Urban Air Mobility Airspace Dynamic Density

Defining Airspace Saturation Metric for Emerging Operations

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Imagine …

Photo credit: https://www.dmagazine.com/frontburner/2021/06/the-average-dallas-driver-spent-49-hours-sitting-in-traffic-last-year/

Imagine …

Photo Credit: https://www.youtube.com/watch?v=1oDaHRbIDH8

Photo Credit: https://www.smithsonianmag.com/history/recapping-the-jetsons-episode-03-the-space-car-67174086/

Motivation

- Air transportation system is expanding to accommodate a broad diversity and vast increase in air traffic
  - New aircraft types are being introduced, ranging from sUAV through supersonic transport aircraft
  - Type of operations are expanding to include sUAV package delivery, urban air mobility, autonomous disaster support, high-altitude/long-endurance ops, etc.

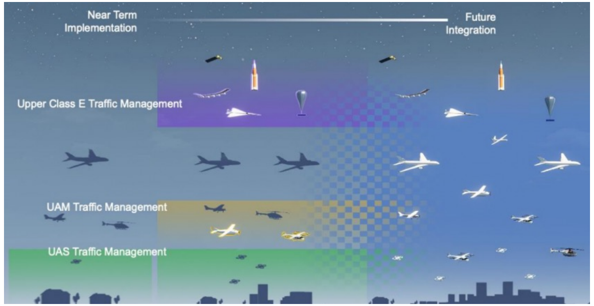


Photo Credit: NASA

- Scale of operations is expected to overwhelm the traditional ATM system due to controller workload required to safely and efficiently manage traffic
  - New architectures being evaluated that rely on increased automation and increased collaboration between airspace users

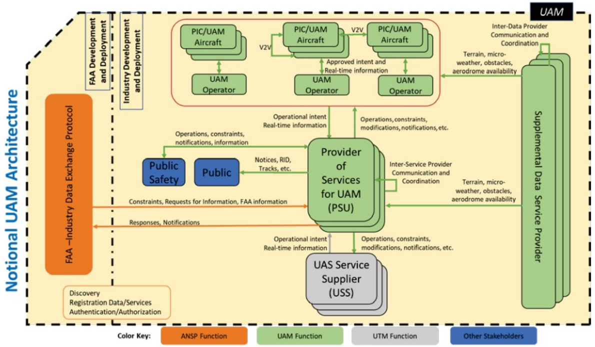


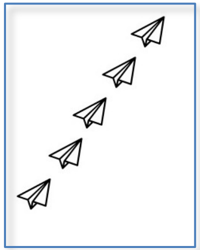
Photo Credit: FAA

Dynamic Density

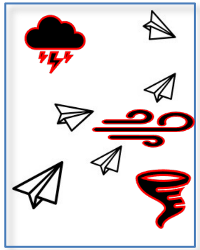
- In traditional ATM, the amount of traffic allowed in a sector depends on the controller workload required to safely and efficiently manage that traffic
  - Number of aircraft is a major contributor
  - Interaction between those aircraft is also important

  Dynamic Density

- Potential interaction depends on sector complexity and operational constraints
  - Previous research explored numerous factors that contribute to controller workload, including spectrum of aircraft types (performance, relative speed, pilot abilities), number of ingress/egress points, number of crossing points, number and geometry of crossing flows and difficulty of predicting conflicts, airspace restrictions that decrease maneuvering opportunity, etc.



Low complexity: homogeneous ops; constrained flow



High complexity: widely diff performance, capability, equipage; intersecting flows; adverse weather

Research Statement

- Define and validate a dynamic density metric that facilitates more autonomous and cooperative management of new operations
  - Expectation is new entrants will not use traditional ATC services. Therefore, controller workload is not a factor
  - Propose and evaluate airspace and traffic factors predictive of airspace congestion (saturation) that may lead to loss of separation between aircraft or less efficient operations

- Limit the scope to urban air mobility (UAM)

Photo Credit: NASA

Outline

- Urban Air Mobility
- Dynamic Density Factors and Aggregation
- Use Cases and Visualization
- Metric Validation
- Summary and Future Work

