Statistical Design and Analysis of Experiments for Next Generation Air Transportation Research

Sara R. Wilson
NASA Langley Research Center

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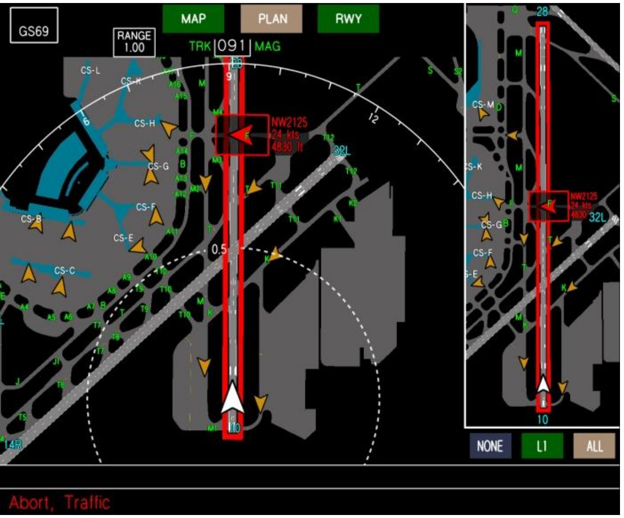
NextGen

- Forecasts project air traffic demand to double by 2030
- The current Air Traffic Management system is already nearing its capacity
- If left unmodified, the current system cannot indefinitely sustain the projected traffic growth without inducing significant delays and inefficiencies
- The objective of the NextGen-Airspace Project is to develop and explore fundamental concepts, capabilities, and technologies to enable significant increases in the capacity, efficiency, and flexibility of the National Airspace System necessary for the Next Generation Air Transportation System (NextGen)
- NextGen Concepts and Technology Development Project
  - Separation Assurance
  - Safe and Efficient Surface Operations
  - Super Density Operations

Safe and Efficient Surface Operations

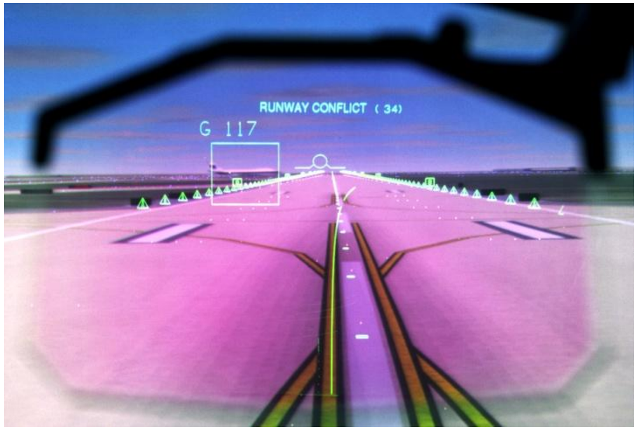
- **The National Transportation Safety Board has runway incursion prevention on its most wanted list for aviation safety**
- **Increase in air traffic forecasted under NextGen could exacerbate this problem**
- **The objective of SESO research is to develop technologies, data, and guidelines to enable conflict detection and resolution in the Terminal Maneuvering Area under NextGen operating concepts providing an additional, protective safety layer**

