Reflections on Collective Autonomy for Air Mobility - Metrics and Models



Husni Idris

NASA Ames Research Center

March 6, 2024

Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

What is Autonomy?

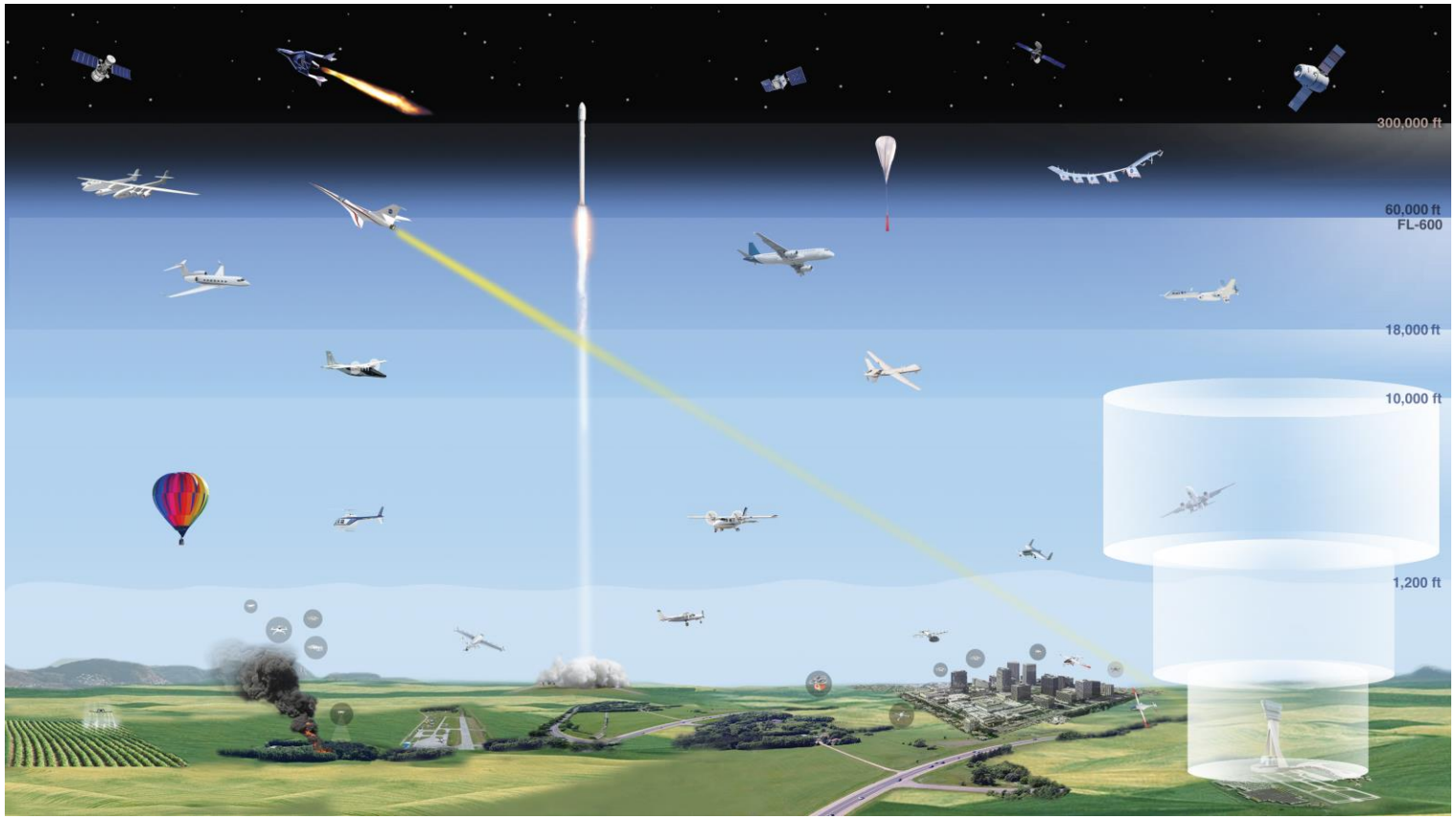
The ability of a system to achieve goals while operating independently of external control*

- NOT artificial intelligence (AI), but may make use of AI methods
- NOT automation, but often relies on automation as a building block
- System can consist of human and/or machine

*From NASA Autonomous Systems Taxonomy by NASA's Autonomous Systems – System Capability Leadership Team (AS-SCLT)

Why Autonomy?

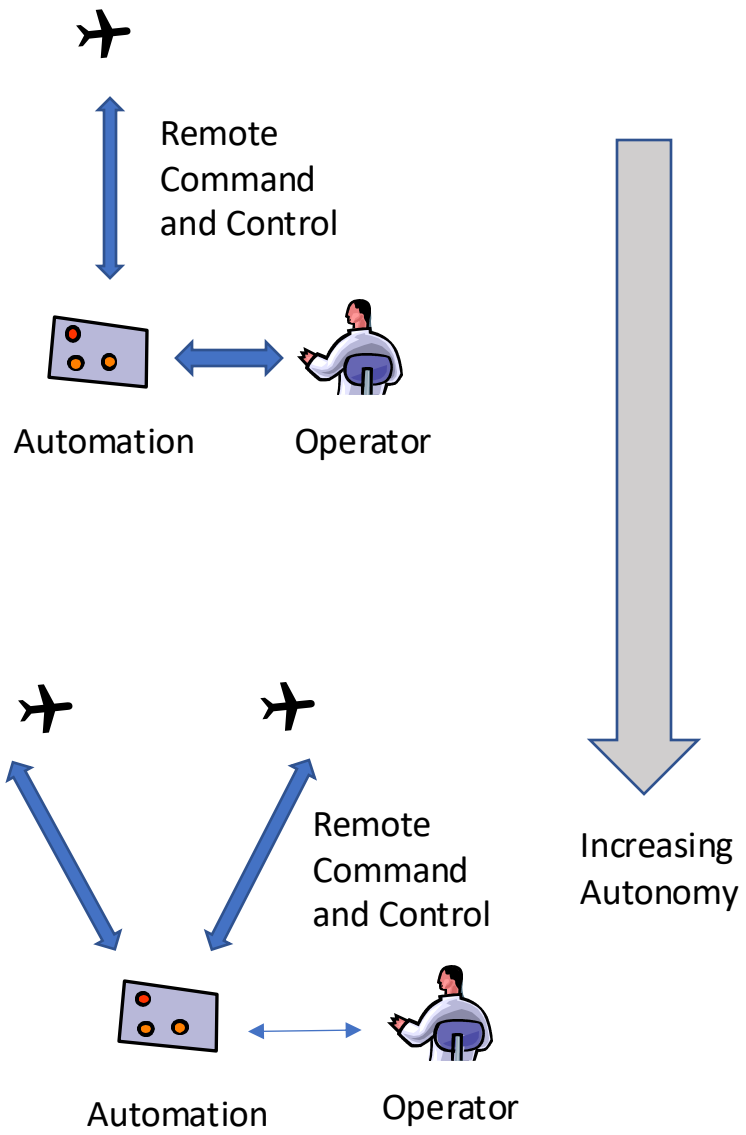
Unprecedented demand needs from high-tempo new-entrants such as urban air mobility (UAM) and unmanned areal systems (UAS), beyond capability and availability of centralized human resources to provide piloting and ATM services



Courtesy of NARI

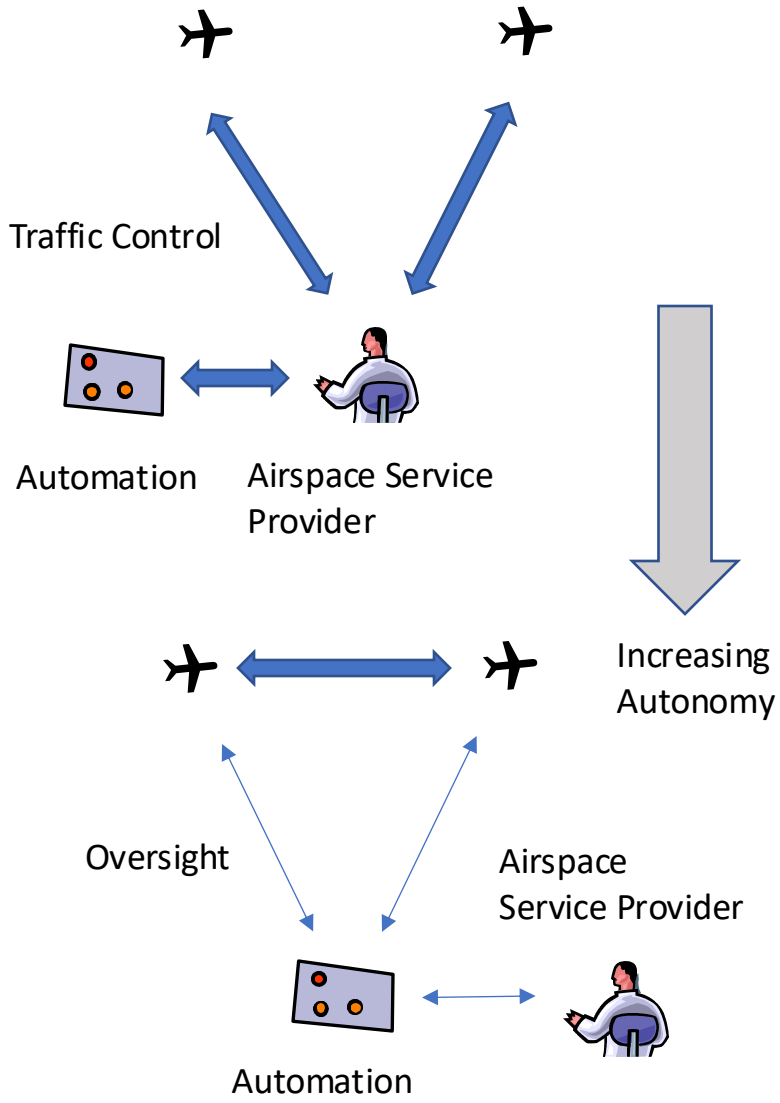
Why Autonomy?