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Urban Air Mobility

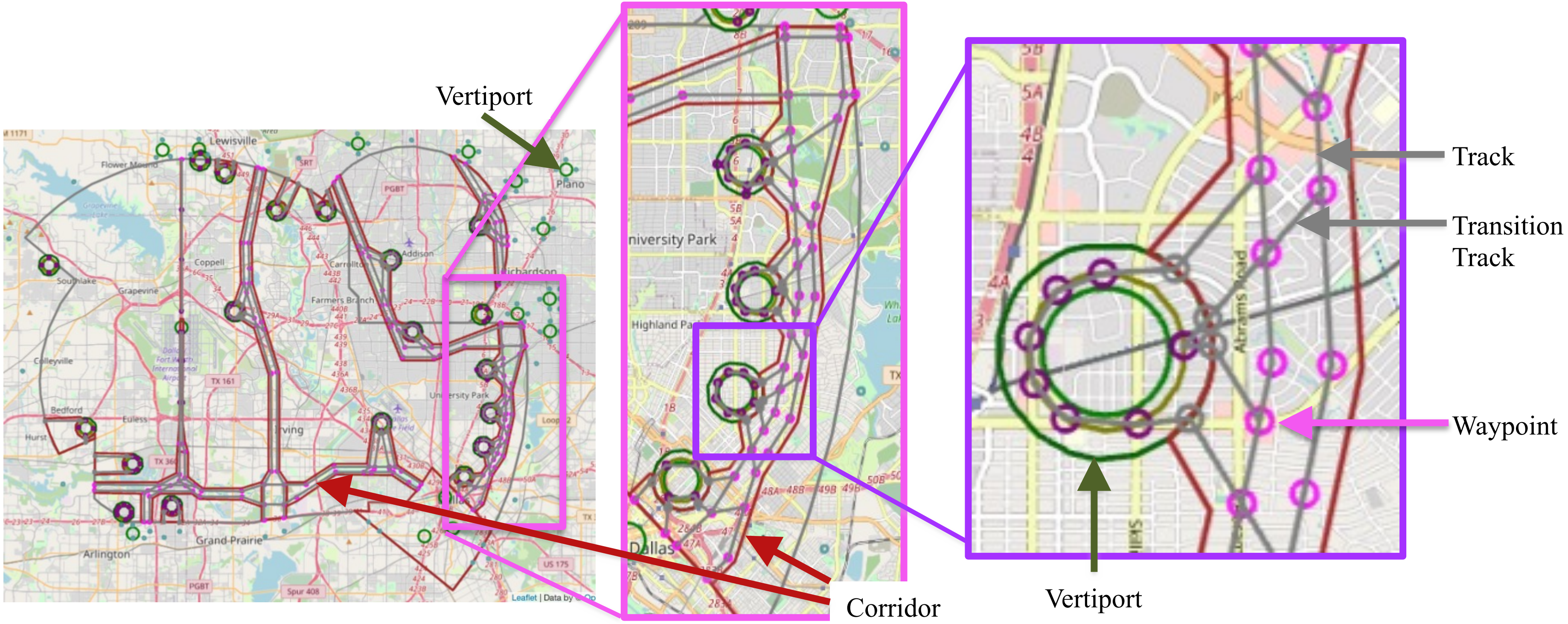
- Use highly automated, electric or hybrid powered, vertical or short takeoff and landing aircraft to transport people and cargo over urban areas
  - Addressing problem of ground congestion, wasted time, environmental pollution

- UAM operations anticipated to be ubiquitous; high density; highly complex; and rely on highly automated vehicles, airspace management, and system-wide optimization capabilities

- NASA Air Traffic Management eXploration (ATM-X) project is helping mature UAM ATM concepts, technologies, and capabilities through a series of simulations with industry partners. Most recent simulation is derived from the FAA NextGen UAM ConOps v1.0 and assumes:
  - Responsibility for safe and efficient operations shifts to third-party service providers (called PSUs)
    - Expectation is that UAM will usually not use traditional ATC services
    - New paradigm is being developed to accommodate expected scale of operations without increasing controller workload
  - UAM aircraft would operate in segregated airspace using specific rules and procedures
    - Meet performance requirements and fly between vertiports on tracks inside corridors
    - May also operate outside corridors where they must follow the encompassing airspace rules
  - Dynamic density is being matured in lock step