Traffic position awareness



Departure Surface Map

Ownship position awareness



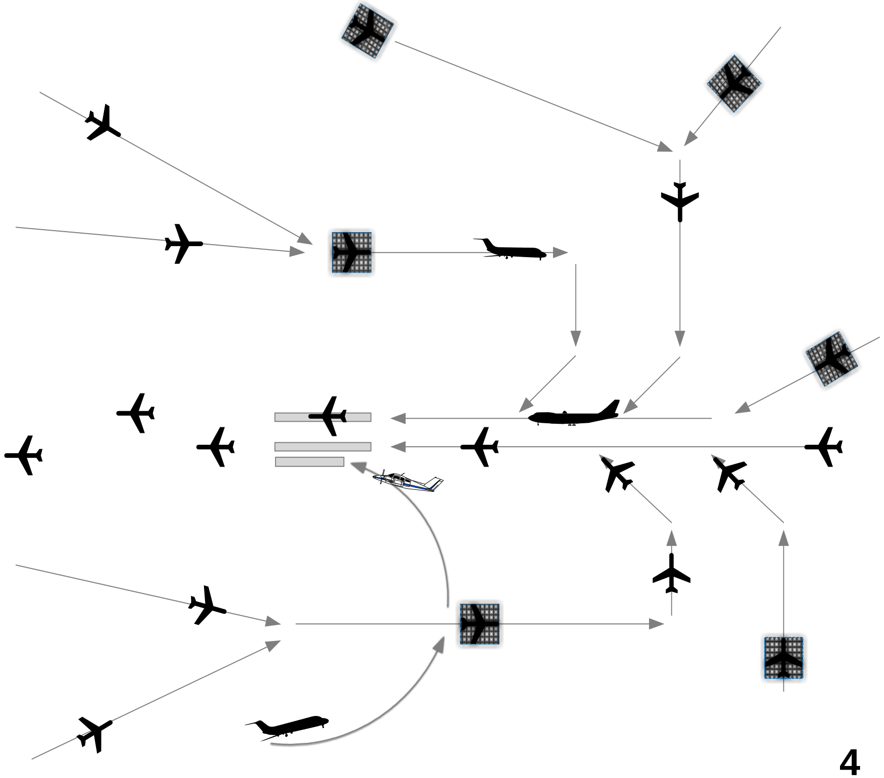
HUD Guidance

Route awareness

Taxi Surface Map

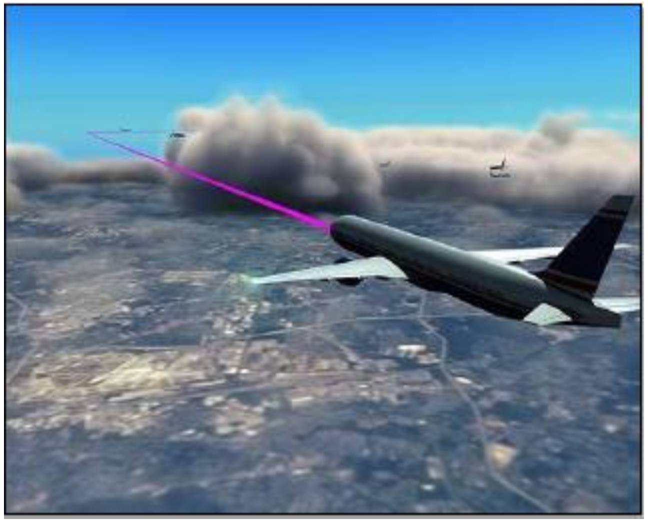
Super Density Operations

- A key to airport efficiency is the ability to schedule, and then manage, the aircraft-to-aircraft spacing at the runway threshold.
- Interleaving complex, three-dimensional routes with time constraints arriving from all directions very difficult for the human mind
- Current scheduling and arrival operations can be made more efficient
- The objective of Super Density Operations (SDO) research is to support the increase in capacity and throughput necessary for NextGen via simultaneous multi-objective sequencing, spacing, merging, and de-confliction for terminal airspace with nearby runway thresholds



Separation Assurance

- The objective of Separation Assurance (SA) research is to develop trajectory-based technologies and human/automation operating concepts capable of safely supporting the increase in capacity necessary for Next Generation Air Transportation System (NextGen)
- In the current Air Traffic Management system, separation of aircraft is the most important task for an air traffic controller in high density airspace and is one of the main factors in controller workload
- This approach is inherently limited by controller workload and will not be able to support the expected traffic growth
- A new airborne trajectory management with self-separation concept developed, in which the pilot is responsible for managing the separation for his or her aircraft supported by onboard automation
- A Human-in-the-Loop (HITL) experiment was conducted to study a new airborne trajectory management with self-separation concept