- Today's aircraft are flown manually by on-board crew of one or more pilots with automation support – does not scale
- Increasing autonomy for piloting is key mechanism for achieving scalability
  - Remotely piloted unmanned aircraft (RPAS)
  - Remotely supervised unmanned aircraft
    - Ratio of pilots (m) to vehicles (N) varies
    - As ratio is reduced autonomy is increased
  - Autonomous aircraft with no human role



Why Autonomy?

- Today's ATM system is based on government, ground-based, human-centric service provider, with automation support – does not scale
- Increasing autonomy for ATM is key mechanism for achieving scalability of services with demand
- ATM Autonomy: Ability of traffic system to self-manage independently from centralized (government, ground-based, human-centric) service provider
    1. Edge agents such as vehicles, pilots, and operators provide their own ATM services
    2. Smart machines enjoy more independence from human agents in order to scale



Outline

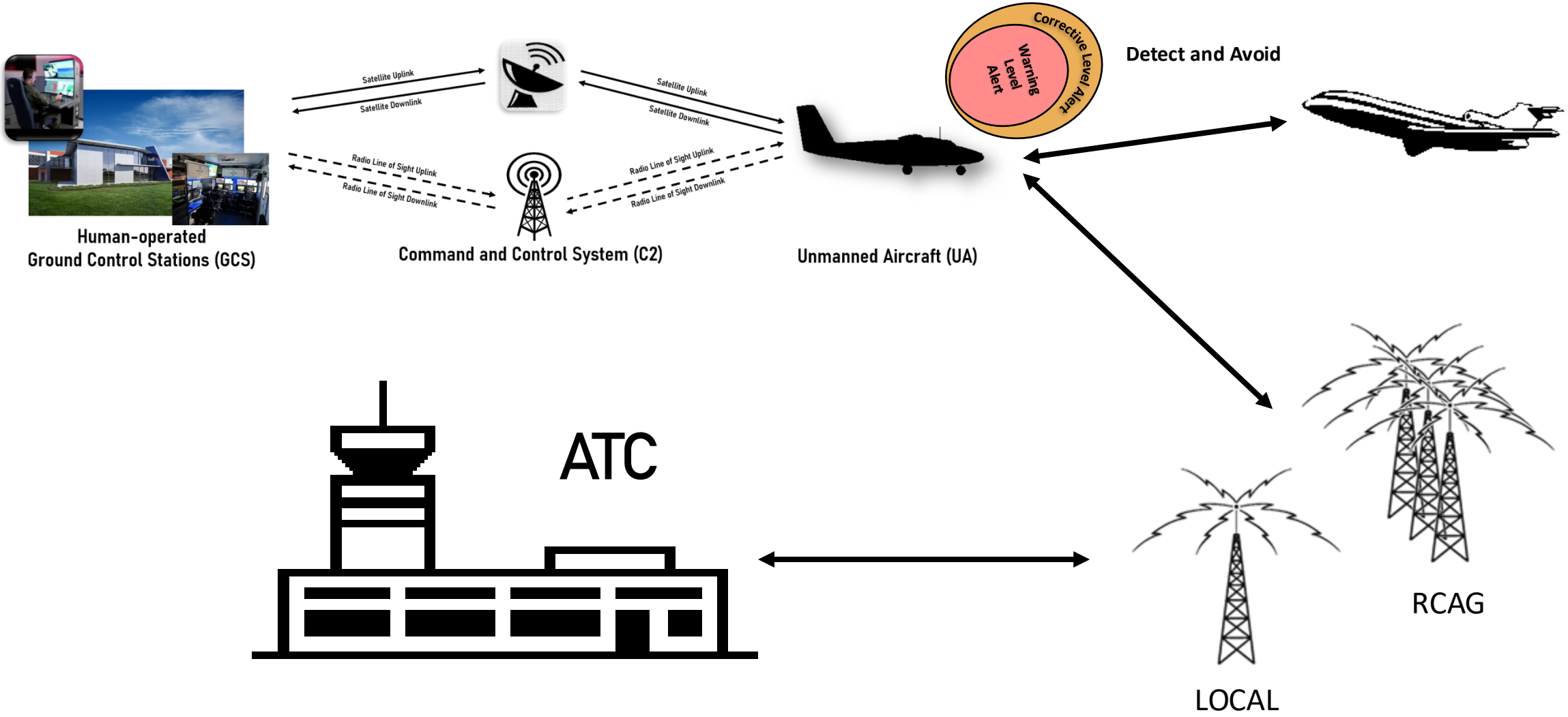
- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Autonomous Air Cargo - Motivation

- Significant market for cargo operations using large unmanned aircraft with increasing autonomy
  - Aerospace Industries Association: “Through 2036, large unmanned aircraft are expected to drive nearly $150 billion in total spending and sustain up to 60,000 R&D, manufacturing, and services jobs annually, according to Avascent and AIA analysis.”
  - Allied Market Research: “The global air freight market was valued at $270.2 billion in 2019, and is projected to reach $376.8 billion by 2027”
- LMI Market Study 2021
  - **Regional (1 – 10T, 75 – 1,000nm): Regional use case is most promising for advancement of automation technology**
    - **Replace current aging fleet**
    - **Benefits through increased asset utilization based on automation**
    - **Higher pilot cost as share of operating costs offers economic incentive**
  - Light (50lbs – 1T, <250nm): Light short range use case is hardest to predict because it is not based on an existing aviation market
    - Continued increases in demand for faster deliveries of high-value cargo
    - Uncertainty due to other competing modes of transportation (e.g., trucks)
  - Longer Range (>10T, 500 – 3,000nm): Industry prioritization of automation for longer-range use case is unlikely
    - Asset utilization would not increase significantly based on automation
    - Pilot costs account for a small share of total operating costs



Remotely-Piloted Cargo Operations



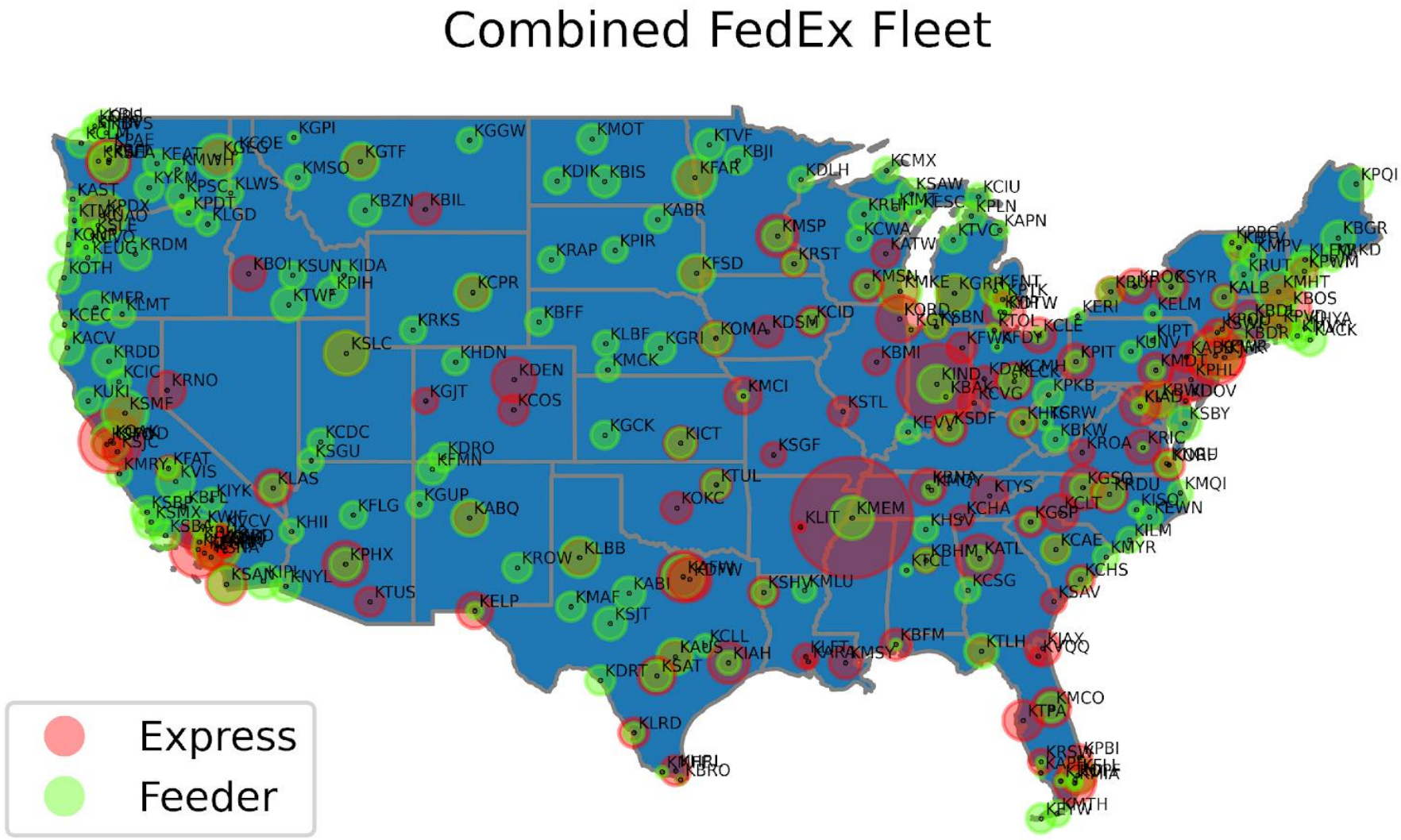
Courtesy of Wayne Bridges

Flight Overview

- Commercial Cargo Carrier operating under CFR Title 14, Parts 121 or 135
- Regularly scheduled IFR flight
- Remotely Piloted Aircraft System (RPAS)
- Representative of flights flown to/from a cargo hub and other airports
- Enroute transition at lower altitudes
- Airspace transition: Class A, Class B, Class C, Class D, Class E, and Common Traffic Advisory Frequency (CTAF) operations
- Departure and Approach procedures