ATM-X Notional UAM Airspace Structure

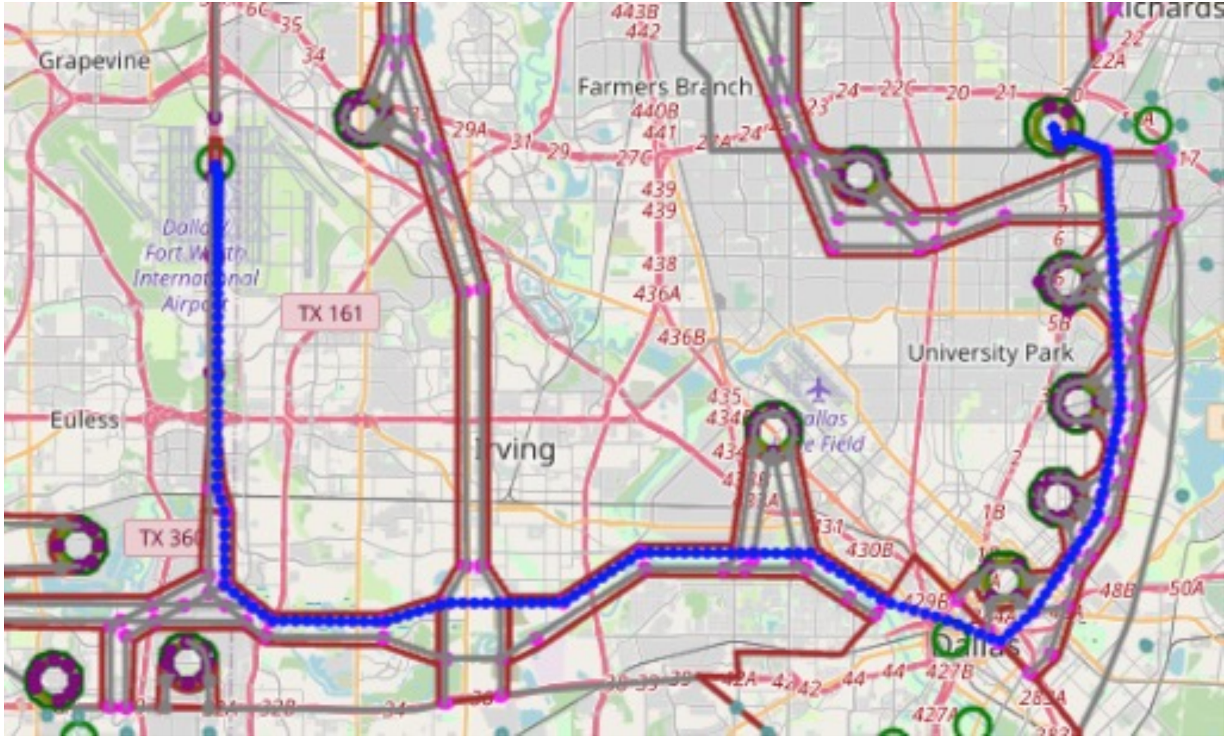
- Derived from FAA NextGen UAM ConOps v1.0



Example UAM Trajectory

- All aircraft cruise at same altitude and same airspeed; same climb/descent profile

- Corridors are bi-directional; each track is one-directional



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Dynamic Density Metric

- Purpose: Ensure corridors are not saturated
  - Prevent excessive de-confliction maneuvering which may lead to premature battery depletion
  - Maintain required maneuvering inside corridors
  - Avoid unplanned delays

- Characterized by factors adapted for UAM and inspired from traditional ATM dynamic density research
  - Factors are expected to change as airspace structures change, vehicles and traffic management systems become more capable, and safety systems are fully vetted
  - Methodology used to determine importance of factors is expected to change as more flight data becomes available. Because of current sparsity of data, our approach relies on analysis, domain knowledge, and conjecture

- Factors are aggregated into a single dynamic density (DD) value, computed independently for each corridor
  - Dynamic density for vertiports and unstructured airspace are future work

Dynamic Density Factors

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- Inspired by analysis of traditional ATM dynamic density research and a highway traffic analogy

- Initial prototype factors, selected as indicators of corridor saturation:
  - Aircraft density
  - Mean distance between aircraft
  - Minimum distance between aircraft
  - Density of populous clusters
  - Mean number of aircraft in populous clusters