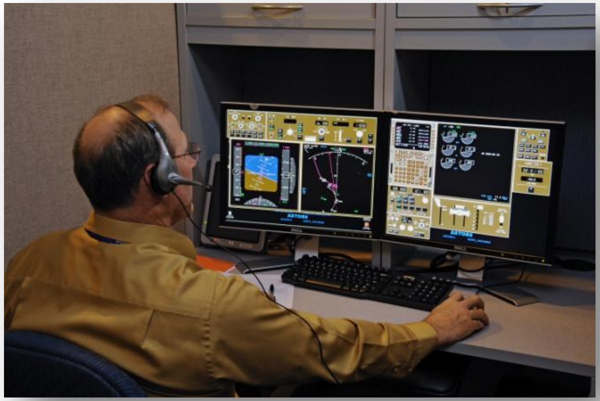
Air Traffic Operations Laboratory

- **The Air Traffic Operations Laboratory (ATOL) hosts a simulation platform which provides a medium fidelity setting for studying the interactions of aircraft**

- **The simulation networks multiple individual pilot stations called Aircraft Simulation for Traffic Operations Research (ASTOR) and a background traffic generator called Traffic Manager (TMX)**

- **The ATOL has over 300 computers, including 12 desktop pilot workstations, for conducting both Human-in-the-Loop (HITL) and batch (simulation) experiments**

Air Traffic Operations Laboratory (ATOL)



