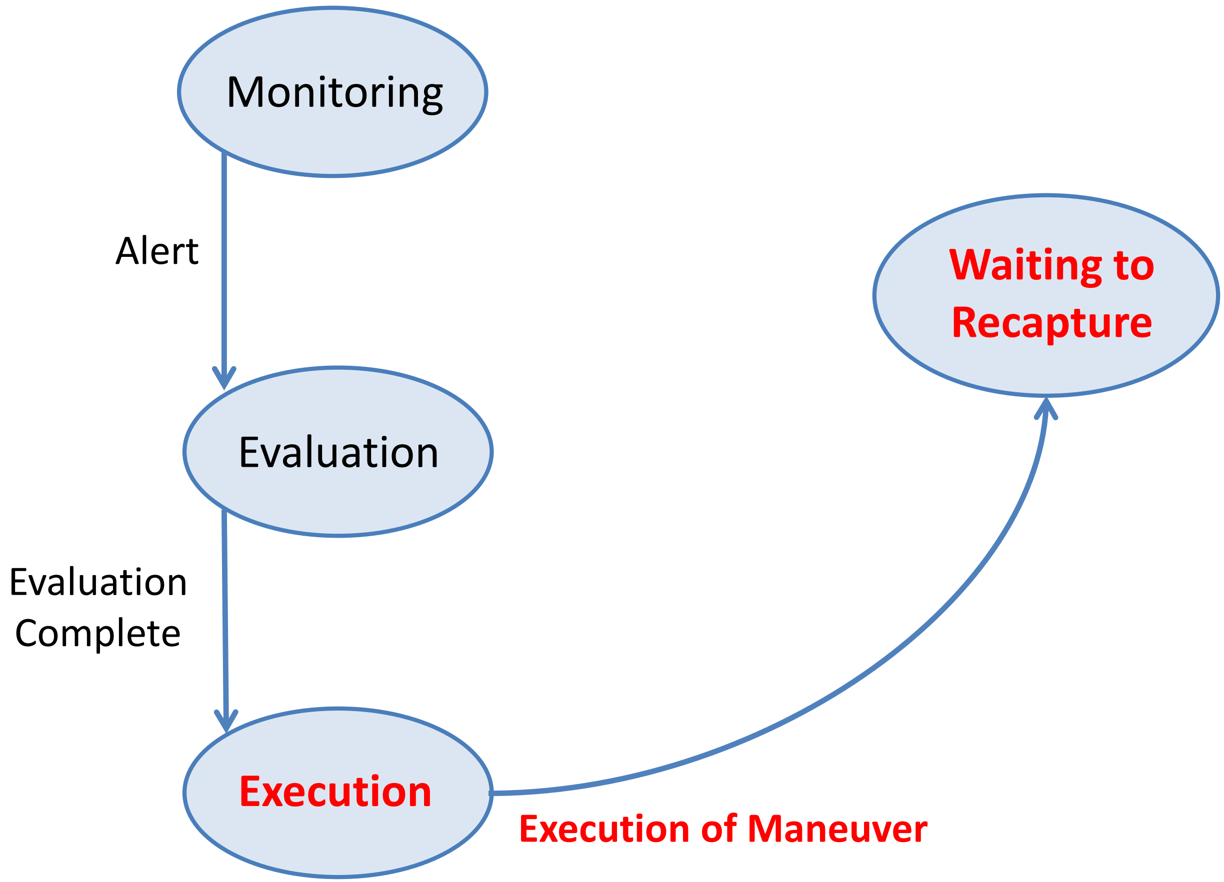
Warning Alerts (w/o ATC coord.)

Mean: 4.25 sec   Median: 4 sec

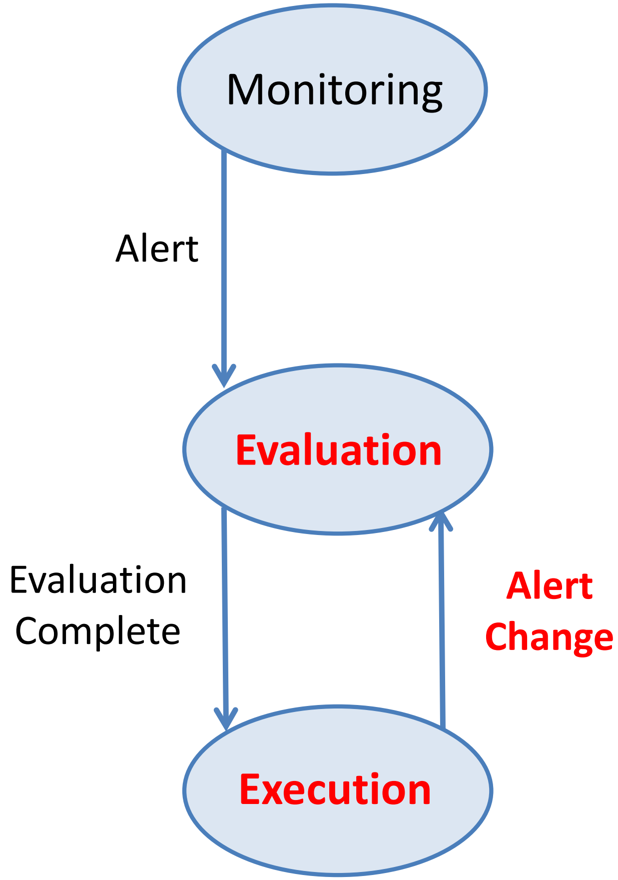


*Part-Task 5 Human-in-the-loop Experiment

Pilot Model State Diagram Flow



Pilot Model State Diagram Flow



Note: During maneuver determination the alerting guidance can change due to surveillance uncertainty and lack of VFR intruder intent.

Summary Table for Pilot Response Times

Condition	Evaluation Time (sec)	Execution Time (sec)
Corrective Alert	Gamma (1.65, 6.43)	Gamma (2.69, 3.31)
Warning Alert	Constant Delay: 4 sec	Constant Delay: 5 sec
Well Clear Recovery	Constant Delay: 3 sec	Constant Delay: 3 sec
Recapture	Constant Delay: 0 sec	Constant Delay: 3 sec

Total time to execute maneuver = (Evaluation time + Execution time)

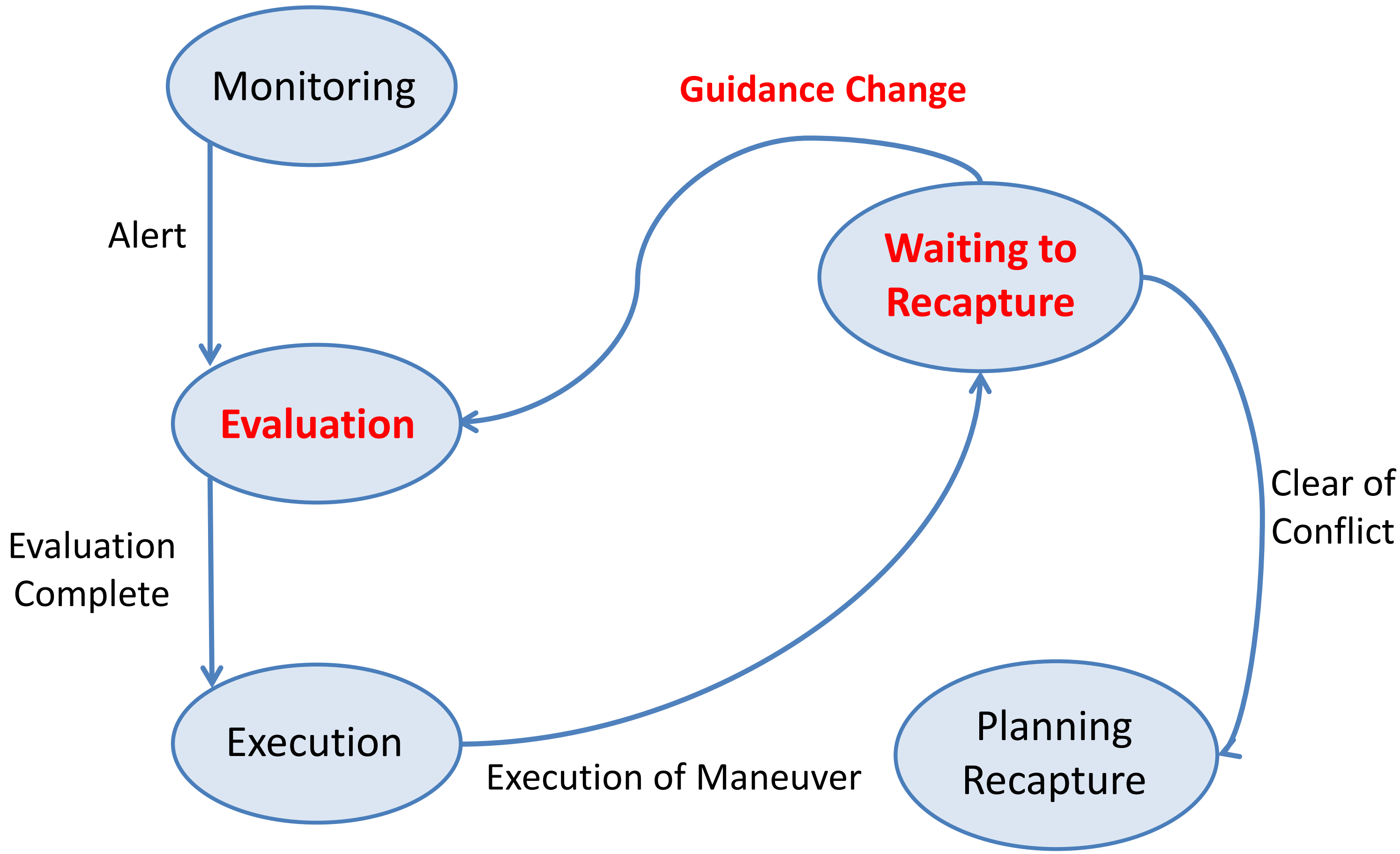
**Note: more information and data in backup slides*