Autonomous Air Cargo – Potential Markets

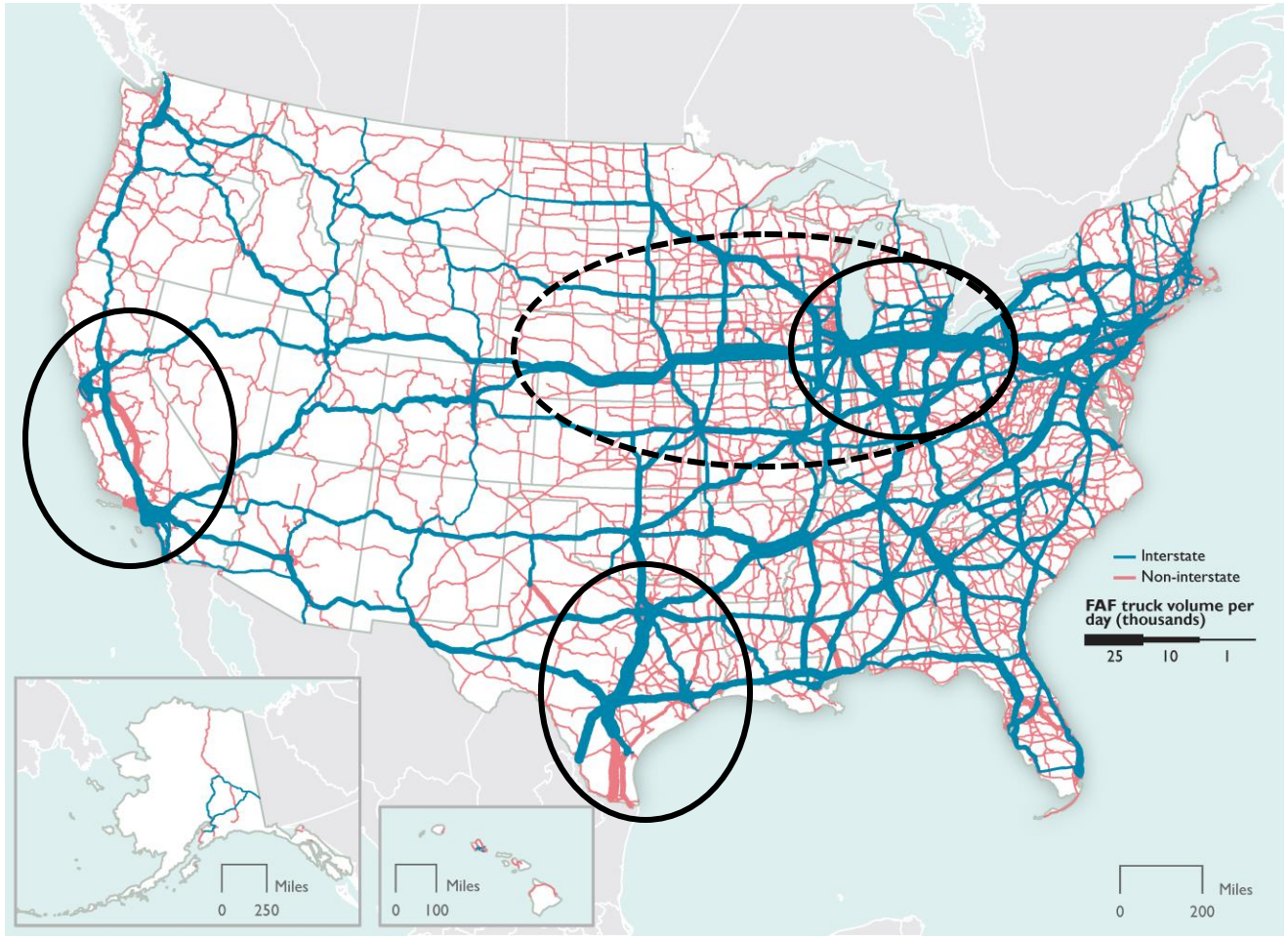


Autonomous Air Cargo – Potential Markets

Potential regional markets based predicted truck traffic

California:
I-5 Corridor

Texas:
I-35/-45/-10
Triangle

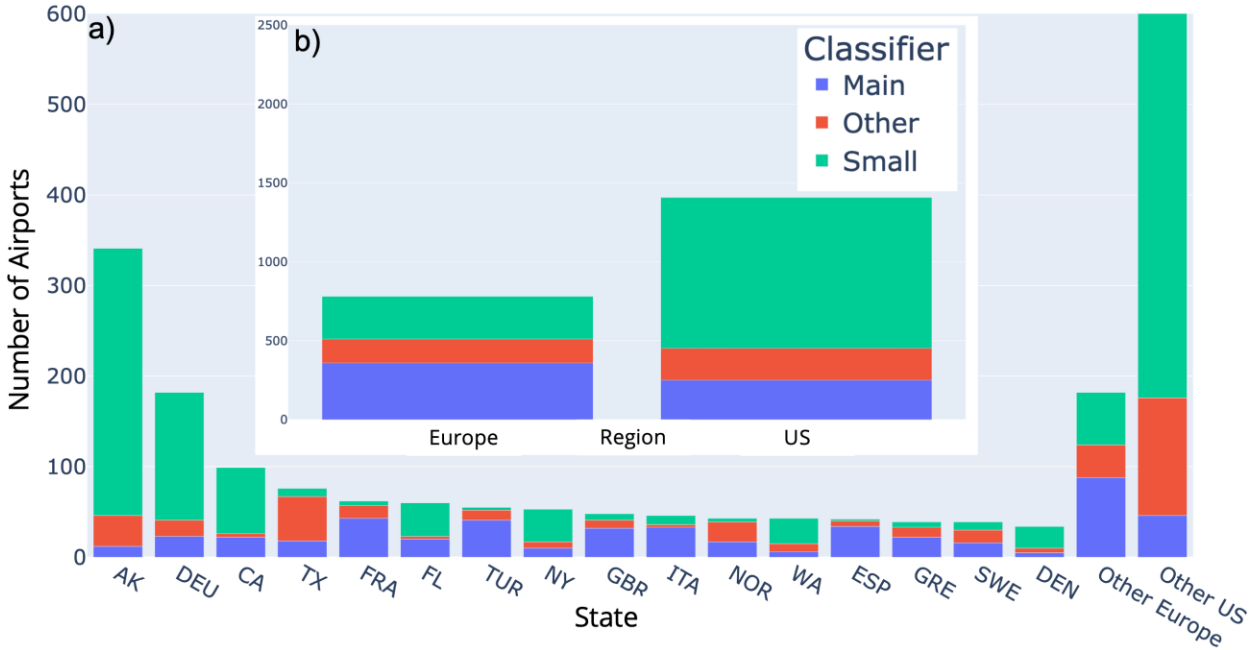


Midwest:
I-80
Corridor

DOT truck traffic forecast 2045

Autonomous Air Cargo – Europe vs US

- Initial US study presented at Aviation 2022 - Jordan Sakakeeny et al
- Comparison of regional cargo markets between US and Europe (DLR collaboration)
  - Papers in ATM R&D Seminar and DASC 2023, by Jordan Sakakeeny, Tim Felix Sievers, and Husni Idris
  - Insight: Europe use predominantly larger aircraft and larger airport (limited regional market)
  - Insight: Germany has highest small airport number/ratio

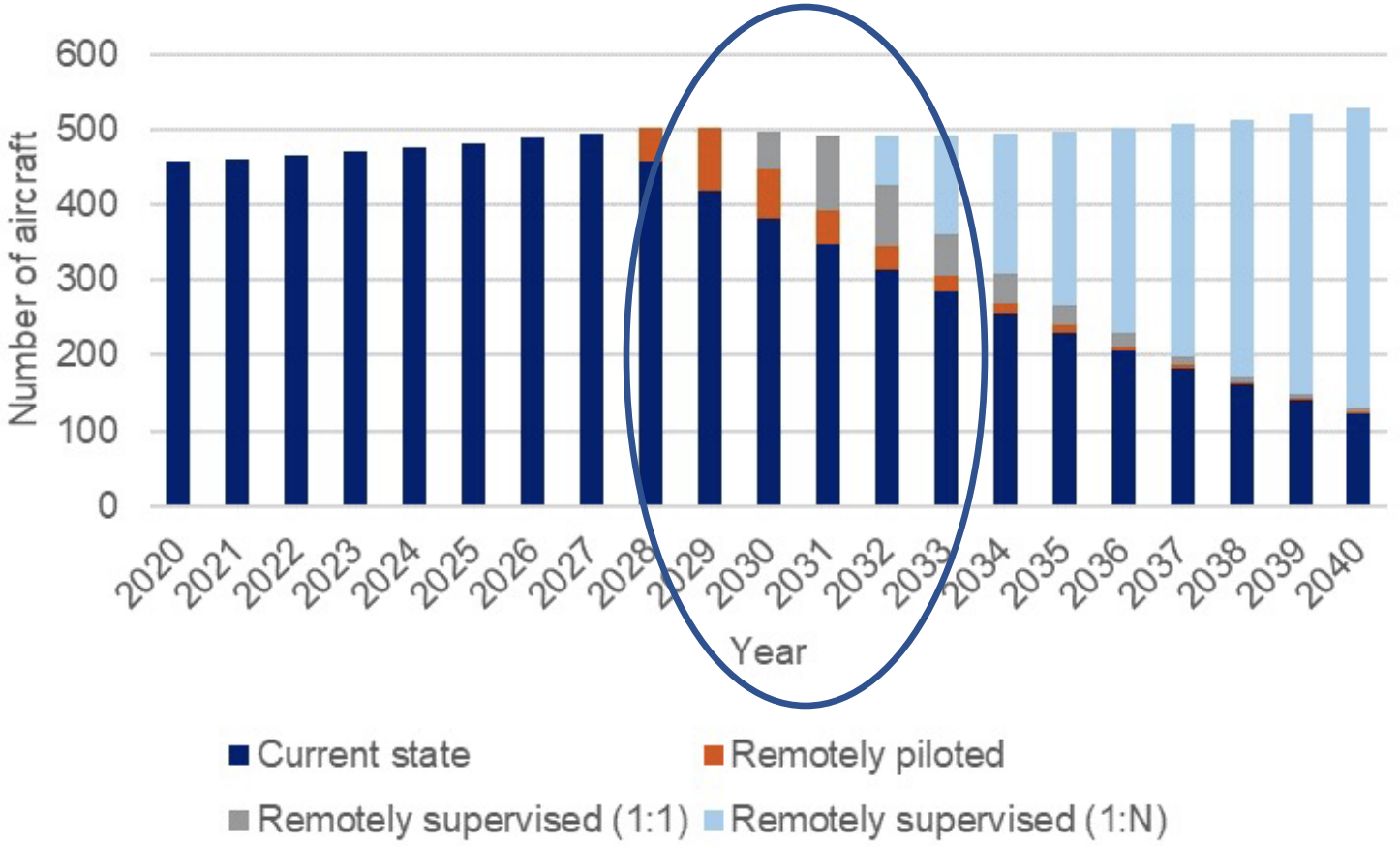


Autonomous Air Cargo – Multi-Vehicle Operations

- Desire quick transition to remotely supervised control of multiple aircraft

- Timeline:
  - 2028: Remotely Piloted
  - 2030: Remotely supervised (1:1)
  - 2032: Remotely supervised (1:N)