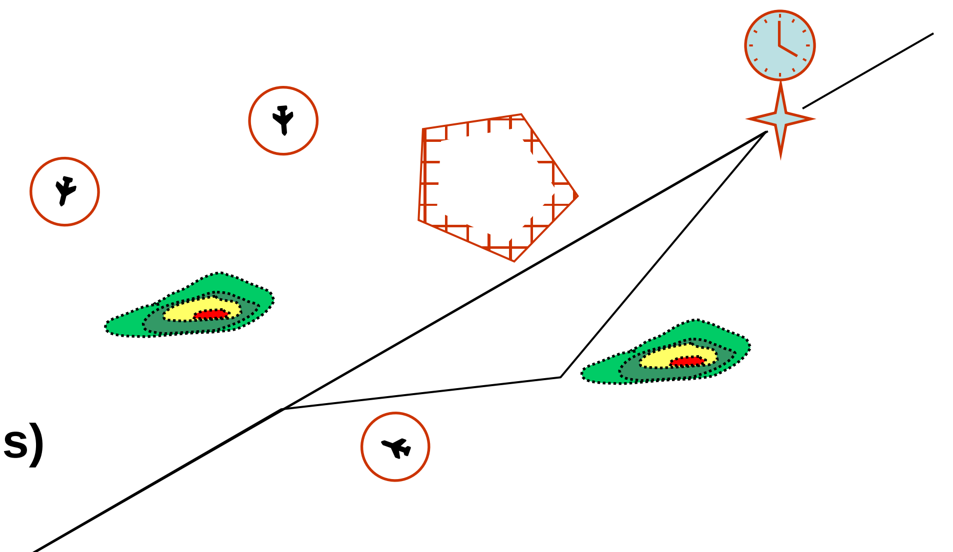
Human Piloted Aircraft

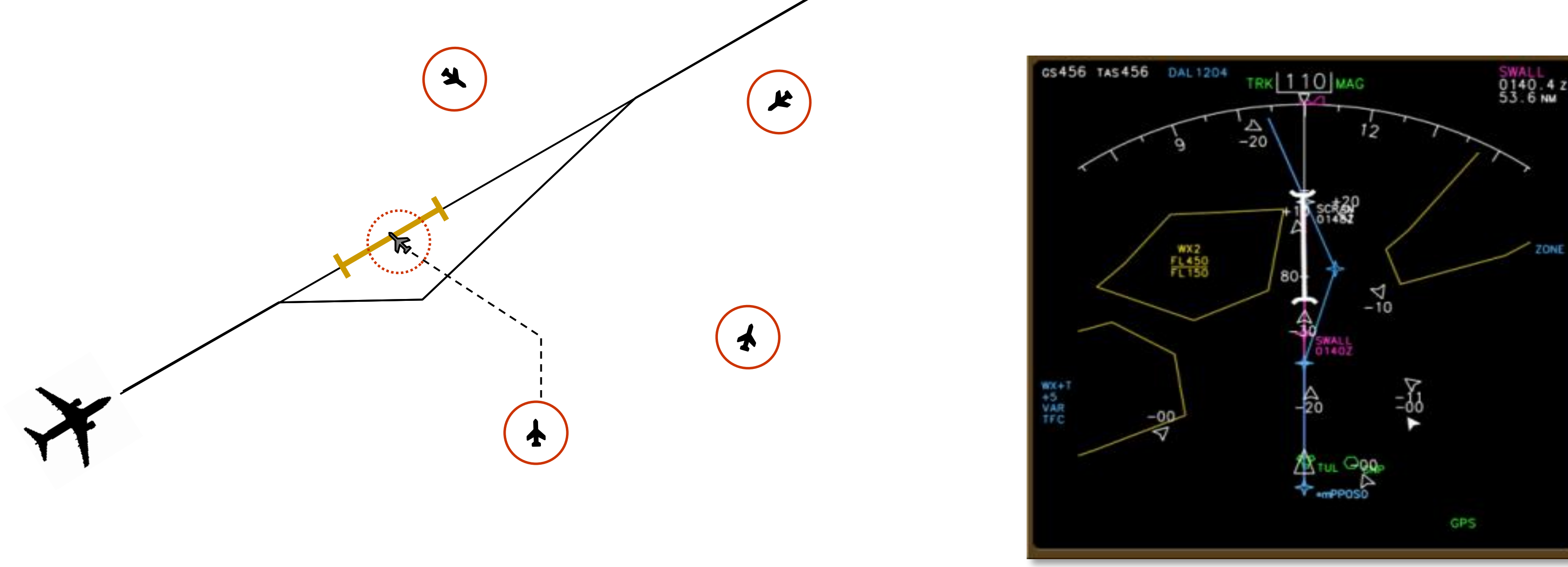
Batch Aircraft (ASTOR & TMX)

Aircraft Simulation for Traffic Operations Research (ASTOR) HITL Interface

Separation Assurance

- Detecting and resolving traffic conflicts
- Verifying all trajectory changes are conflict-free
- Conforming trajectory to additional operational constraints
  – Service provider (e.g. flow constraints, SUA)
  – Operator (e.g. company policy, optimization criteria)
  – Environment (e.g. weather hazards)





Statistical Design of SA HITL

- **Research questions are framed as statistical hypotheses to test in the experiment**
  - **Flight path deviation will be larger in far-term (2.0x) traffic density conditions than in mid-term (1.5x) traffic density conditions**

- **The experiment is designed to investigate these hypotheses**

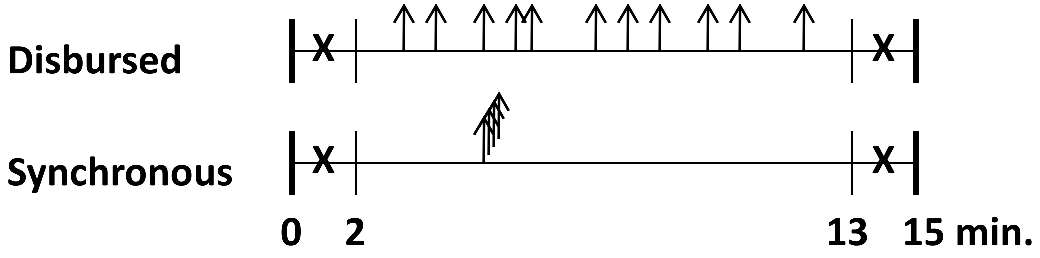
- **A formal peer-driven review process is employed to ensure the objectives are met**
  - **Preliminary Experiment Review (PER)**
  - **Simulation Requirements Review (SRR)**
  - **Final Experiment Review (FER)**

Experiment Factors / Independent Variables

- **Traffic Density (1.5x, 2.0x)**
  - **Reference: 1x = 18 aircraft per 10,000 nm^2**
  - **Maintained constant throughout data run**

- **Scheduling Assignment (No RTA, Yes RTA)**
  - **Required Time of Arrival (RTA)**

- **Trajectory Change Event Timing (None, Disbursed, Synchronous)**
  - **Revised RTA sent via data link**
  - **Approx 6-8 minute delay requiring path stretch**