- Impact of a factor on DD is determined by a heuristically-derived function
  - Functions and constants are chosen based on analysis and face validity. A more rigorous approach will be investigated in future work
  - Variety of considerations influence the choice including:
    - UAM operation rules and regulations
    - Detect and avoid sensor capabilities
    - Autonomy capabilities
    - Aircraft navigation system speed and accuracy
    - Navigation facilities availability and capability

Impact of DD Factors

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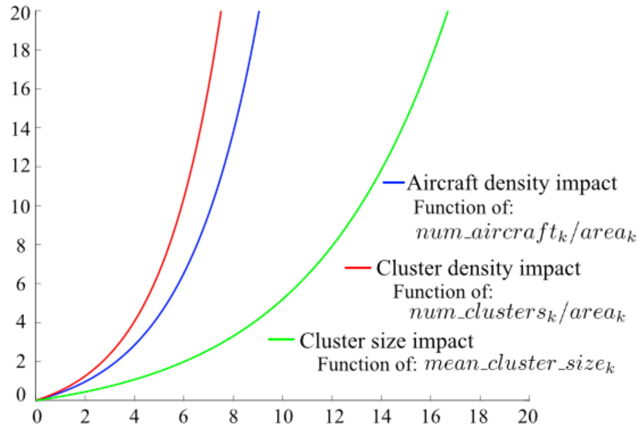
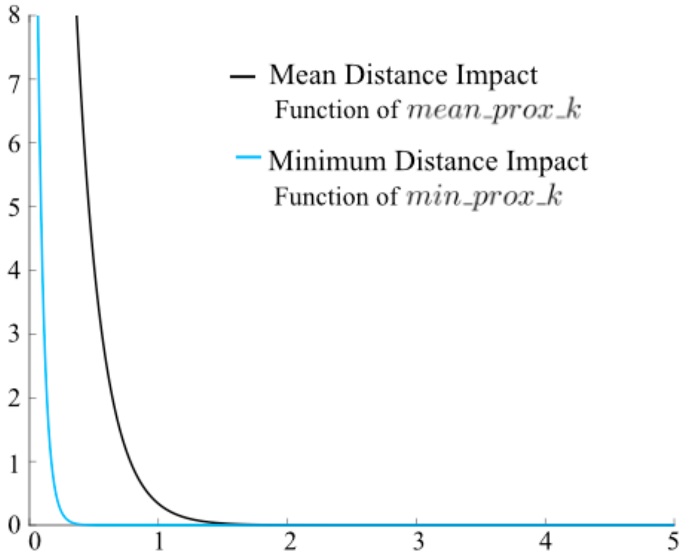


$$Aircraft\_density\_impact = 1.4^{num\_aircraft/corridor\_area} - 1$$

$$Cluster\_density\_impact = 1.5^{num\_clusters/corridor\_area} - 1$$

$$Cluster\_size\_impact = 1.2^{mean\_cluster\_size} - 1$$

- Cluster is defined as set of aircraft within ~0.7 mi



$$Mean\_distance\_impact = 50*e^{-5*mean\_prox}$$

$$Min\_distance\_impact = 30*e^{-20*min\_prox}$$

Dynamic Density Aggregation

- Factors and aggregated DD are computed per corridor:

$$DD = w_1 * \text{aircraft\_density\_impact} + w_2 * \text{cluster\_density\_impact} + w_3 * \text{cluster\_size\_impact} + w_4 * \text{mean\_distance\_impact} + w_5 * \text{min\_distance\_impact}$$

- DD values are categorized into four bins with empirically set thresholds:

DD	Category
< 1.0	NONE / NEGLIGIBLE
(1.0, 3.0]	LOW
(3.0 , 5.0]	MODERATE
> 5.0	HIGH

- Nowcast DD is computed based on position report for each airborne aircraft
- Forecast DD with a 15 min lookahead is computed based on operational intent of each aircraft. Operational intent includes departure time, route of flight, and estimated time of arrival at each waypoint