From LMI Market Study 2021



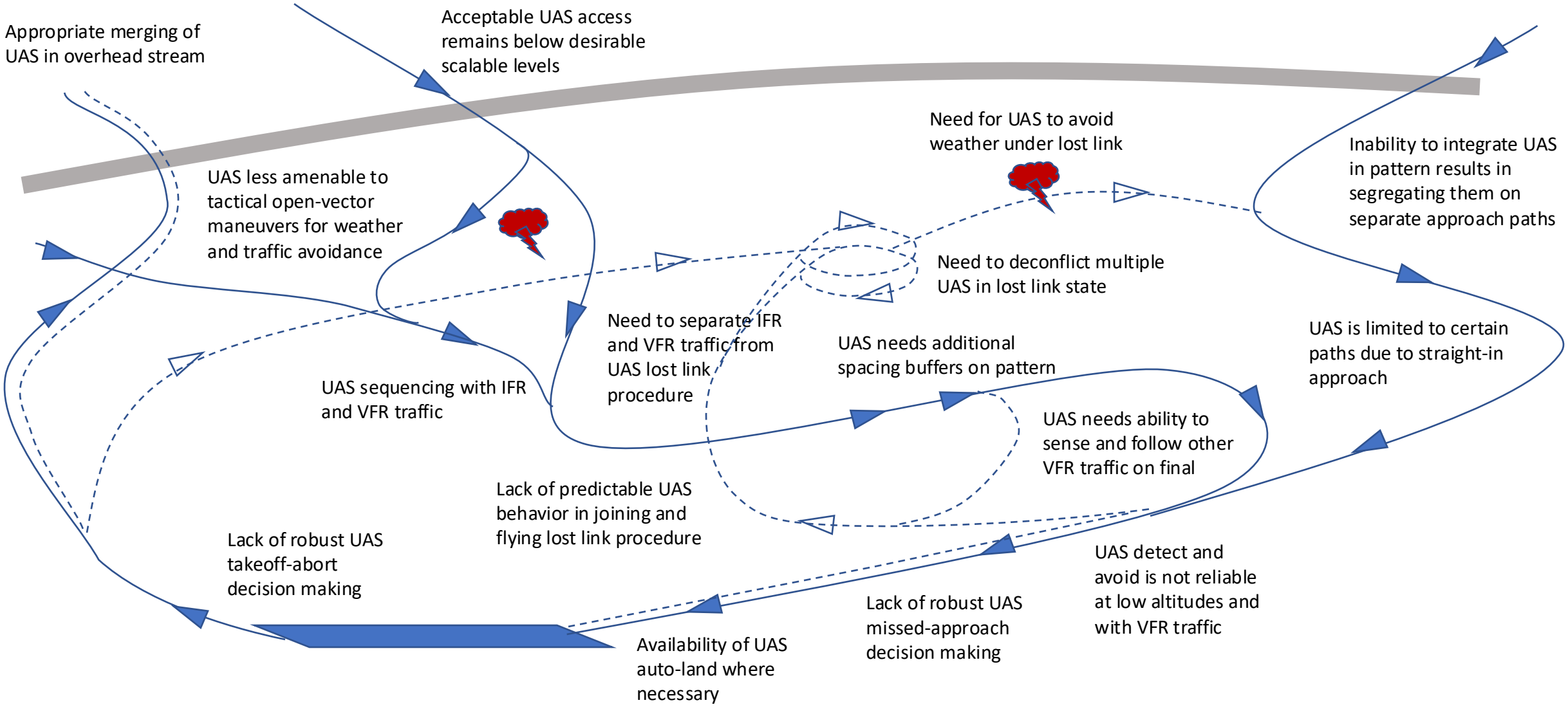
Concept Research

- Conducted four tabletop activities from 2020 - 2022
  - Participation from pilots, remote pilots, dispatchers, and air traffic controllers
  - First 3 focused on 1:1 near term operations
  - Tabletop 4 focused on m:N far term operations
  - Identified key challenges to integrating UAS operations and obtained solution suggestions

- Main challenges
  - Availability of fast and robust C2 and communication link
  - Interaction with ATC separation and flow management under IFR
  - Interoperability between strategic and tactical separation (DAA and ACAS)
  - Integration with VFR traffic especially in non-controlled airspace and non-towered airports
  - Predictability of behavior under lost C2 link conditions
  - Enabling m:N supervisory control for scalability
  - Auto takeoff, landing and taxi

- Initial concept document published with initial concept solutions and will continue to be updated based on stakeholder feedback and trade studies

Functional Shortfalls



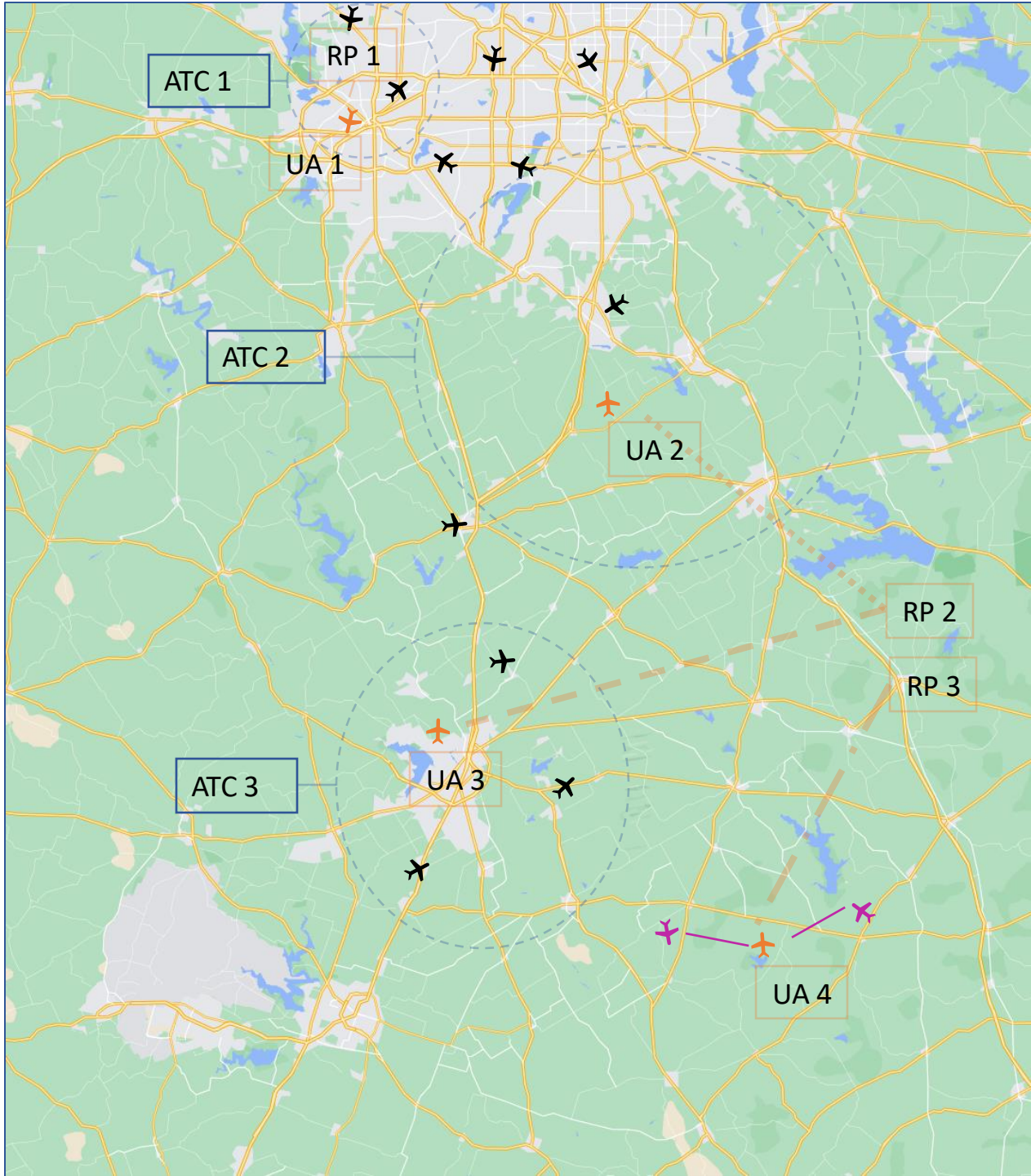
Architectural Shortfalls

Three RP's and four UA's:

RP 1 located at KAFW supervising UA1 (1:1), using cellular link, in terminal with tower (classes C or D) and monitoring one ATC frequency ATC 1

RP 2 supervising 2 UAs: (1:2), using terrestrial link for UA2 and SatCom for UA3, in en route classes A or E, monitoring two different ATC sectors (ATC2 and ATC3)

RP 3 supervising one UA4 (1:1) using SatCom, on a common frequency (CTAF) in airspace classes E or G with low level of traffic cooperation