Maneuver Selection

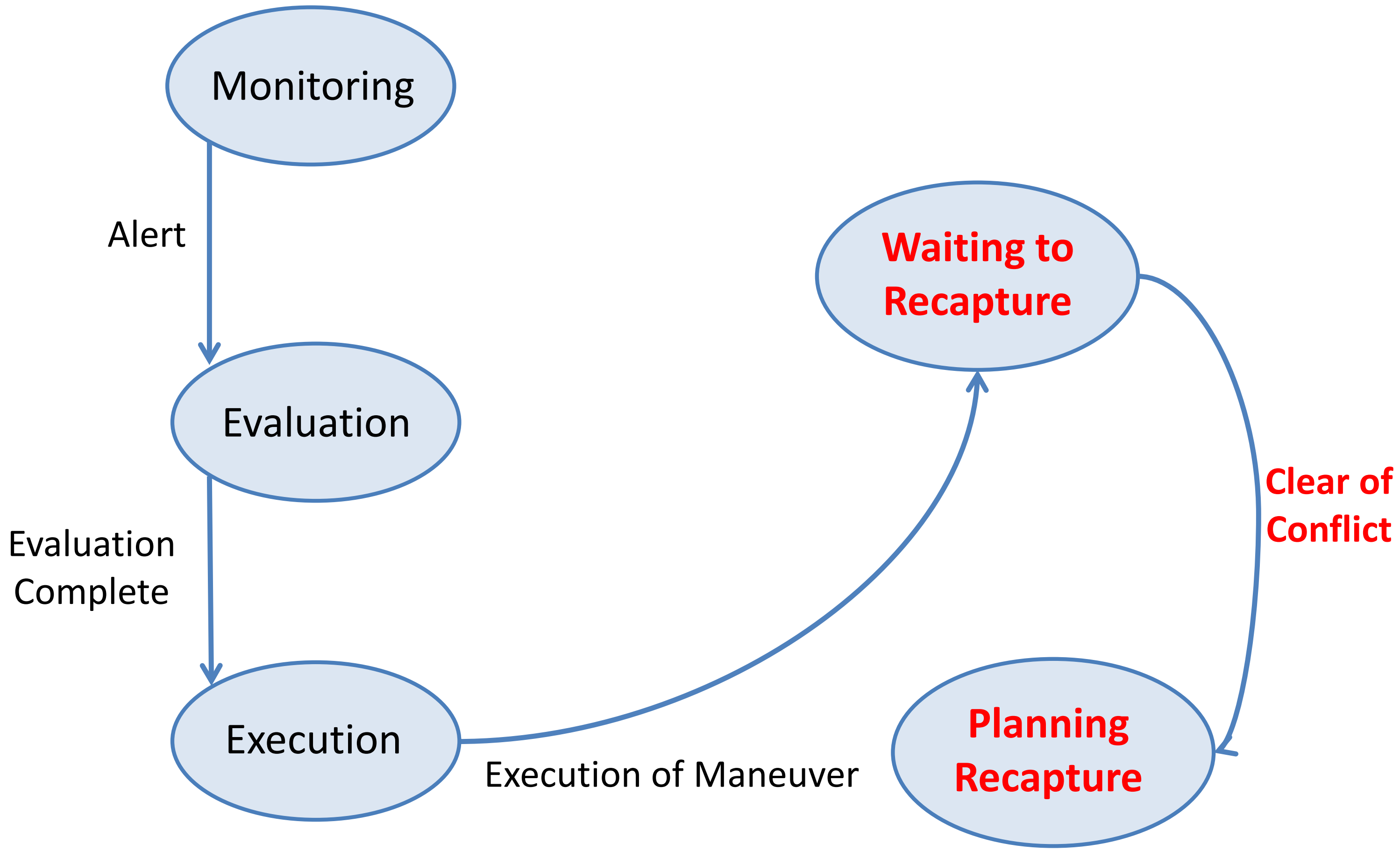
- A simple heuristic to choose maneuver direction and magnitude based on conditional preferences and a cost function.
  - Preliminary model with deterministic behavior for maneuver selection/magnitude
  - Pilot model chooses a single horizontal or vertical maneuver based on OmniBands horizontal and vertical guidance suggestions

- Maneuver preferences depend on current navigation mode.
  - Cruise Status: Prefer horizontal maneuvers over vertical maneuvers (descent or climb)
  - Climb or descent Status: Prefer temporary altitude holds over horizontal maneuvers
  - Near top of descent: prefer temporary altitude holds over horizontal maneuvers (Optional)