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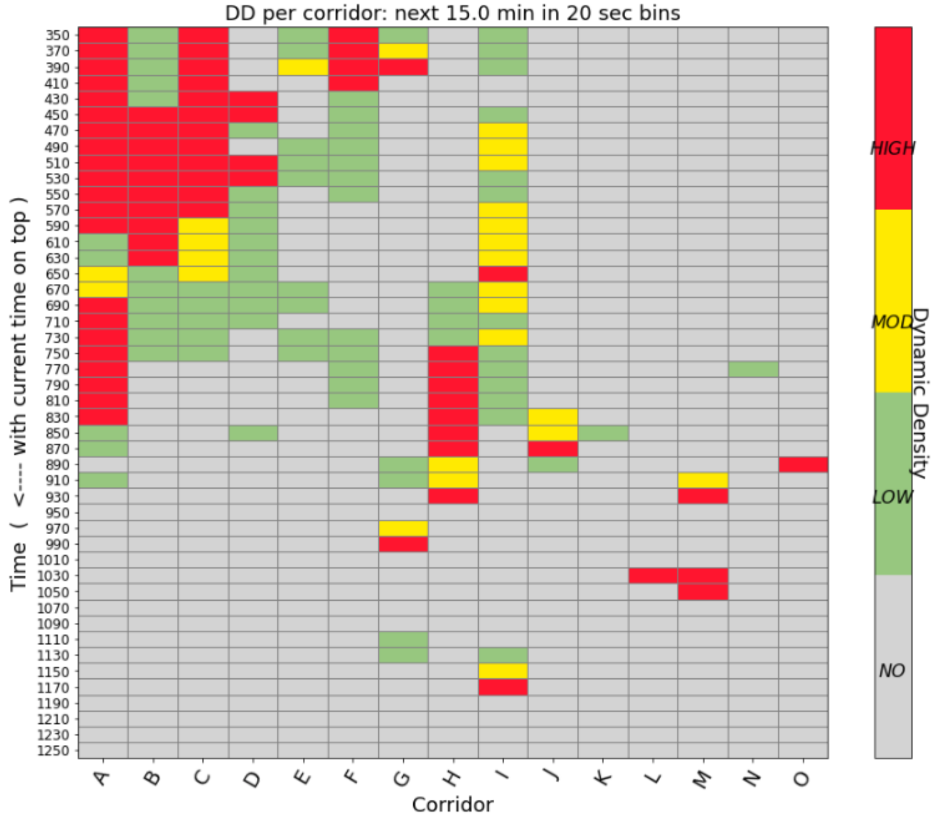
Airspace-wide DD Prediction

- During initial flight planning stages or for airborne-required re-routing, a 15-20 min airspace-wide DD prediction can alert the operator and airspace authorities of expected saturated corridors
- Operator can plan to avoid those corridors by taking a different route, taking off with extra battery energy, or implementing another business-appropriate mitigation strategy
- Airspace authorities may open additional or other corridors if mitigation is required