Multi-Vehicle Operations Challenges

- Some key factors that influence m:N ratio
  - Amount of interaction airspace requires of the unmanned aircraft (UA) and therefore the attention of the remote pilot (RP)
  - Communication architecture: radio-only, data link-only, or a combination of both
  - Maturity of RP supporting user interface design and technologies, including automation
  - Seamless transfer of a UA from one RP to another
  - Segment flights for RPs that operate in similar geographical areas
- Other factors described in report

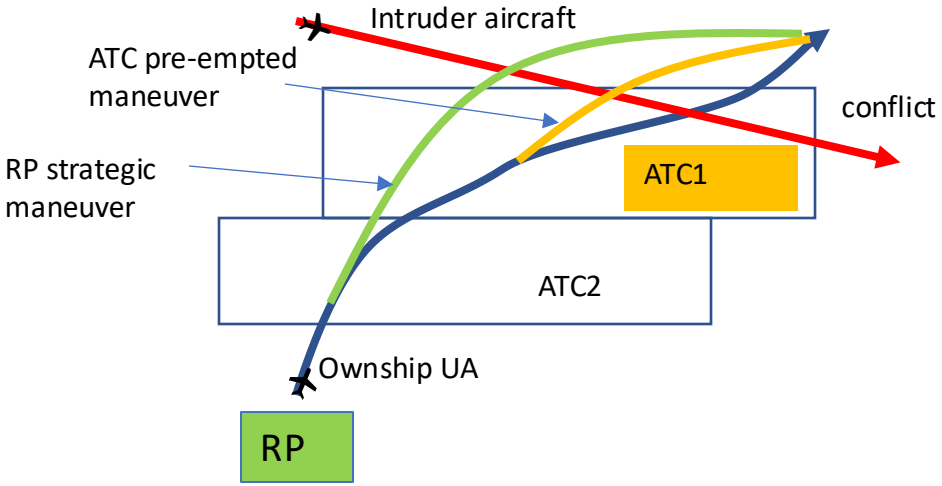
Wolter, C.A., Davikoff, K.V., & Rorie, C. (2023). *Pathfinding for Airspace with Autonomous Vehicles (PAAV) Tabletop 4 Final Report*, NASA/TM-2023-20230006884, NASA Ames Research Center, Moffett Field, CA.

Some Solutions and Associated Studies

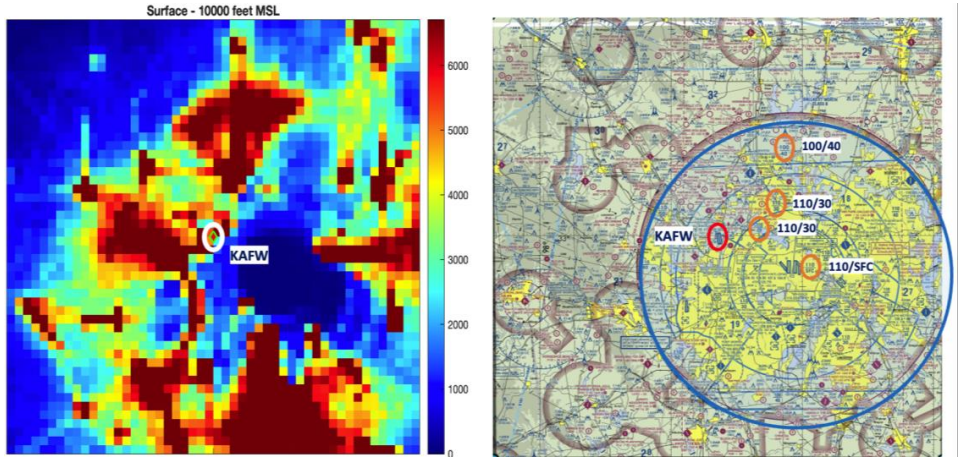
Availability of fast and robust C2 and communication link	- Robust C2/Comm architecture - Vehicle to Anything communication
Interaction with ATC separation and flow management under IFR	- Data Comm based tailored trajectory solutions - Scheduling and routing UA to minimize ATC interactions
Integration with VFR traffic	- Characterization of VFR traffic uncertainty - VFR traffic intent inference - VFR traffic pattern integration algorithm
Enabling m:N supervisory control	- Remote-pilot complexity metrics for m:N assessment and optimization - Remote-pilot strategic trajectory solutions to pre-empt ATC interactions - Far-term digital flight rules: remote-pilot responsible for separation and spacing
Contingency Management for lost C2 link	- Assessment of lost C2 link procedure system impacts - Optimized UA routing for C2/Comm availability - UA automation for hazard avoidance under lost C2 link - UA automation for multi-UA coordination under lost C2 link
Auto takeoff, landing and taxi	- Currently considering out of scope - significant efforts by industry

Related Research – Trajectory Management Mitigations

Tailored trajectory management by operator to pre-empt ATC interaction (Thipphavong et al Digital Avionics Systems Conference 2023)



Characterization of VFR traffic patterns and uncertainties – identifying spatial and temporal concentrations and gaps of VFR traffic (Bulusu, et al AIAA Aviation Forum 2023, 2024)



Traffic pattern integration – developing of algorithms for sequencing and spacing with VFR traffic pattern



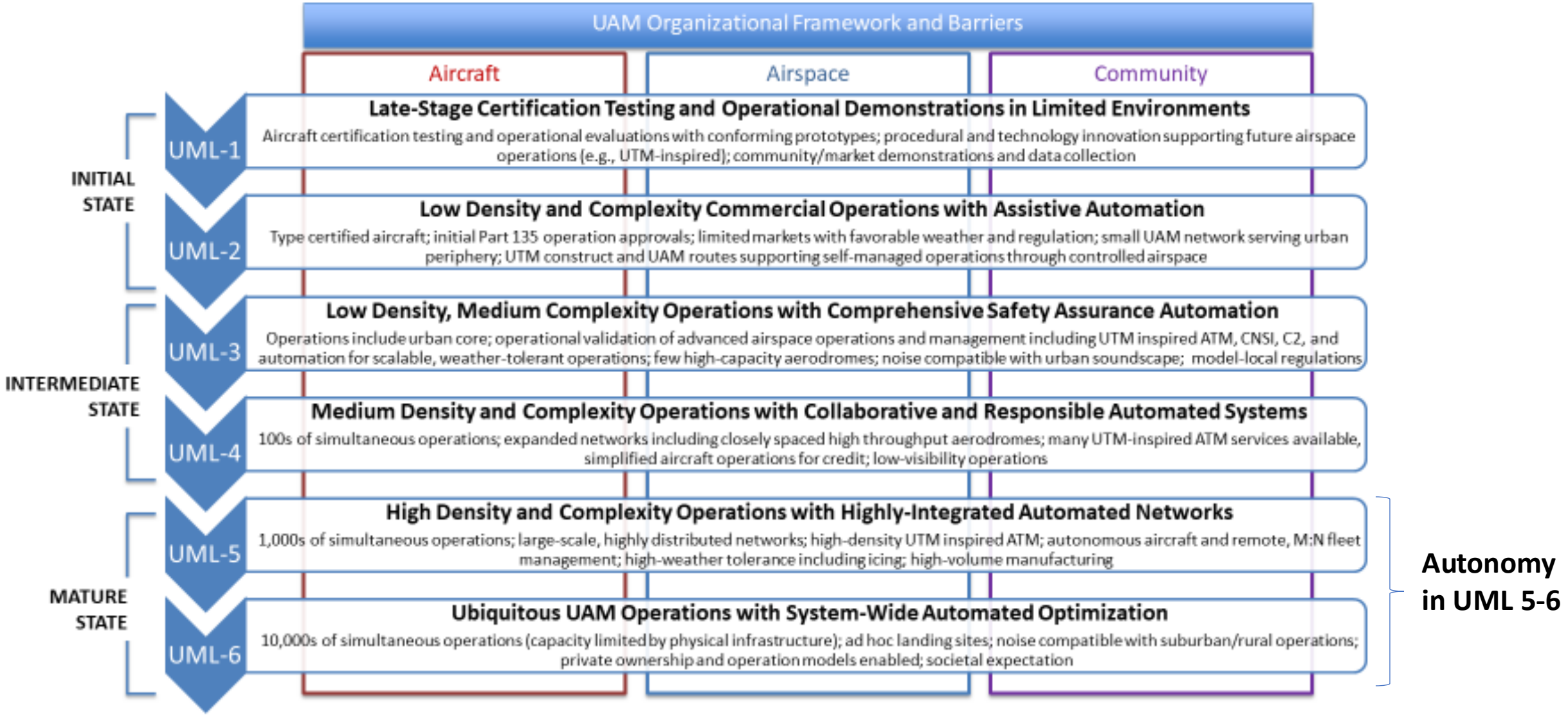
Ref AC 90–66B

Urban Air Mobility - Motivation

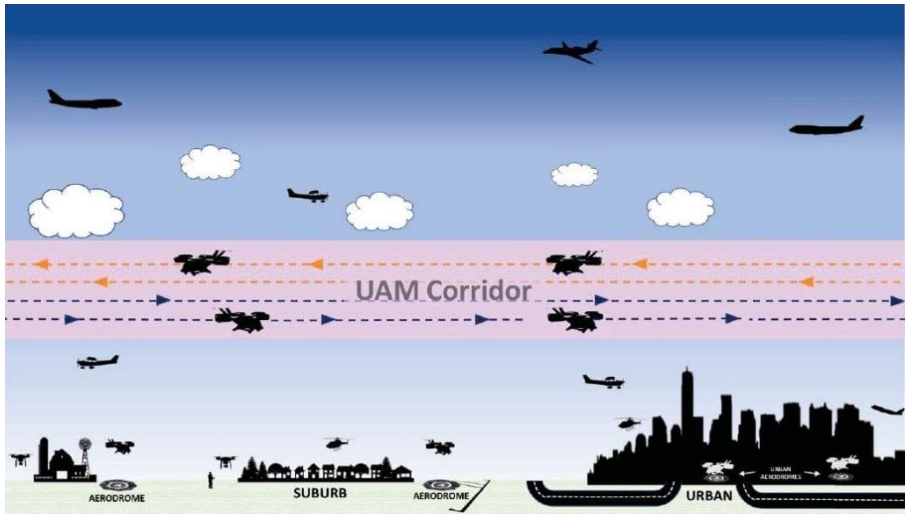
- Significant interest in urban air taxi operations using emergent electric vertical takeoff and landing (eVTOL) vehicles
- Autonomy is considered key enabler of business case and scaled high-tempo operations