Experiment Design Matrices

- **30-minute scenarios**
  - **Within-subject design**
  - **No trajectory change events**
  - **2 replicates (8 runs total)**

Scheduling Assignment		1.5x	2.0x
	No	M1	M2
	Yes	M4	M3

Traffic Density (columns: 1.5x, 2.0x)

- **15-minute scenarios**
  - **Within-subject design**
  - **Traffic density (2.0x)**
  - **Scheduling assignment (Yes)**
  - **2 replicates (6 runs total)**

Timing of Trajectory Change Event

	None	*Disbursed*	*Synchronous*
2.0x Traffic Density	S1	S2	S3

Pilot Participants and Experimental Protocol

- **48 pilots: 4 groups of 12 pilots each**
  - **Groups 1-3: all domestic U.S. pilots**
  - **Group 4: mix of domestic U.S. and international pilots**
    - **To support global research perspective on airborne self-separation**

- **3 day experiment sessions for each group of participants**
  - **Day 1: Classroom and hands-on training (10 training scenarios)**
  - **Day 2: Final training scenario + 8 experiment scenarios (30 min)**
  - **Day 3: 6 experiment scenarios (15 min) + group debrief session**

Blocking Strategy

- Blocking is a method of partitioning the runs into homogeneous sets, or blocks, based on a blocking factor
- Analysis of a block design involves the comparison of runs within the same block, which removes variability due to the blocking factor
- This reduces experimental error and provides more precise answers to research questions
- Group was a blocking factor
  - Four independent groups of 12 pilots participated in four separate three-day experiment sessions
  - Groups 1, 2, and 3 consisted solely of American pilots
  - Group 4 included European pilots to support a global perspective on Air Traffic Management research
  - The groups of pilots were trained separately

Experiment Run Order

- **Order in which treatments are assigned can have important effects on the experiment results and answers to research questions**

- **This is particularly true in HITL experiments where order can affect the behavior of participants due to fatigue, learning curve, or other outside factors**

- **Two of the ways to control for order effects are *randomization* and *counterbalancing***

- **Randomization of the treatments is the most common approach**
  - **Minimizes the impact of any systematic bias on the results**
  - **Is an underlying assumption of most commonly used statistical methods**

Experiment Run Order

- **Counterbalancing assumes a confounding order effect exists which cannot be controlled or randomized out of existence**
  - **Distributes equal amount of the confounding effect to each treatment in such a way that the effect will counterbalance itself and not bias the results**
  - **Main disadvantage is the additional complexity introduced into both the experiment design and data analysis**

- **In the SA HITL, aircraft callsigns were randomly assigned to pilots**
  - **Randomized separately for each run and for each group of pilots**
  - **Scenario difficulty and conflicts encountered varied by callsign**

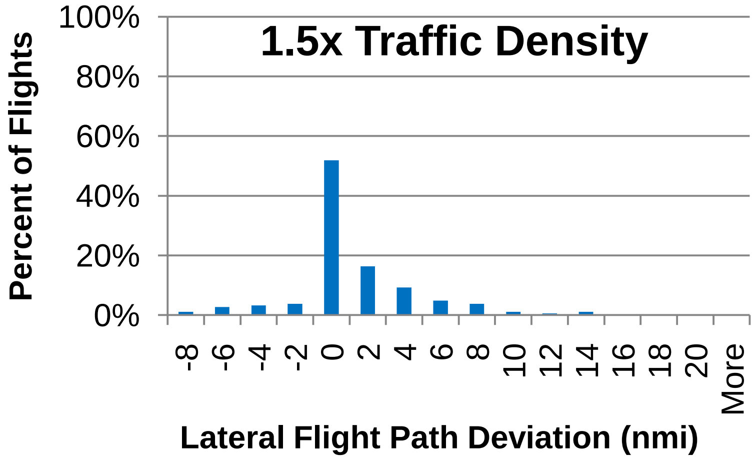
- **Blocked by group of pilots, so the order of the scenarios was randomized separately for each group**