Trajectory-Specific DD Prediction

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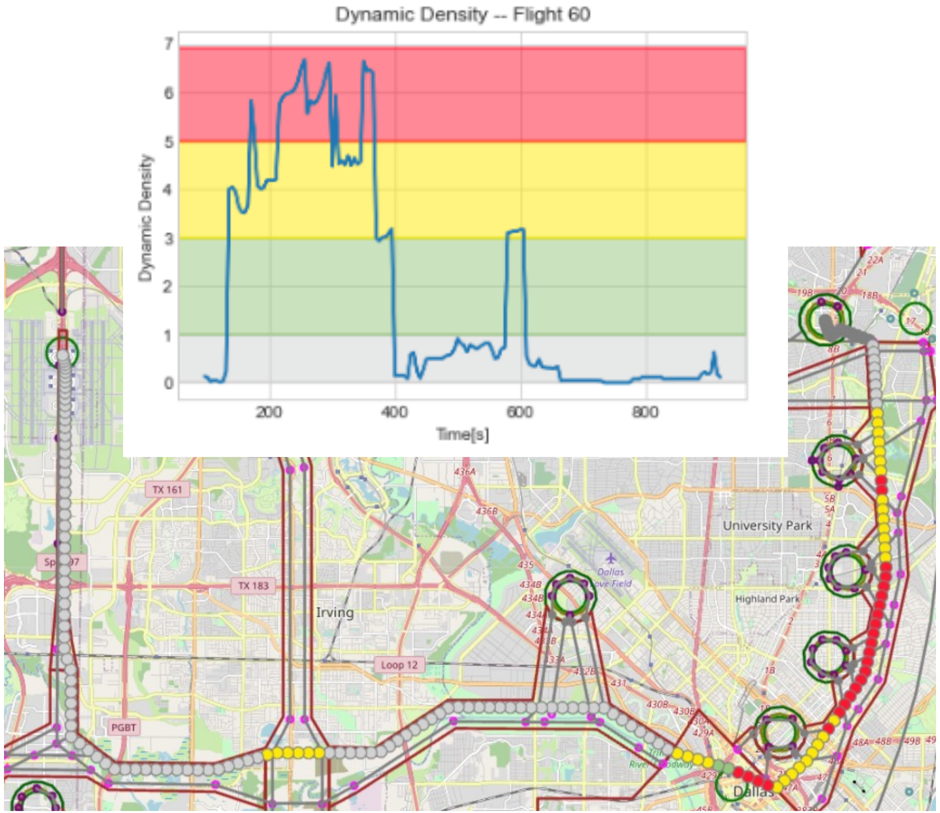
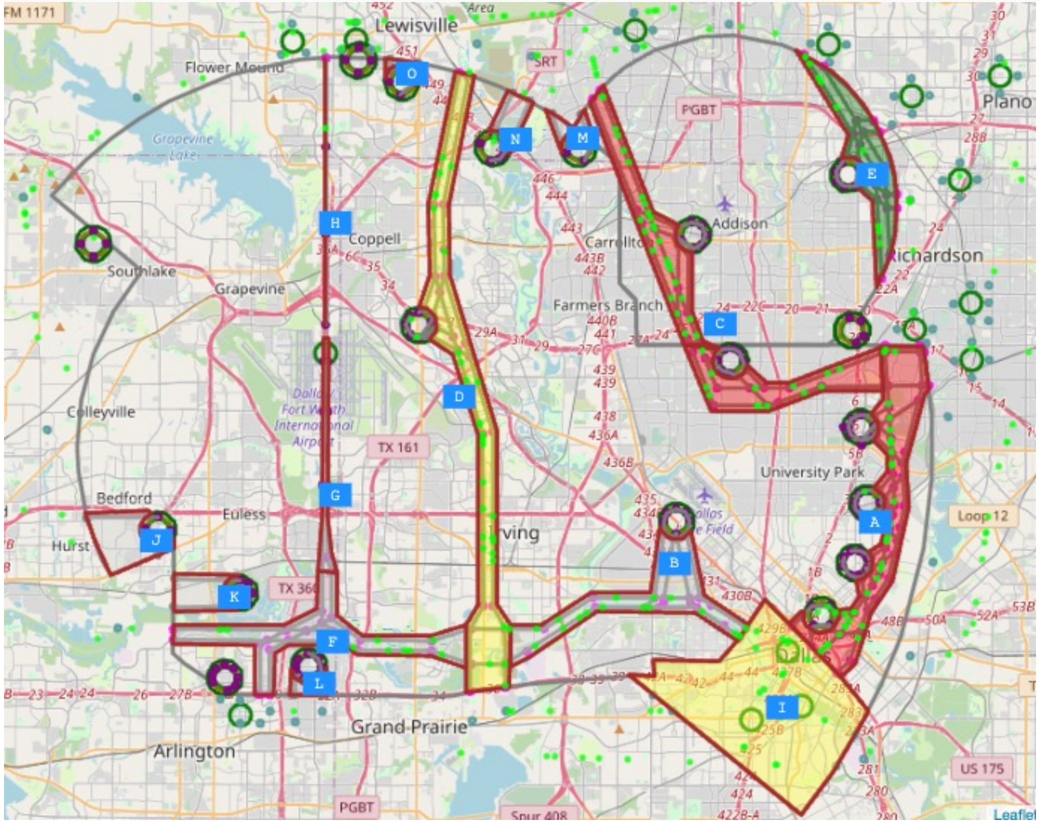
- Prior to finalizing operational intent, operator can assess anticipated DD by visualizing the prediction along a planned trajectory