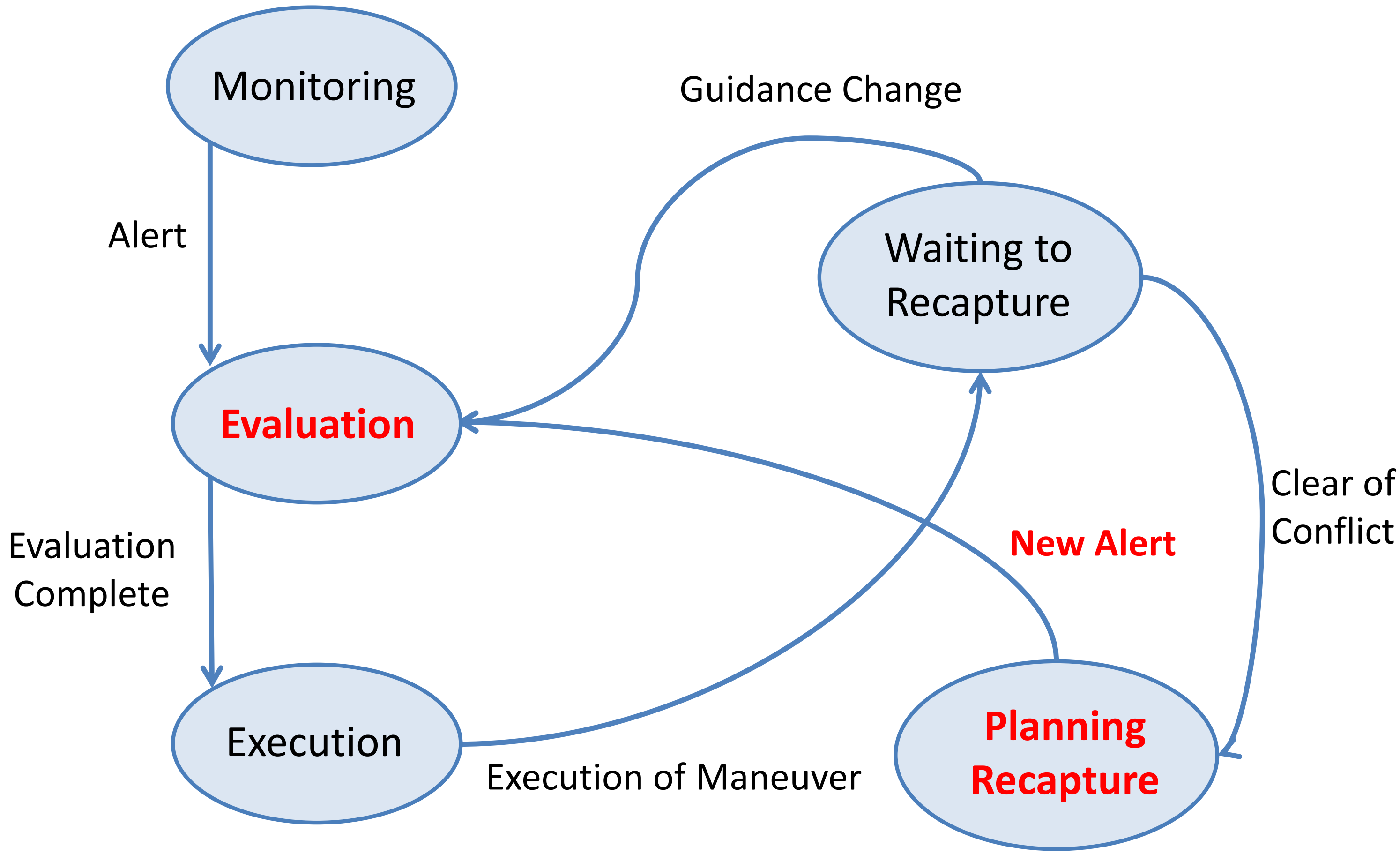
Pilot Model State Diagram Flow



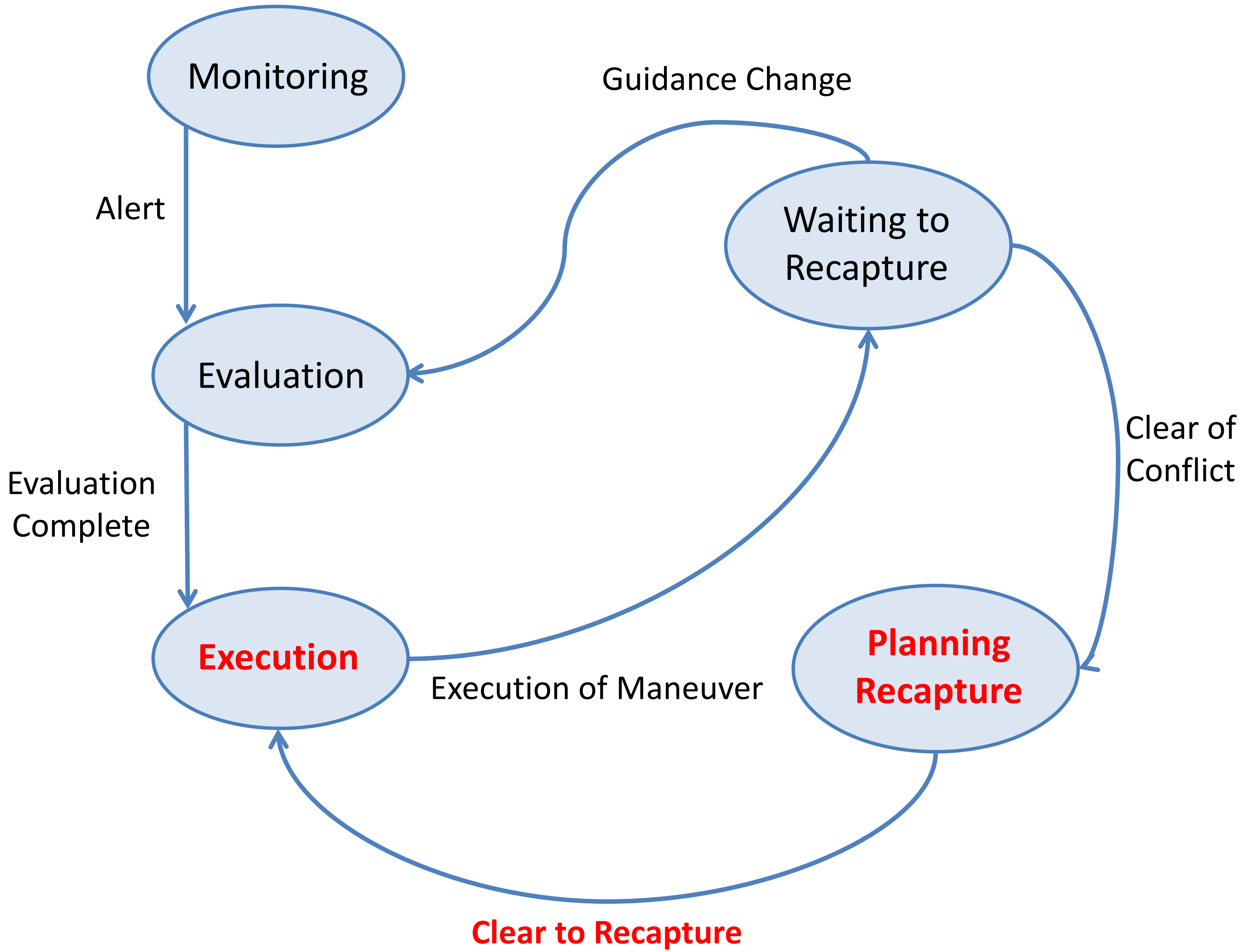
Pilot Model State Diagram Flow



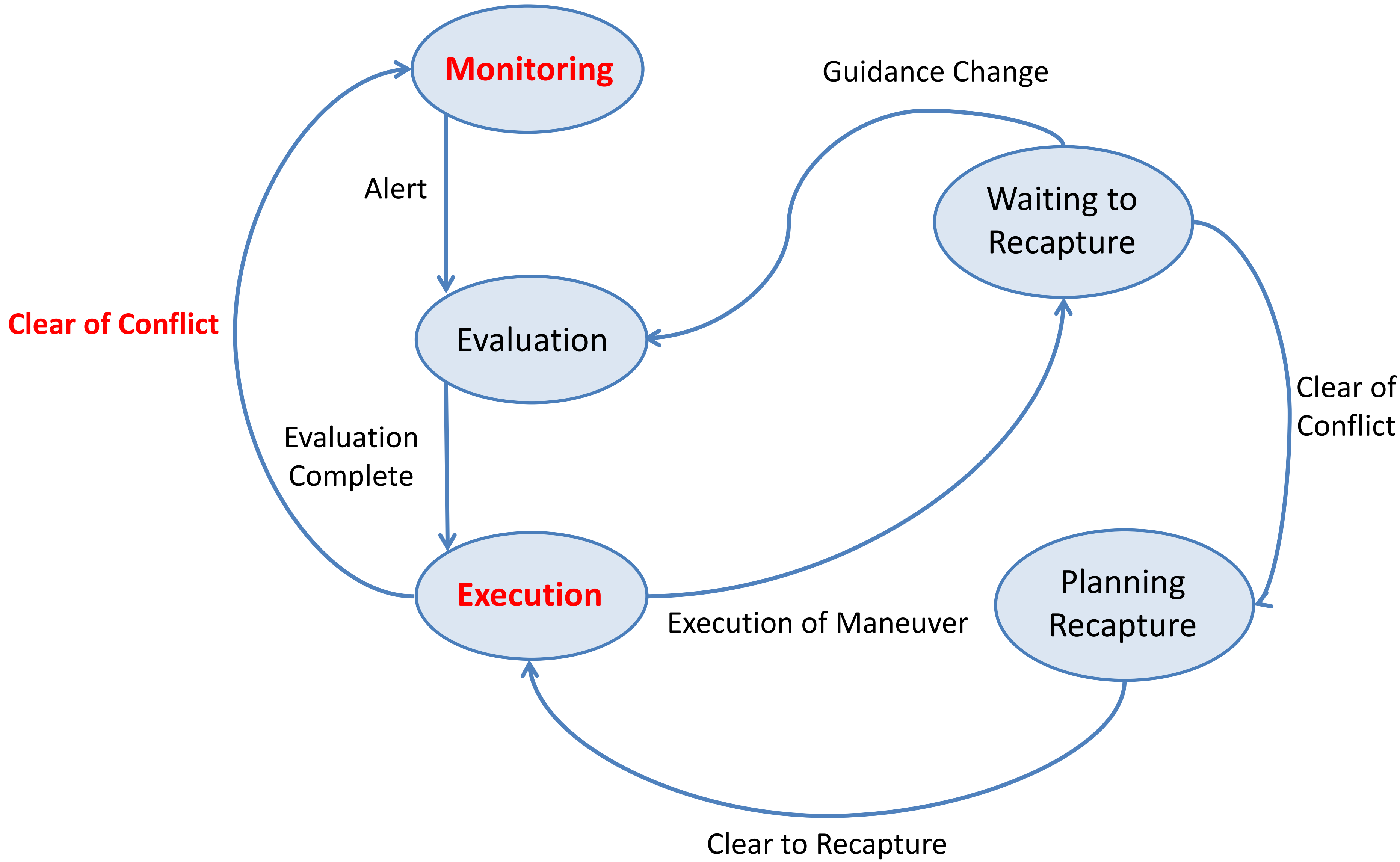
Pilot Model State Diagram Flow



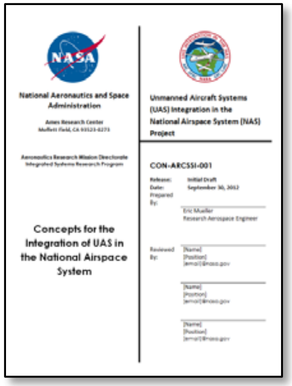
Pilot Model State Diagram Flow



Pilot Model State Diagram Flow



How All Research Capabilities Tie Together


National Aeronautics and Space Administration

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

CON-ARCSSI-001

Concepts for the Integration of UAS in the National Airspace System

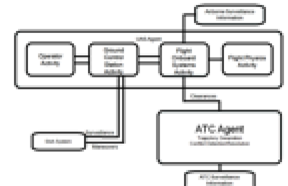
UAS-NAS integration concepts

New UAS-related modeling and simulation capabilities

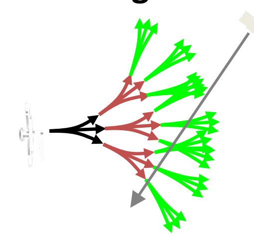
19 UAS mission profiles

17 UAS types

UAS models, comm. link models



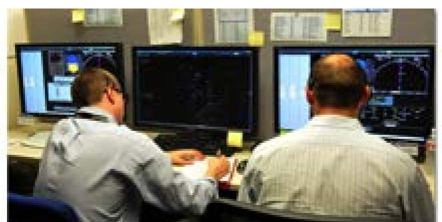
DAA algorithms



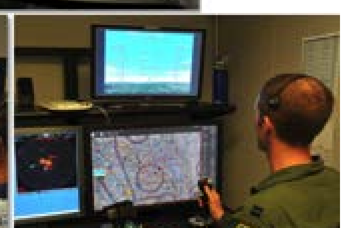
DAA sensor models

Human-in-the-Loop and Flight Test Evaluation

Pseudo-pilot stations



Air Traffic Control Stations



Vigilant Spirit Control Station

Traffic displays, DAA algorithms, ATC, Ground Control Station

NAS-wide Simulation

ACES: Flight plan and NAS-agent modeling system

Questions?