Urban Air Mobility – Maturity Levels



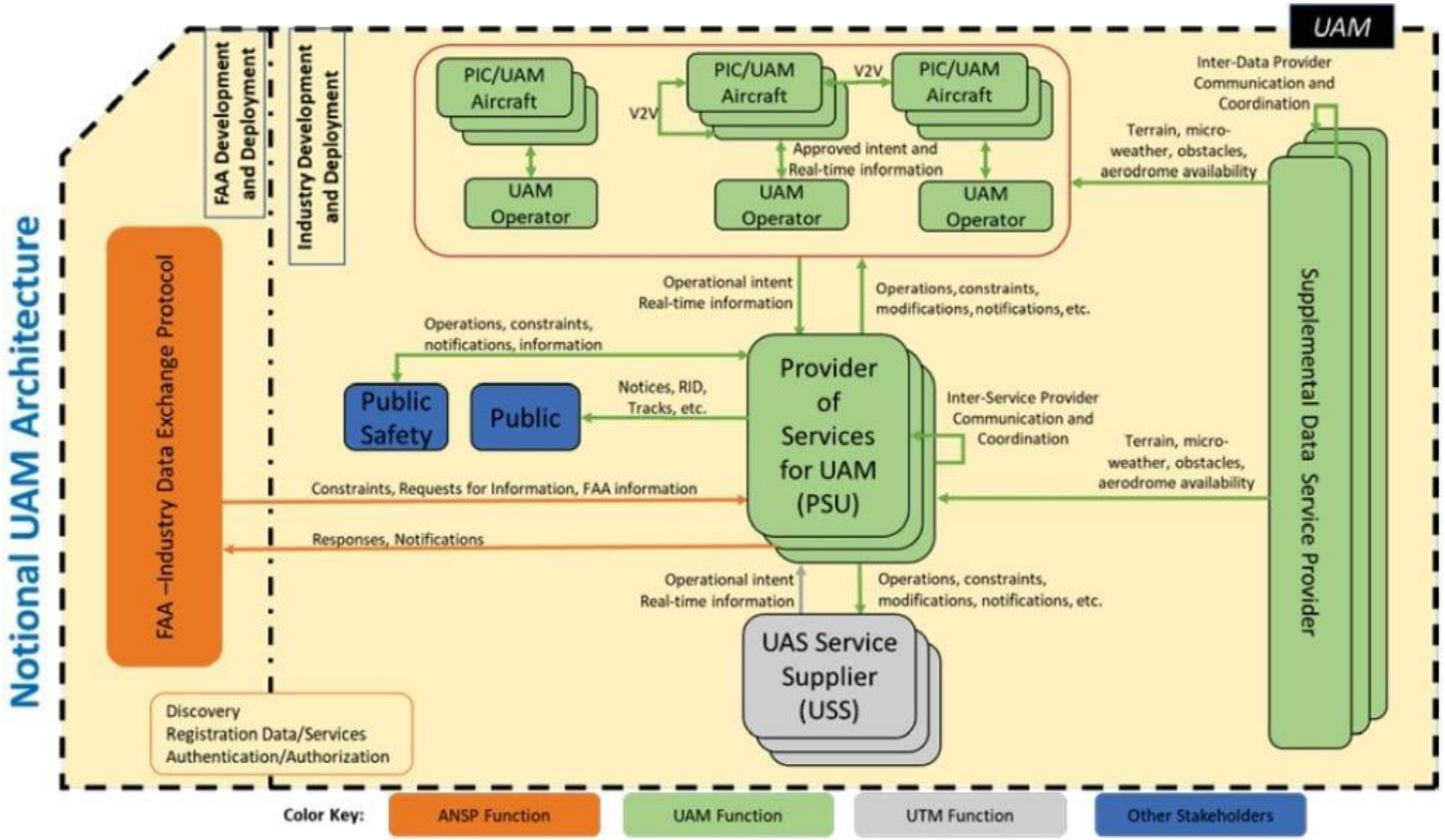
UTM-Inspired Airspace Management



Higher UML levels envision less structured airspace and higher levels of automation and autonomy

Need models to study these architectures and concepts to assess their effectiveness, scalability, and robustness

Initial concepts suggest segregated corridors for UAM operations with cooperative traffic management within the corridors provided by operators and third-party providers of service (PSU) – e.g., UAM ConOps v1.0



Urban Air Mobility – Autonomy Research

Example NASA's research on UAM

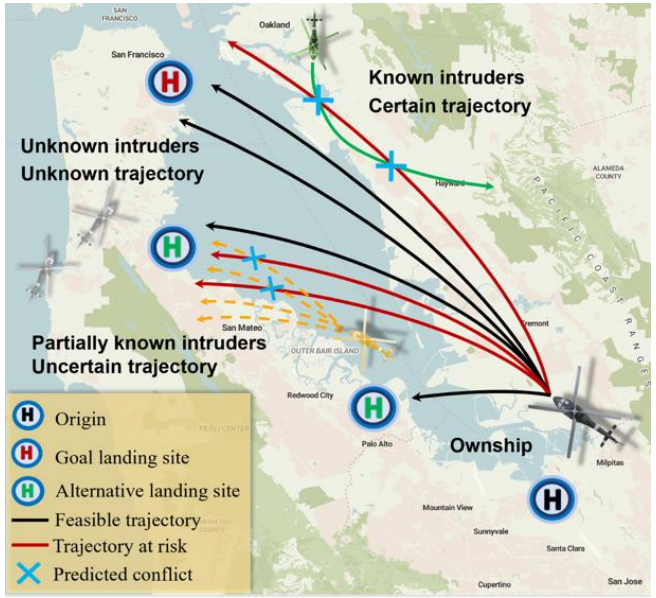
1. Advanced Air Mobility (AAM)
   - National campaign unlocking UML 1-4
   - High Density Vertiport (HDV) operations
   - Focus on procedure development and prototyping and validation of some services such as flight planning, trajectory management and conformance monitoring

2. Air Traffic Management – Exploration (ATM-X) – Low UML's, example activities:
   - Corridors along helicopter routes
   - Assessment of impacts on air traffic controllers
   - UAM separation requirements – challenge lack of data on vehicle performance

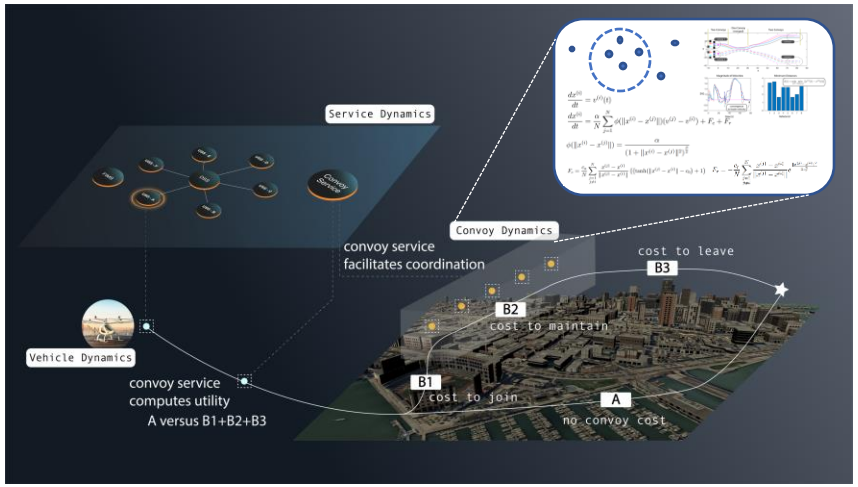
3. Transformative Tools and Technologies (TTT) Autonomous Systems Discipline (AS) – focus on high UML's (5-6). Example activities:
   - Perception
   - Human autonomy teaming
   - Intelligent contingency management
   - Collective Autonomous Mobility

Collective Autonomous Mobility

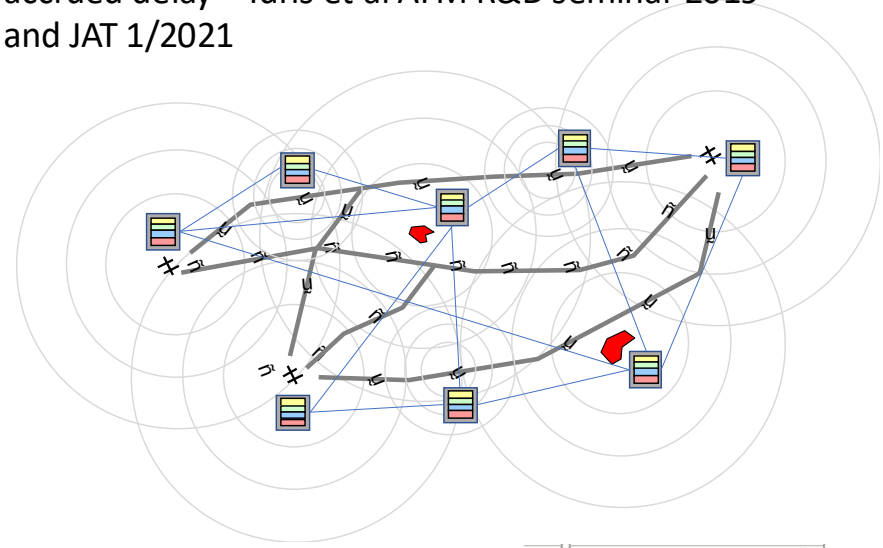
Path planning under extreme uncertainties –
Zeng et al, ATM R&D seminar 21 and SciTech 2022