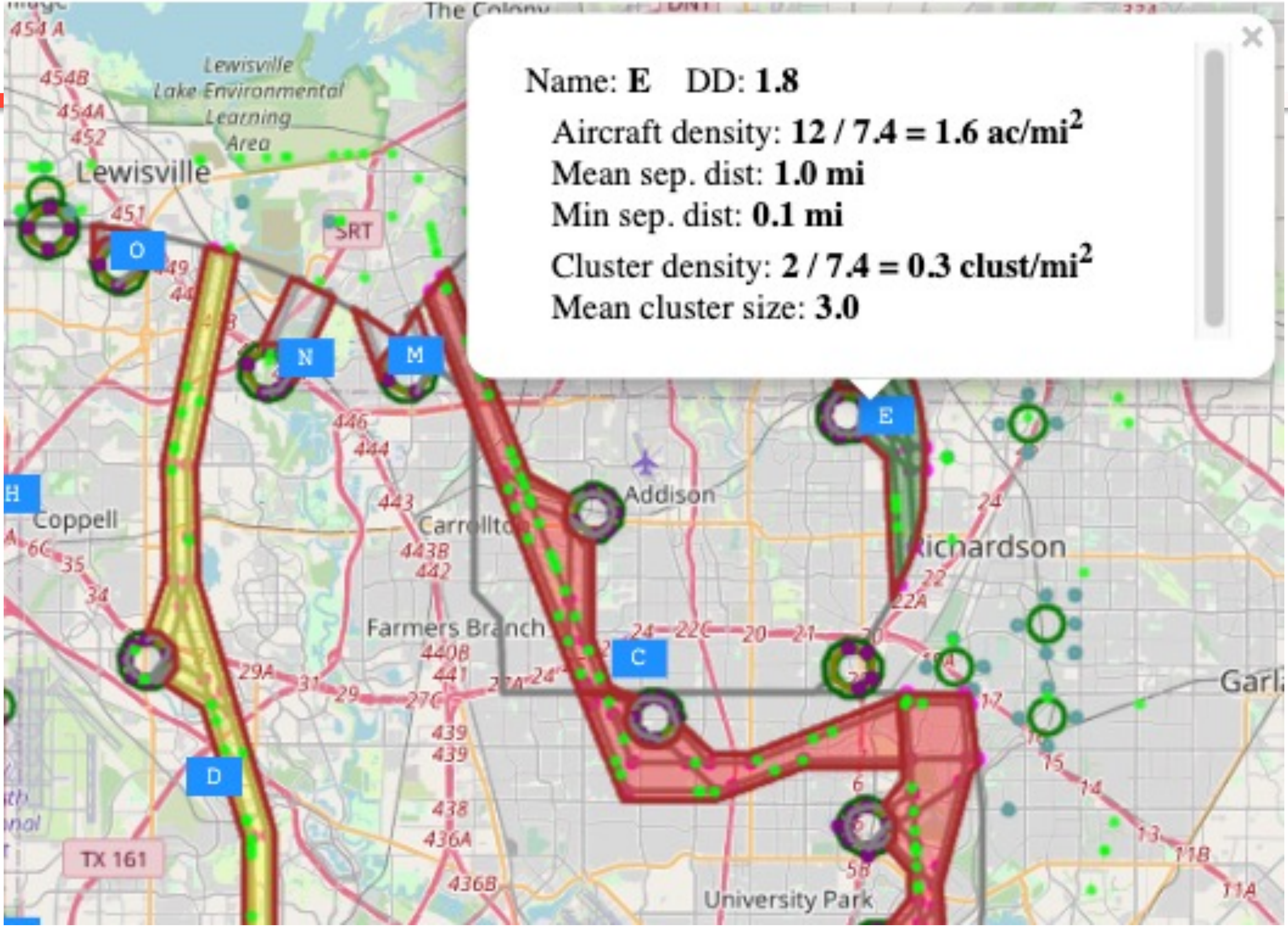
- Once airborne, trajectory-focused DD prediction can be monitored for change. Changes could occur due to a variety of reasons, including:
  - Newly airborne aircraft may increase DD into a higher category
  - Weather, an emergency vehicle, or other airspace disturbance may require widespread re-routing, increasing DD in previously-acceptable corridors
  - Subject aircraft itself may be rerouted due to, e.g., a corridor closure.