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UAS Integration in the NAS: SSI-ARC Sub-team

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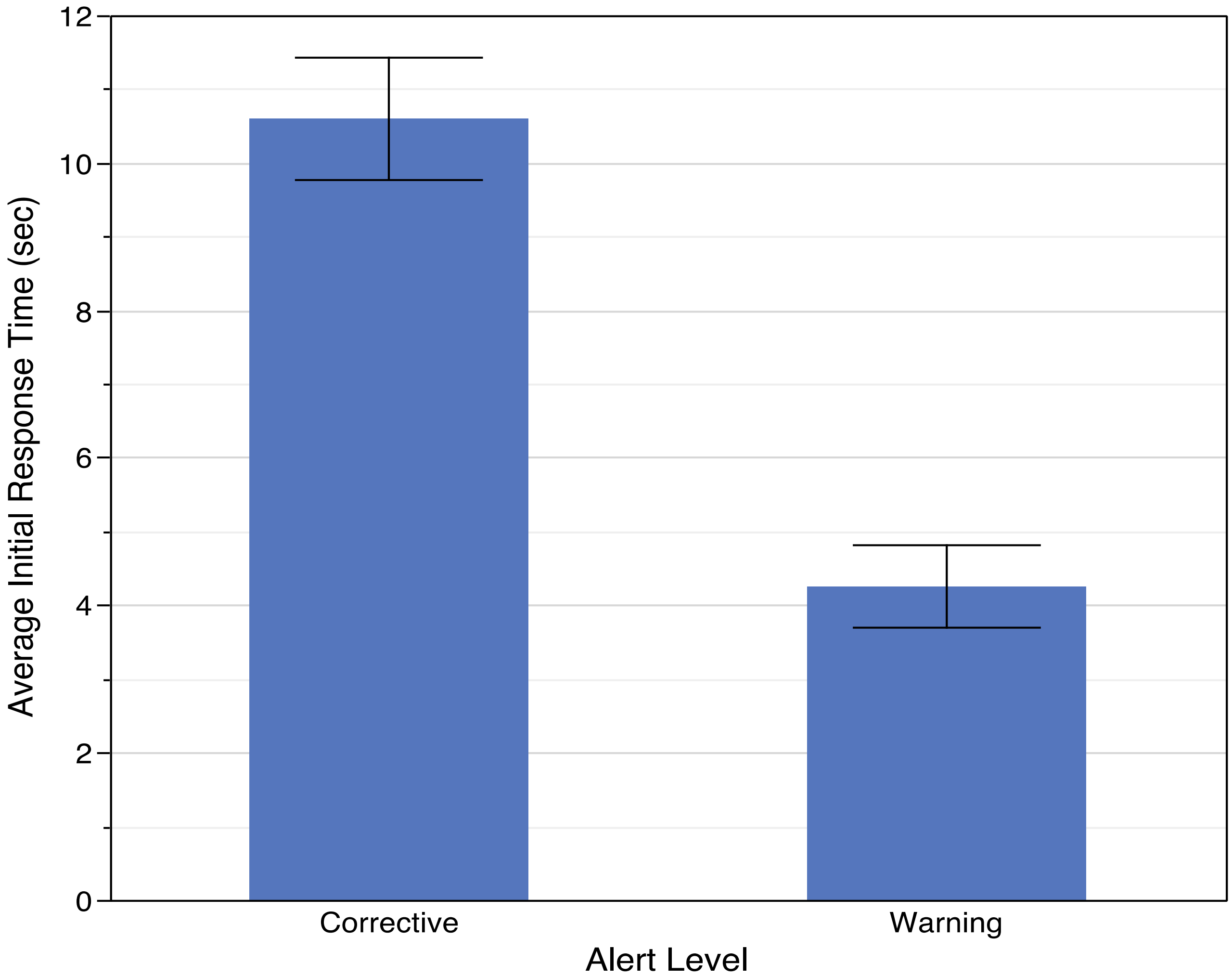
More pilot model slides - BACKUP

Average Pilot Evaluation Time vs. Alert Level

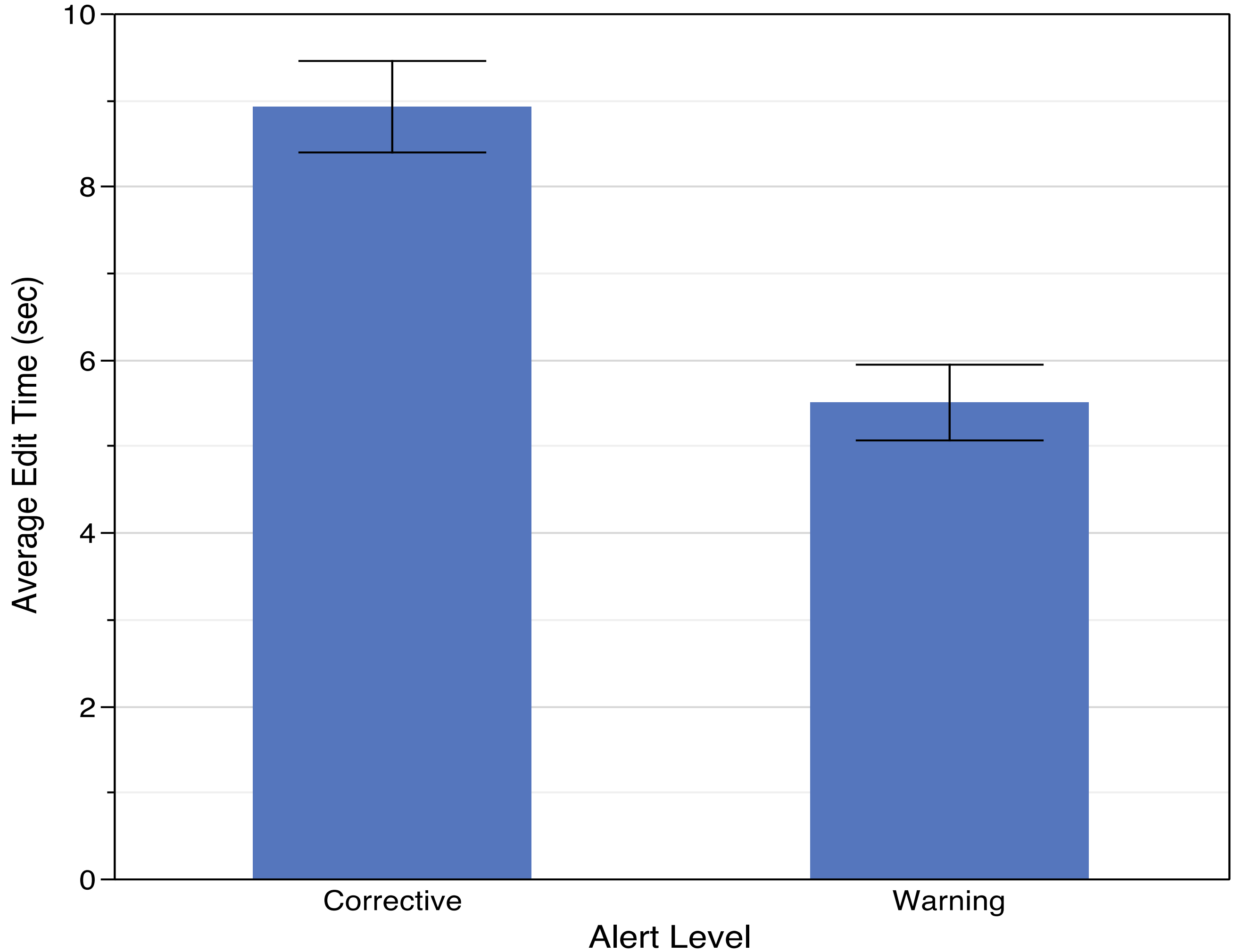
- There was significant effect of alert level on pilot evaluation time (p-value < 0.05).



Note. Evaluation Time = Initial Response Time in PT5

Average Pilot Execution Time vs. Alert Level

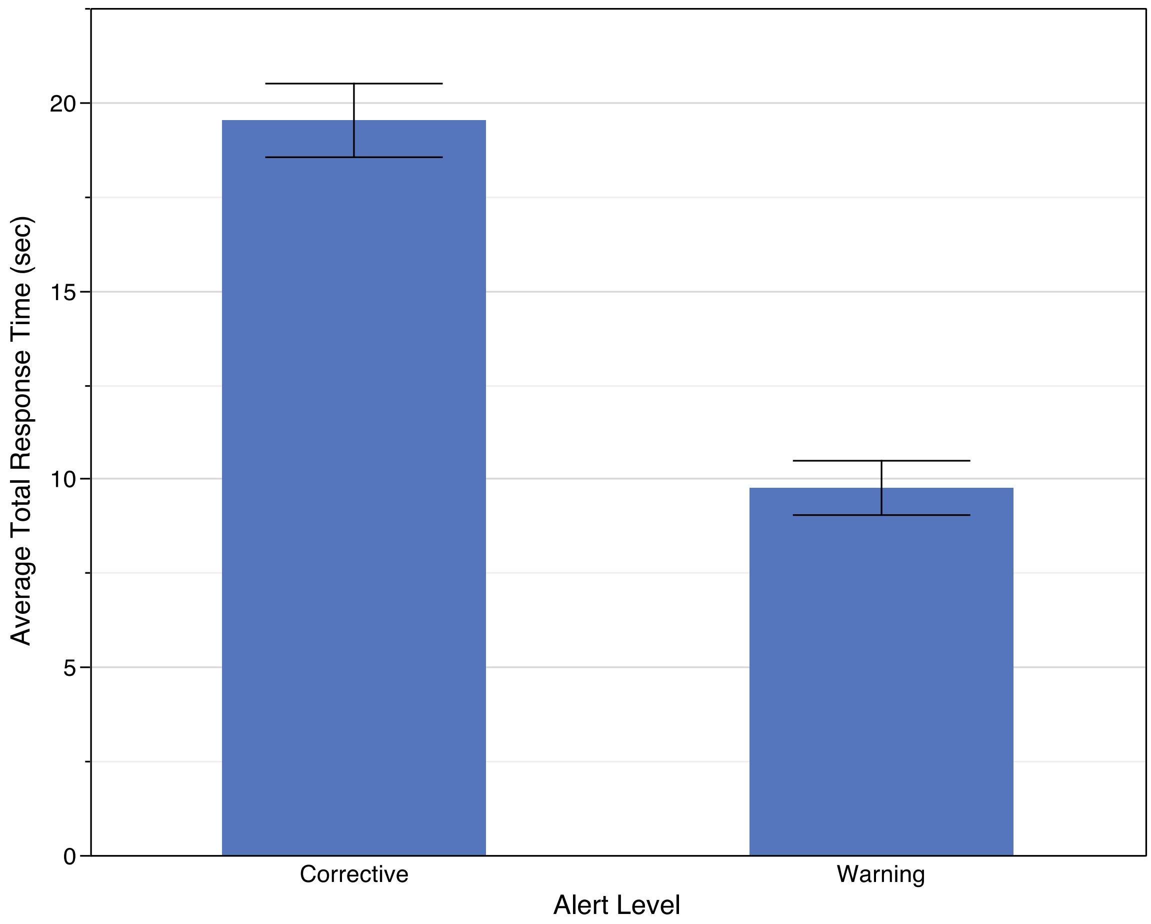
- There was significant effect of alert level on pilot execution time (p-value < 0.05).