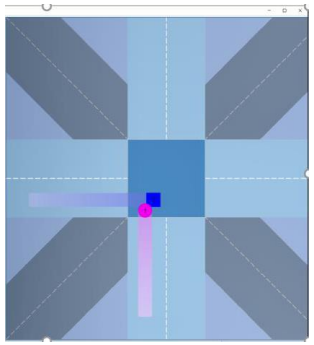
Convoy Formation and Entropy
– Ishihara et al Aviation 21
– Jain et al submitted to ICRAT 24

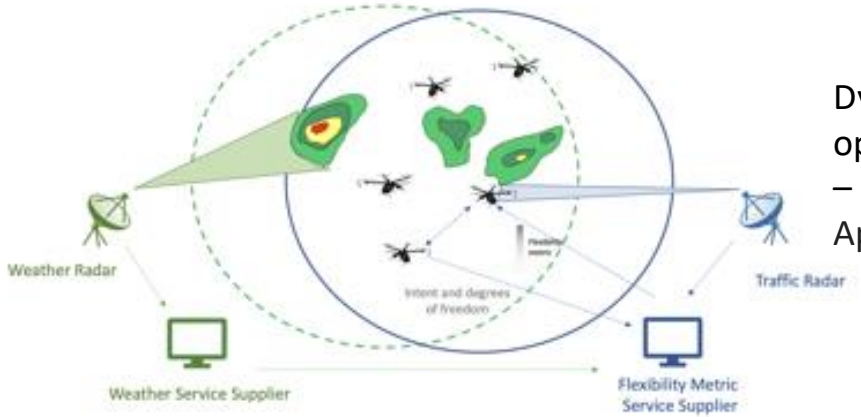


Closed network distributed scheduling using accrued delay – Idris et al ATM R&D seminar 2019 and JAT 1/2021



Edge AI for conflict detection and distributed negotiation using credit mechanisms – Das et al Aviation 20, 22, SciTech 21





Dynamic information sharing optimization using quantum annealing – Gonzalez et al Physical Review Applied Nov 22

Collective Autonomous Mobility

Supporting Research

MIT Grant to Dr. Hamsa Balakrishnan – studied internet-inspired models for supply-side service-service coordination

Two current NRA efforts studying metrics, models and coordination mechanisms for heterogeneous, multi-agent, collective autonomous air mobility systems, inspired by other collective autonomous systems

- NRA by Dr. Hamsa Balakrishnan of MIT
- NRA by Dr. Huy Tran of Illinois Urbana Champaign and Dr. Max Li of Michigan Ann Arbor

Outline

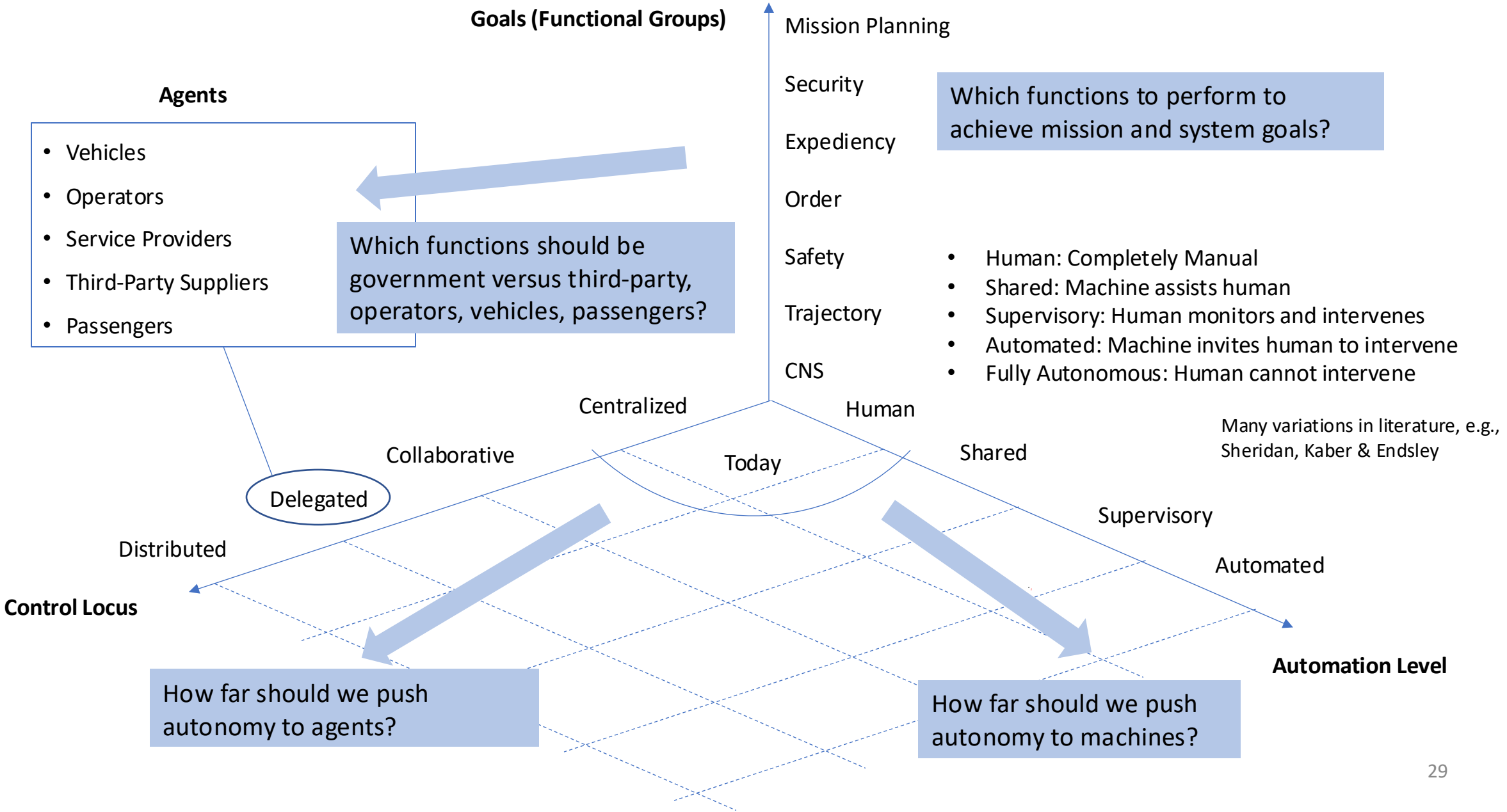
- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Motivation

Abstraction framework is needed to identify autonomy challenges, solutions and research needs in methodical and comprehensive manner

- Consider continuum of autonomy levels
- Decompose functions required for achieving the goals of safe, orderly, expeditious, and secure traffic operations
- Abstract functions independently from which agent performs a function (vehicle, remote pilot, controller) and whether a human or automation performs a function
- Support dynamic architectures and functional allocations depending on changing flight and airspace conditions

Autonomy Dimensions - Operational

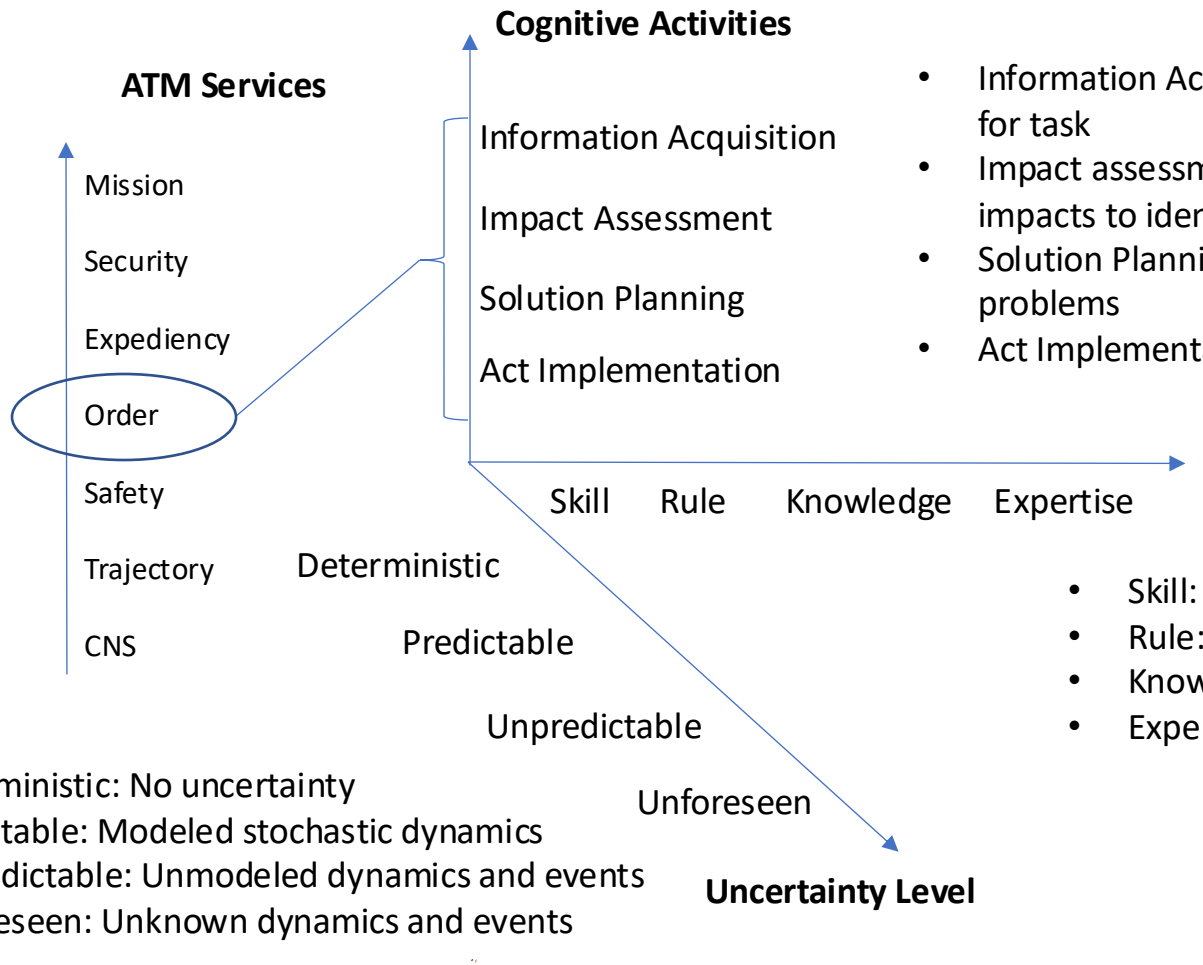


Levels of Autonomy

Term	Definition
Human Control	• The function is performed completely by the human.
Shared Control	• The human and the machine/automation perform the function in a cooperative manner (i.e., with decision support from automation). • The machine/automation can perform the function with human approval.
Supervisory Control	• The function is performed by the machine/automation with monitoring, teaching, and intervention from the human as needed. • The machine/automation can perform the function without human approval and will inform the human.
Automated Control	• The machine/automation performs the function independently without any involvement from the human, except when the machine decides.
Fully Machine Autonomous Control	• The machine/automation performs the function independently without any involvement from the human. • The machine/automation decides to perform the function. • The human is unable to take control of the system.