DD Nowcast and Change Monitoring

- Current state of airspace saturation can alert an operator of the necessity to activate contingency plans
- Nowcast also helps an operator confirm that conditions are proceeding as predicted
- Changes from predicted conditions could be alerted textually, or machine-to-machine if the ‘operator’ is an autonomous system





Name: **E** DD: **1.8**
Aircraft density: **12 / 7.4 = 1.6 ac/mi²**
Mean sep. dist: **1.0 mi**
Min sep. dist: **0.1 mi**
Cluster density: **2 / 7.4 = 0.3 clust/mi²**
Mean cluster size: **3.0**
Lewisville
Coppell
Addison
Carrollton
Farmers Branch
Richardson
University Park
O
N
M
E
C
D
H

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Validation – Ideal

- Broad set of traffic scenarios necessary for selection of indicators of corridor saturation and DD metric validation
  - Data should come from actual operations or high-fidelity aircraft simulation
  - Traffic should follow UAM operations rules and regulations
  - Gamut of corridor (generally, airspace) occupancy should be included
  - Off-nominal scenarios should be included

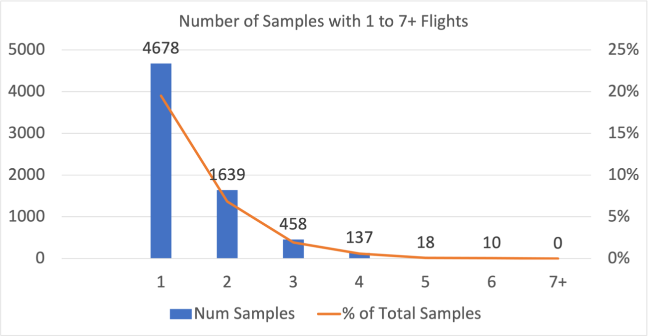
- Scenario annotation using objective criteria or expert judgment for expected DD is also necessary
  - Reaching unsafe state such as loss of separation, depleted battery, encountering wake turbulence, etc.
  - Decreased efficiency of operations (delays)
  - Experts can recognize problematic situations without easily identifying important characteristics[1]

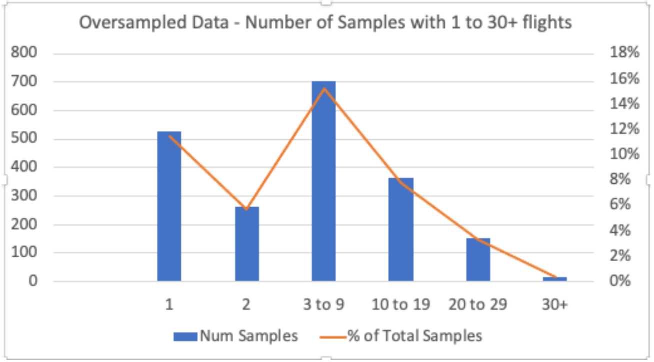
[1] Ref: Klein, G. (1993), "A recognition-primed decision (RPD) model of rapid decision making," in G. Klein, J. Orasanu, R. Calderwood & C. Zsambok (Eds): Decision Making in Action: Models & Methods, Ablex Publishing, Norwood, NJ.

Validation – Practical

- Initial development is using simulated traffic from ATM-X experiments
  - Mostly low corridor occupancy operations
  - Oversampled to create congested corridors
    - Aircraft follow approved routes along defined tracks to vertiports
    - Aircraft sometimes fly in tight formation or collide because strategic (takeoff time constraints) and tactical (detect-and-avoid) deconfliction are not implemented

- DD metric was designed to result in moderate and high DD for scenarios with loss of separation





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Summary and Future Work

- Contributions
  - Introduced a dynamic density metric to facilitate emerging UAM traffic management
    - DD metric contributes awareness of adverse traffic situations – saturated corridors – that require mitigation to ensure a safe flight outcome
  - Developed a methodology and used it to prototype a DD metric
  - Presented DD metric use cases and visualization alternatives to inform and expedite strategic and tactical flight planning by humans or autonomous systems
  - Suggested approaches for validation of the metric to measure how accurately it captures the relationship between traffic situations and subsequently reaching an unsafe state (loss of separation, battery depletion, etc.)

- Future Work
  - Perform a more rigorous analysis to select indicators of corridor (airspace) saturation. Augment as UAM operations mature
  - Expand DD to vertiports and unstructured airspace
  - Verify performance against objective criteria
  - Validate usefulness with operators and airspace authorities

Inspire additional research so that the DD metric can be ready when the UAM vehicles and airspace are ready