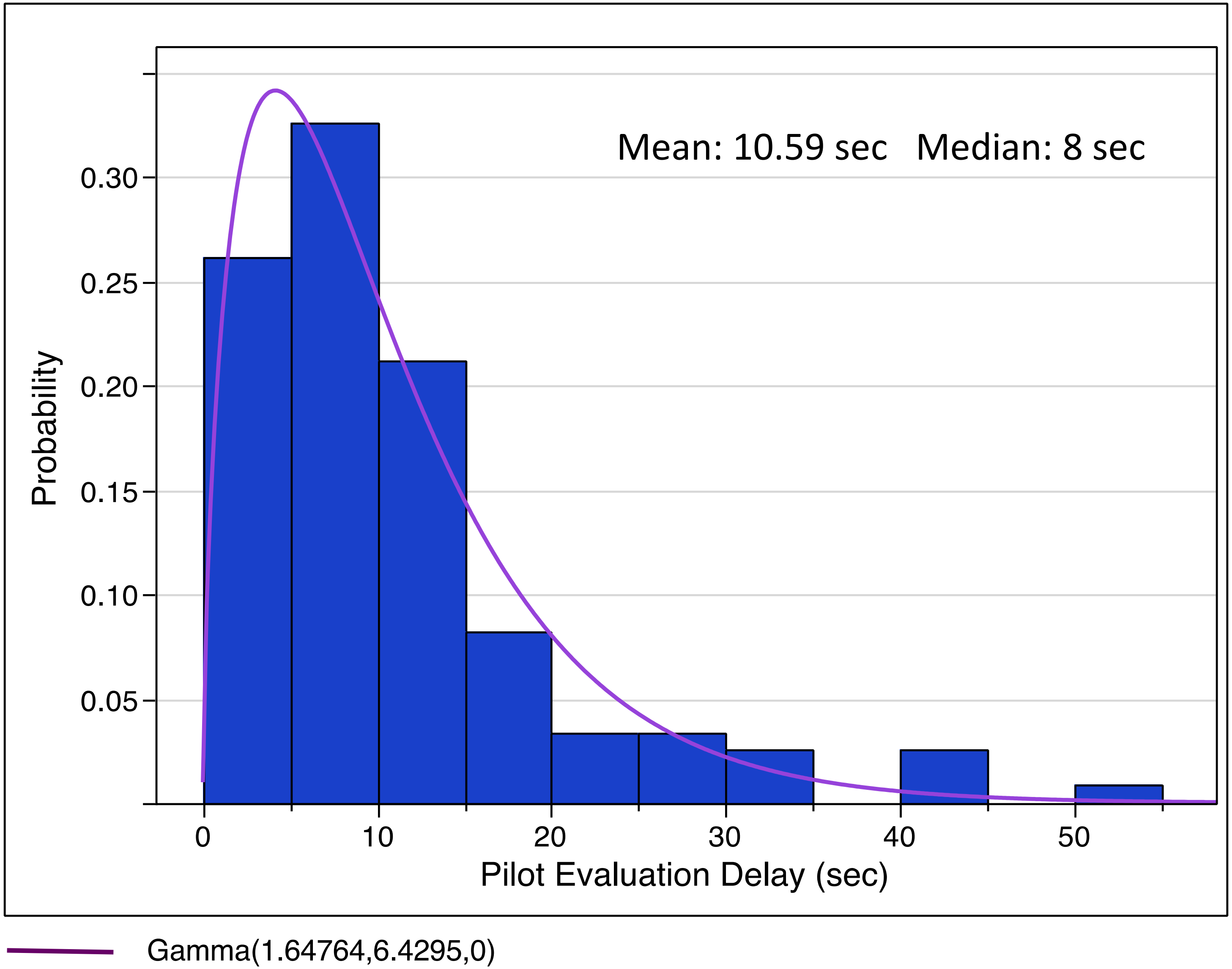
Note. Execution Time = Initial Edit Time in PT5

Pilot Total Response Time vs. Alert Level

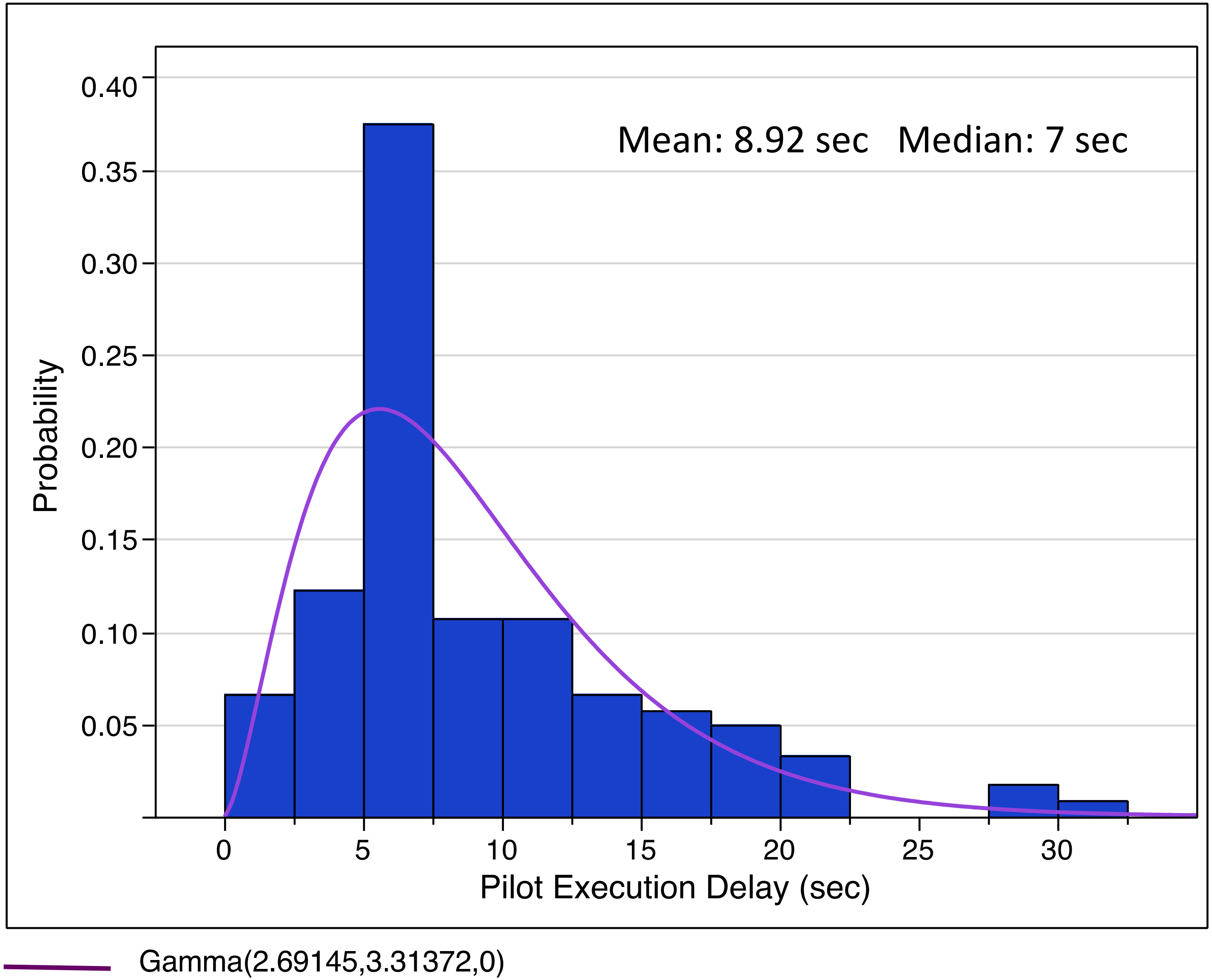
- Total Response Time = Pilot Evaluation Time + Pilot Execution Time (Time from first alert until pilot uploads first edit)
- Pilots, on average, started a maneuver roughly 10 second faster in response to DAA Warning alerts than they did to Corrective alerts.