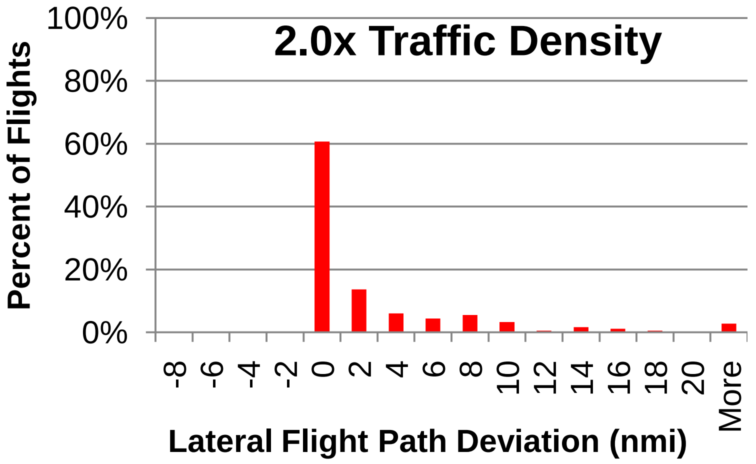
Correlation

- **Standard statistical analysis methods are based on the assumption that observations are independent**
- **However, in HITLs the data have a specific correlation structure**
  - **Aircraft flown by the same pilot are not independent**
  - **Aircraft flown by pilots in the same group are not independent**
  - **Aircraft flown by pilots in different groups are independent**
- **Three methods for addressing this correlation structure are to ignore it, estimate it, or account for it in the design**
  - **Ignoring correlation violates the assumption of independence and can lead to over- or under-estimation, which affects all hypothesis tests and conclusions**
  - **Obtaining a good estimate of the covariance matrix to address the correlation in the data analysis can be very difficult**
  - **Accounting for the correlation structure in the experiment design is often the best choice, but requires careful planning prior to data collection**

Statistical Data Analysis and Interpretation

- **Hypothesis: Flight path deviation will be larger in far-term (2.0x) traffic density conditions than in mid-term (1.5x) traffic density conditions.**
- **Conclusion: The traffic density effect was found to be significant at the alpha = 0.05 level, indicating that increasing the traffic density from 1.5x to 2.0x increased the mean lateral flight path deviation.**





Coordinated Experiments

- This SA HITL simulation was part of a coordinated experiment with NASA Ames Research Center
- The primary goal of these coordinated experiments was to assess the degree of comparability possible
- This was the first in a series of experiments within a multi-year research plan to study advanced function allocation concepts for NextGen separation assurance in high density airspace
- Although these experiments were jointly designed and conducted in parallel, they differed in the number of replicates, the blocking strategy, and the method for controlling for order effects
- Differences in the experiment designs resulted in differences in the data analysis, which made comparison of the results more difficult

Coordinated Experiments

- **One way to compare the concepts is by conducting statistical hypothesis tests to determine which factors have a significant effect on the response**
- **The quality of a hypothesis test depends on its power, which is the probability of making a correct decision**
- **Initial results can be used to design future coordinated experiments so that statistical hypothesis tests with the same power can be conducted**
- **This would provide a higher degree of comparability for the two concepts**

Conclusions

- Taking lessons learned from this HITL and other simulations, future experiments will continue to use statistical design of experiments to
  - improve efficiency
  - answer more research questions with greater precision
  - ensure that the experiment design and data collected will allow for the evaluation of the hypotheses of interest

- Currently developing experiment plan for the next Separation Assurance HITL investigating a mixed-operation concept

References

- **Wing, D.J., et al., "Function Allocation With Airborne Self-Separation Evaluated in a Piloted Simulation." Proc. 27th ICAS Congress, Nice, France.**

- **Consiglio, M.C., et al. (2010). "Human in the Loop Simulation measures of Pilot Response Delay in a Self-Separation Concept of Operations." Proc. 27th ICAS Congress, Nice, France.**

- **Wing, D.J., et al. (2010). "Comparison of Ground-Based and Airborne Function Allocation Concepts for NextGen Using Human-in-the-Loop Simulations." Proc. 10th AIAA Aviation, Technology, Integration, and Operations (ATIO) Conference, Fort Worth, TX.**