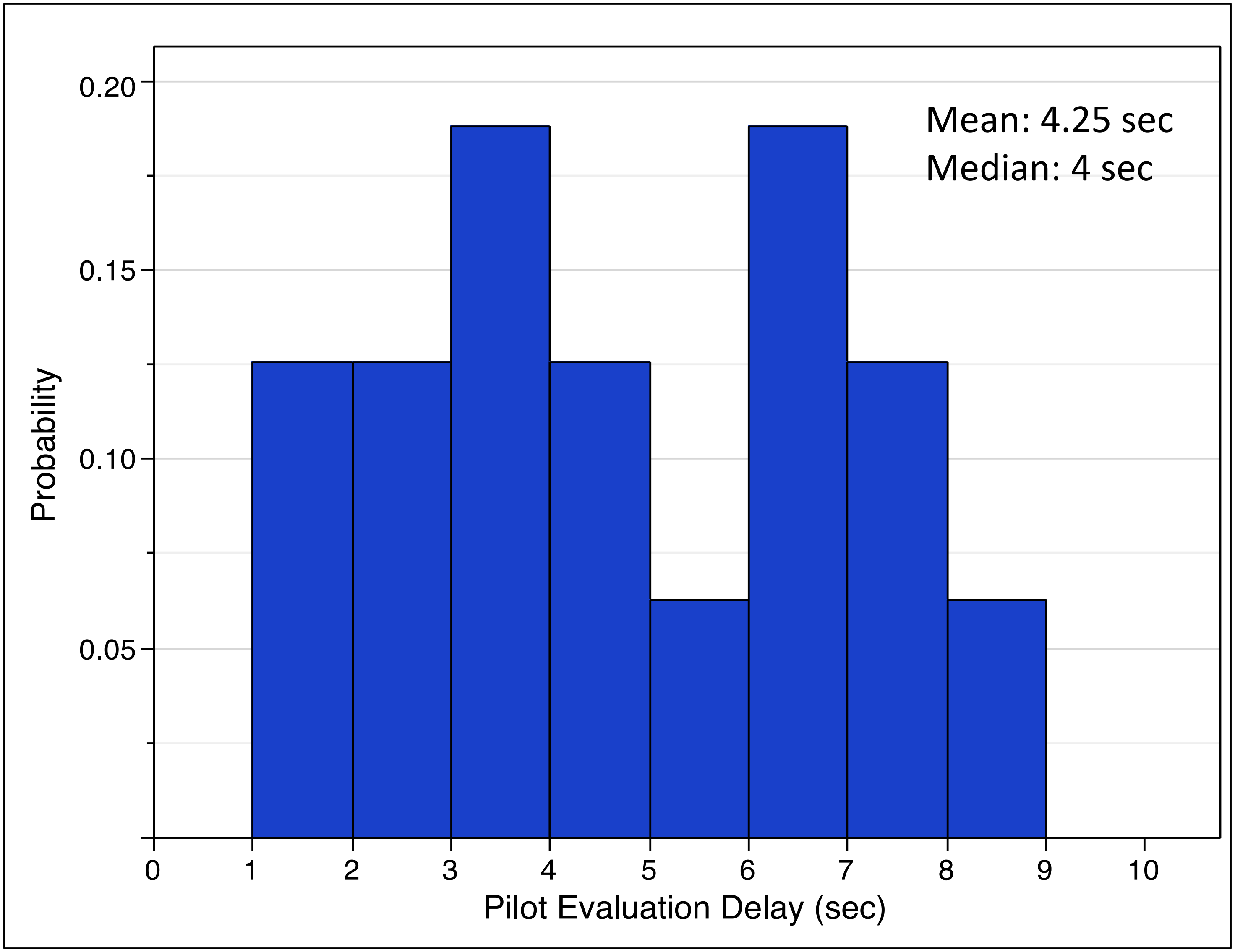
Pilot Evaluation Delay Distributions for Corrective Alerts



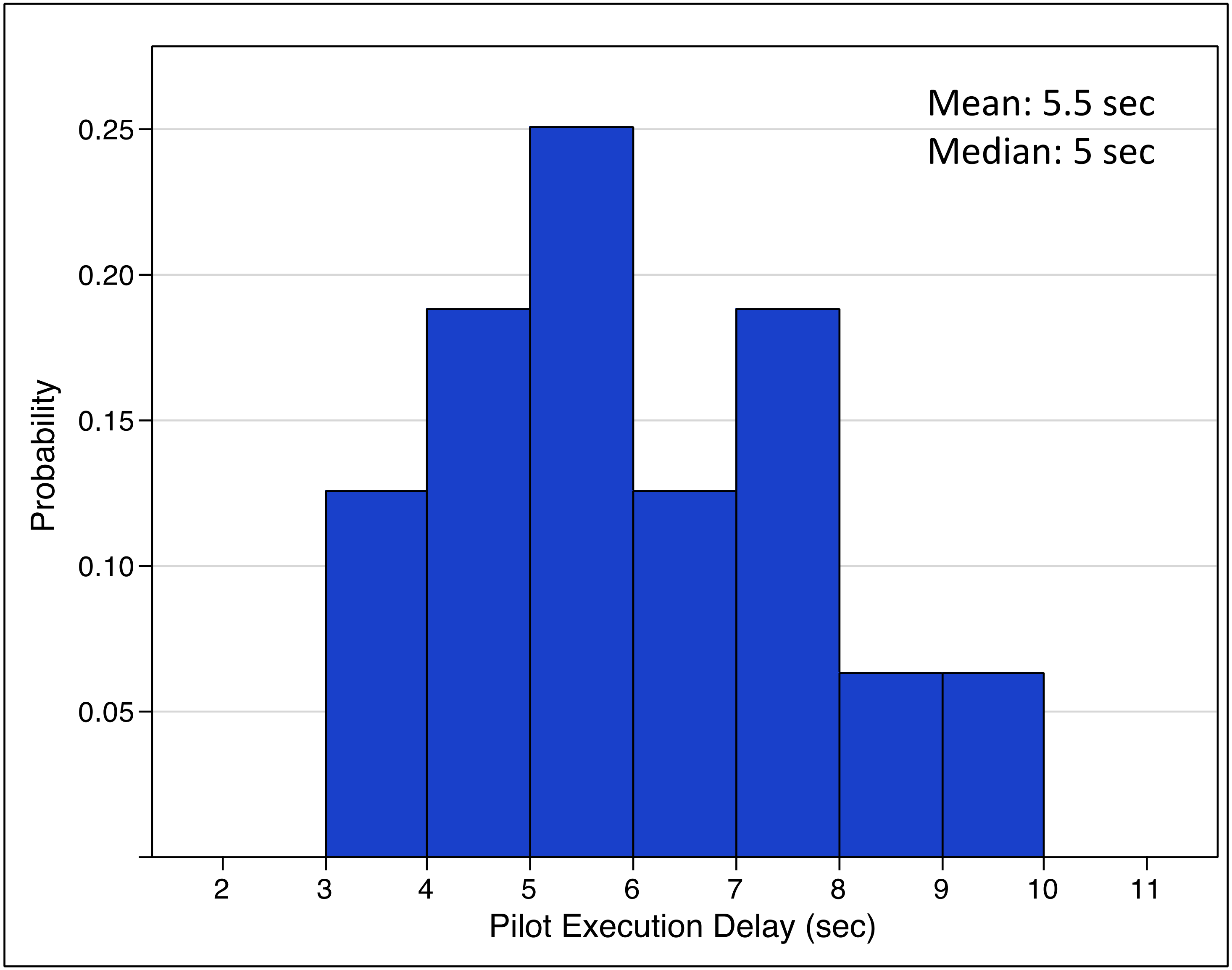
Pilot Execution Delay Distributions for Corrective Alerts



Pilot Evaluation Delay Distributions for Warning Alerts

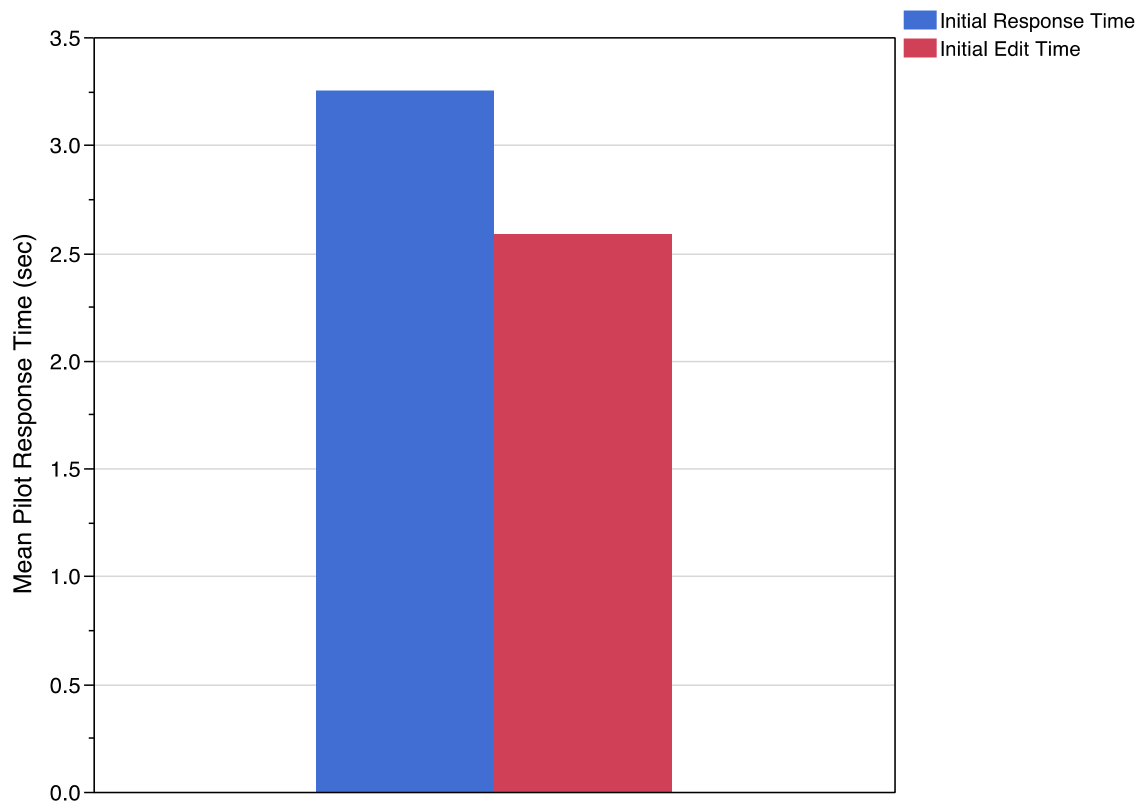


Pilot Execution Delay Distributions for Warning Alerts

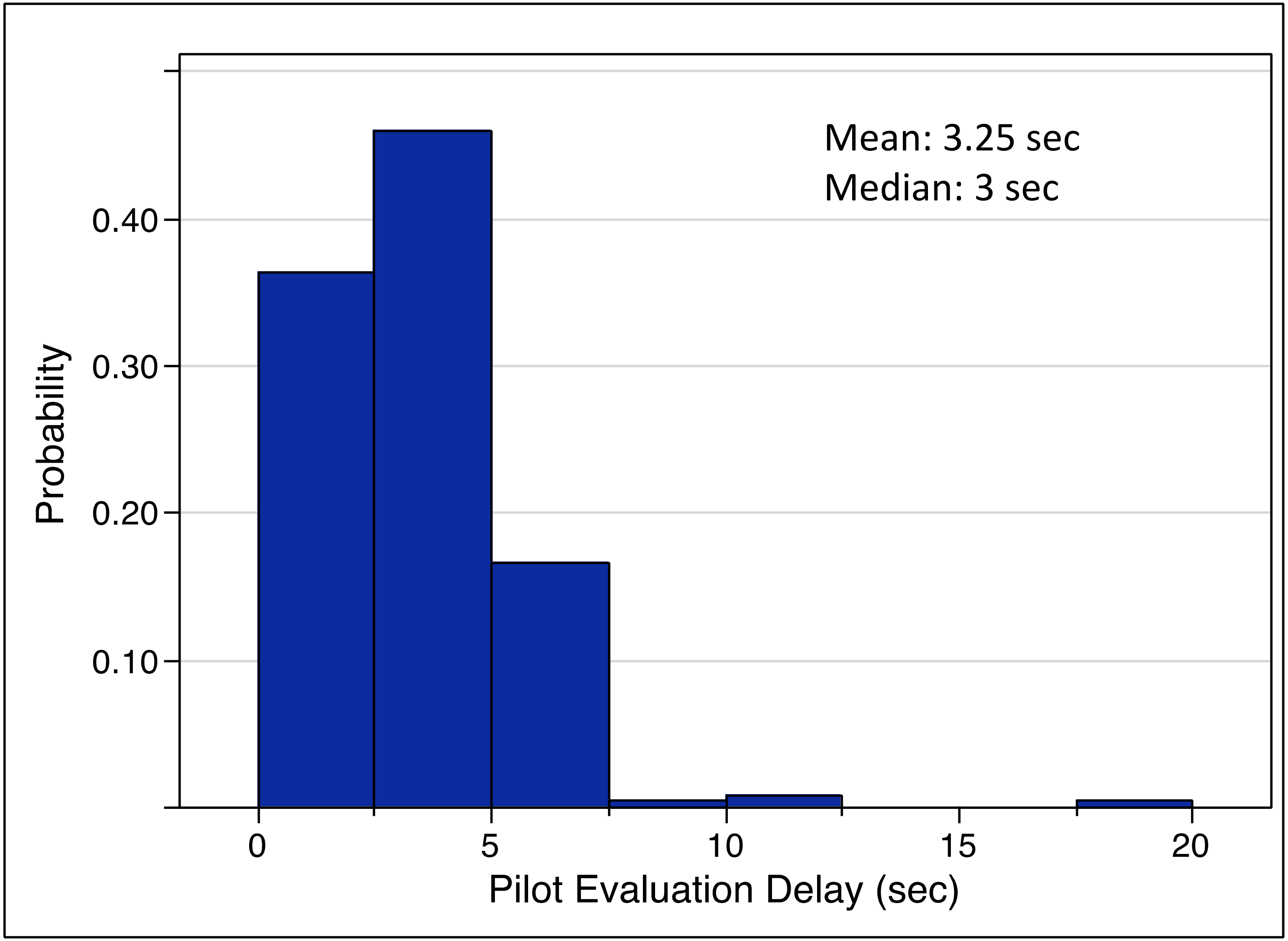


Pilot Response Time for Well Clear Recovery

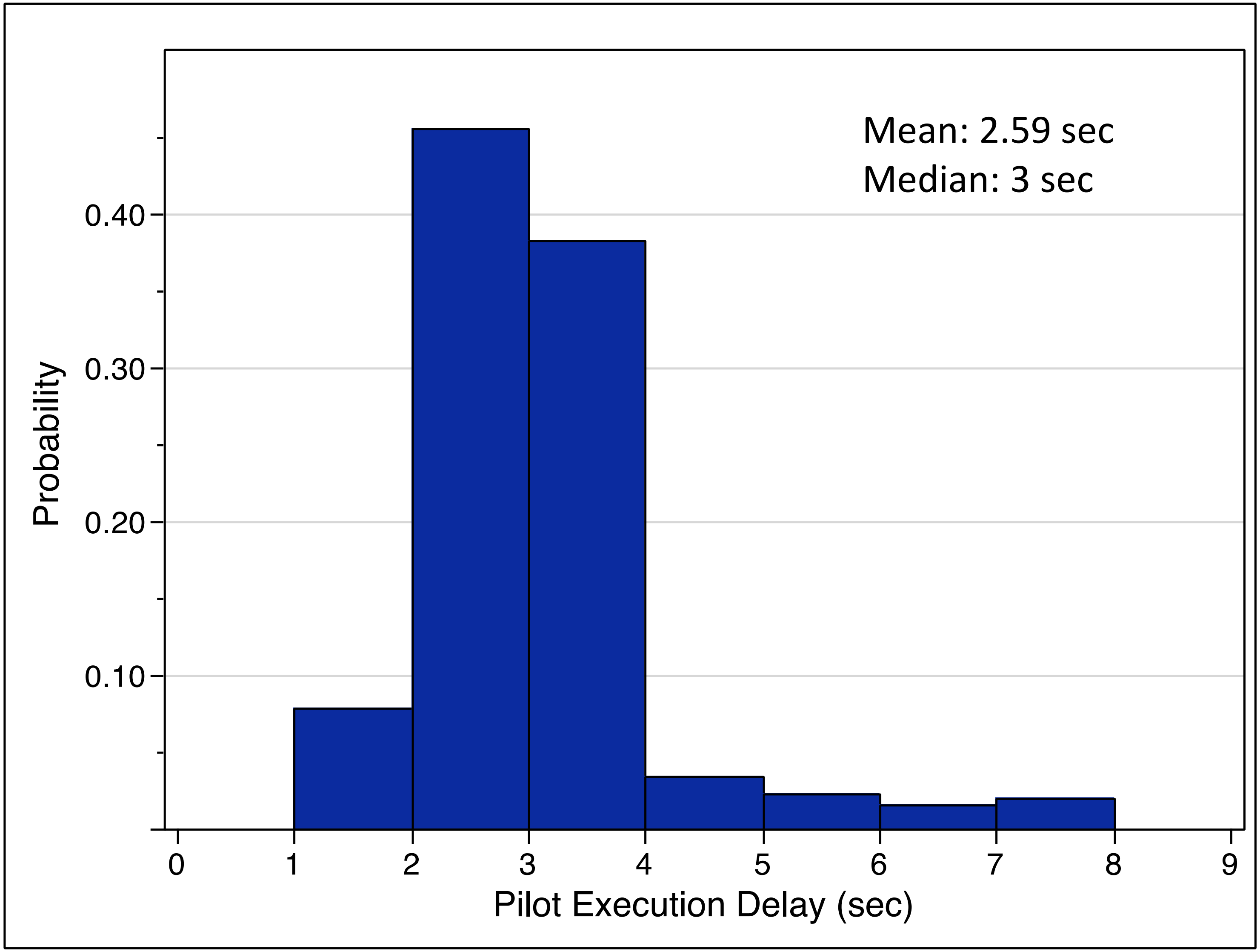
- Pilot response times for WCR cases at first alert or very close to WCR (spent less than 3 seconds as a warning before becoming well clear recovery.
- Pilots were far quicker in responding to these threats because
  - They didn’t have secondary tasks,
  - They didn’t have to contact a real ATC (and deal with busy frequencies), and
  - They were seeing conflict after conflict, priming them to be ready to respond the second an alert was generated.



Pilot Evaluation Delay for Well Clear Recovery



Pilot Execution Delay for Well Clear Recovery



Key Results for Pilot Response Model

- Pilots' evaluation times, on average, were 6.35 seconds faster in response to DAA Warning alerts than they did to Corrective alerts (p-value < 0.05).

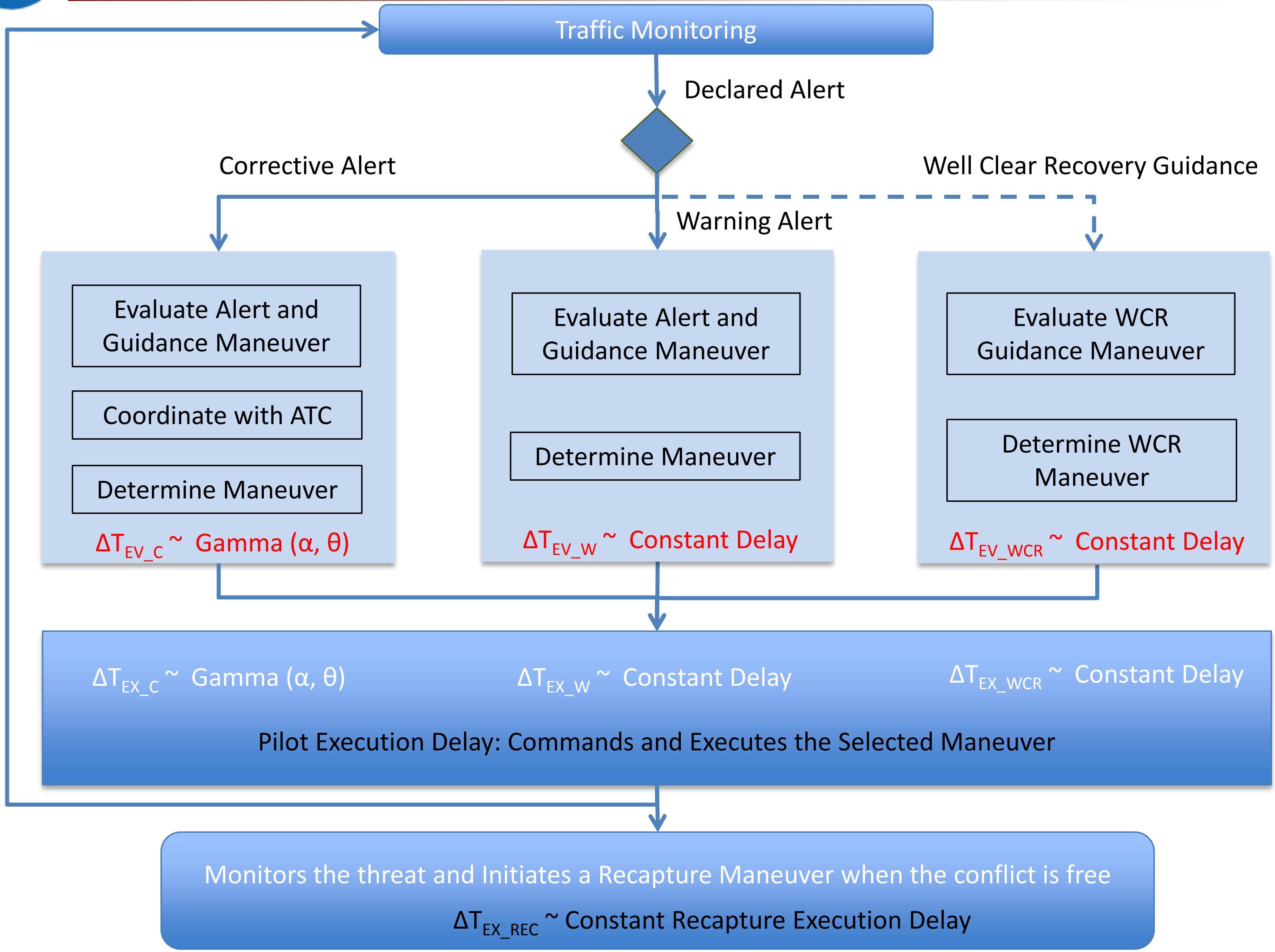
- Pilots, on average, uploaded a maneuver to aircraft 3.5 seconds faster in response to DAA Warning alerts than they did to Corrective alerts (p-value < 0.05).

- Gamma distribution fits well for pilot response times (evaluation and execution times) responding to DAA Corrective alerts.

- There was no significant variability on pilot response times (constant response latencies: 4 sec for evaluation and 5 sec for execution on average) for DAA Warning alerts.

- Constant response latencies (3 sec on average) for pilot evaluation and pilot execution times under Well Clear Recovery mode.

Stochastic Pilot Response Model



Pilot Model: DAA Resolution Module

- A simple heuristic to choose maneuver direction and magnitude based on conditional preferences and a cost function.
  - Preliminary model with deterministic behavior for maneuver selection/magnitude
  - Pilot model chooses a single horizontal or vertical maneuver based on OmniBands horizontal and vertical guidance suggestions

- Well Clear Recovery Mode: If no maneuver is available that avoids well clear violation, maneuver that maximizes minimum separation selected.

- Once a maneuver clears a conflict, the pilot will recapture to next ‘viable’ waypoint when the recapture path (and turn toward it) is clear of conflict.
  - The pilot will use OmniBands to assess whether the target heading (and/or altitude) is clear of conflict and within the same green band as the current course (In other words, there should be no alerted regions between current course and target heading or altitude required for recapture).

Pilot Model: Maneuver Preference

- Maneuver preferences depend on current navigation mode.
  - Cruise Status: Prefer horizontal maneuvers over vertical maneuvers (descent over climb)
  - Climb or descent Status: Prefer altitude holds over horizontal maneuvers
  - Near top of descent: prefer altitude holds over horizontal maneuvers (Optional)

- A cost function is used to select an appropriate maneuver so long as the cost function also complies with the selection rules.
  - Maneuver selection rules are not absolute. For example, a maneuver that generates an excessive turn is less desirable than a small altitude change.
  - Try to find minimum turns to the right and left that avoid conflict based on the OmniBands guidance, then choose turn with the smallest magnitude (+ buffer).
  - Maneuver reversal should be discouraged.
  - Avoid really thin bands when possible.

- For the tie breaker, it favors the right turns over left turns for horizontal maneuver and it gives a preference to climb over descent for vertical maneuver.

- When WCR is active, the pilot only has to select the target value.
  - Maneuver preference (direction) is already taken care of by WCR guidance algorithm.

Results - Backup

Surveillance Requirements (ACES Simulation)

- Research Objective:
  - Analyze the performance of updated sensor (ADS-B, TCAS, and radar) range and fields of regard requirements and sensitivities against Draft MOPS Alerting requirements
  - Assess airborne radar intruder detection frequency against realistic NAS traffic (IFR, cooperative VFR, and non-cooperative VFR) to inform radar tracker requirements

- Results, Conclusions, and Recommendations
  - 5-nm range appears to cover 99% of potential warning alerts DAA system would encounter with non-cooperative VFR providing verification that 5-nmdeclaration range for airborne radar is suitable
  - When UAS had at least one non-cooperative VFR intruder in its field of regard, there were 3 or fewer non-cooperative aircraft 98% of the time

Non-Cooperative Sensor Surveillance Requirements for DAA MOPS

Integrated Human-in-the-loop Experiment (Test 1)

- Research Objective:
  - Evaluate air traffic controller acceptability of UAS maneuvers in response to detect and avoid advisories and pilot performance for remaining Well Clear

- Results, Conclusions, and Recommendations:
  - Controllers reported maneuvers requested between 60 and 90 seconds until closest point of approach were acceptable, and at 120 seconds were unacceptable.
  - Size of requested maneuvers was frequently judge to be too large, indicating a difference between the separation standard used by UAS pilots to remain Well Clear and manned aircraft.

Integrated Human-in-the-loop Experiment (Test 2)

- Research Objective:
  - Evaluate the pilot's ability to remain well clear as a function of detect-and-avoid display features and whether the display was stand-alone or integrated within the main traffic display

- Results, Conclusions, and Recommendations:
  - Of all advanced maneuver guidance tested, maneuver recommendations (Autoresolver) were the most effective in aiding the pilots to remain well clear
  - Although non-cooperative aircraft can only be detected at a limited range, most losses of Well Clear can be prevented given alert time of at least 60 seconds to closet point of approach

DAA Self-Separation Alerting Methods, Performance, and Robustness Study (ACES Simulation)

- Research Objective:
  - Gather data to support development of alerting logic, methods, and performance requirements using cooperative and non-cooperative VFR traffic and the SC-228 definition of Well Clear considering target level of safety and NAS-interoperability

- Interim Results, Conclusions, and Recommendations:
  - DAA Warning Alerts that actually result in a loss of well clear have at least 15 seconds of lead time to LOWC in 83% of cases
  - 72% of DAA Warning alerts resulted in a loss of well clear suggest alerting criteria is within suitable performance bounds
  - Even though a large proportion of false alerts were observed, most of the encounter fall near the well clear boundary, thus trading these false alerts for minimizing missed alerts seemed acceptable
  - Also, given the low frequency of DAA alerts (about 1 every 10 flight hours), these large false alert proportions are minimal

Self-Separation Alerting Requirements for DAA MOPS

Upcoming: Flight Test 4

Objectives:

1. Validate DAA requirements in stressing cases that drive MOPS requirements
   - High-speed intruder (> 500 knots)
   - Low-speed intruder (~ 100 knots)
2. Validate collision avoidance/DAA alerting and guidance interoperability concept in the presence of realistic sensor, tracking and navigational errors
3. Validate well clear recovery guidance when well clear is lost in the presence of realistic sensor, tracking and navigation errors
4. Validate DAA alerting and guidance requirements under normal circumstances in the presence of realistic sensor, tracking and navigational errors

Key verification and validation activity for RTCA SC-228