Note: May adjust to be more consistent with other terminology in literature.
For example: shared = human within the loop, supervisory = human on the loop, automatic = human over the loop, autonomous = human out of the loop

Autonomy Dimensions - Cognitive



- Information Acquisition: Observe information needed for task
- Impact assessment: Analyze information and compute impacts to identify problems
- Solution Planning: Decide on solution to mitigate problems
- Act Implementation: Execute selected solution

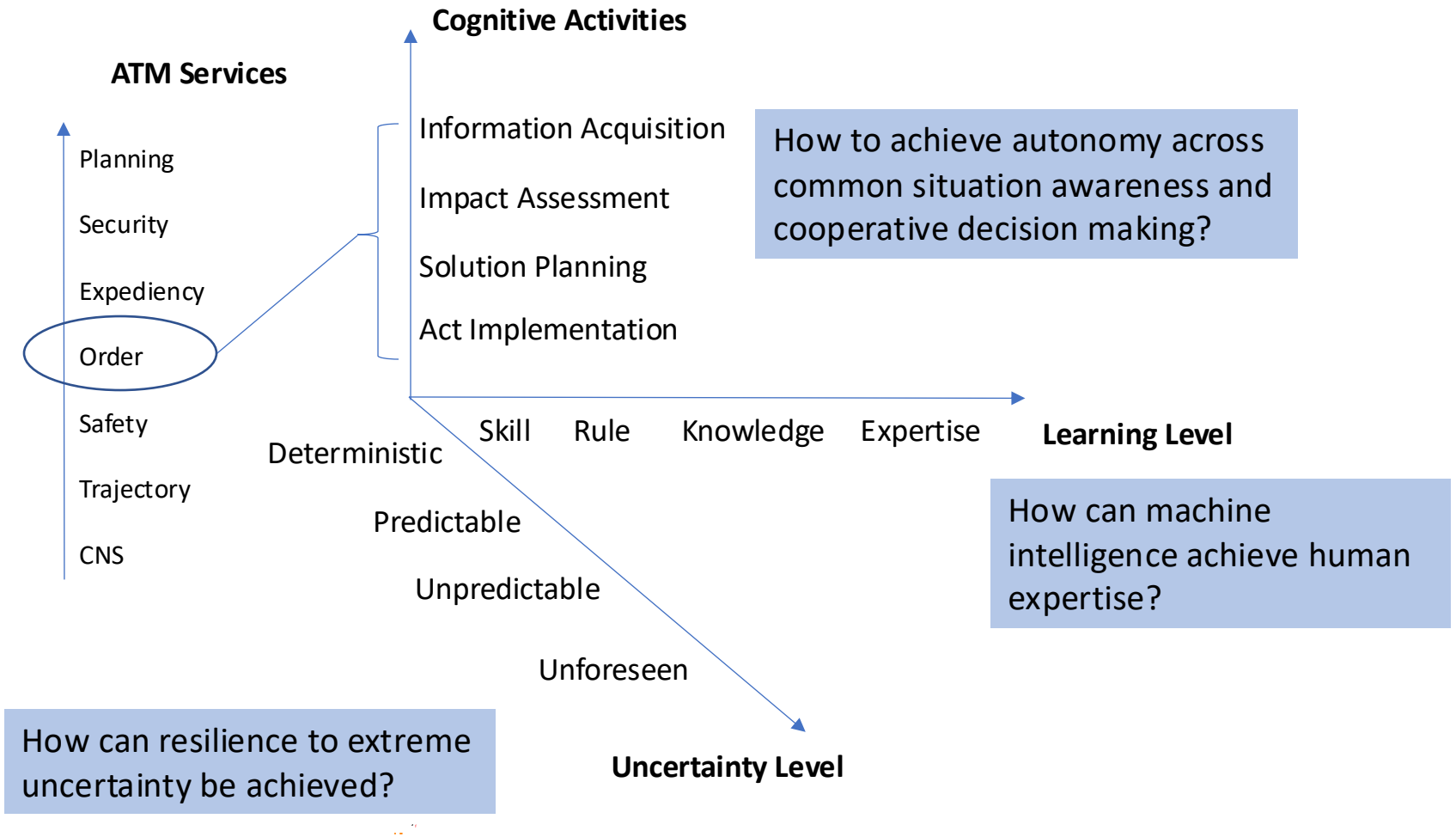
Many variations in literature, e.g., Proud, Alexander

- Skill: Routine, stimulus response
- Rule: Programmable, if then rules
- Knowledge: Logic, symbolic reasoning
- Expertise: Intuition, meta-knowledge

Many variations in literature, e.g., Rasmussen, Cummings, Gill&Hicks

- Deterministic: No uncertainty
- Predictable: Modeled stochastic dynamics
- Unpredictable: Unmodeled dynamics and events
- Unforeseen: Unknown dynamics and events

Autonomy Dimensions - Cognitive



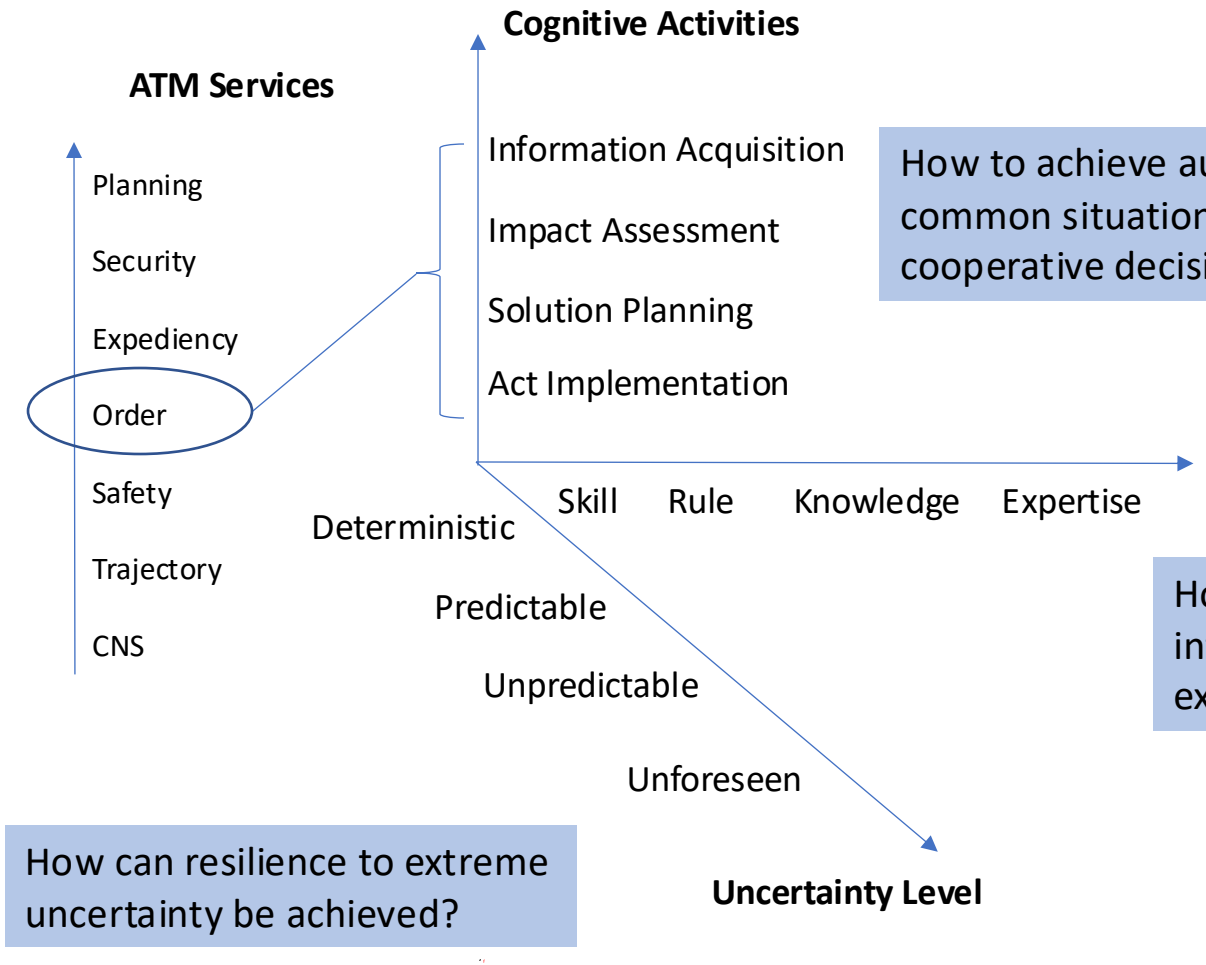
How to achieve autonomy across all system goals and functions?

How to achieve autonomy across common situation awareness and cooperative decision making?

How can machine intelligence achieve human expertise?

How can resilience to extreme uncertainty be achieved?

Autonomy Dimensions - Cognitive



How to achieve autonomy across all system goals and functions?

Closed network distributed scheduling using accrued delay – Idris et al ATM R&D seminar 2019 and JAT 1/2021

Convoy Formation and Entropy
– Ishihara et al Aviation 21
– Jain et al submitted to ICRAT 24

How to achieve autonomy across common situation awareness and cooperative decision making?

Dynamic information sharing optimization using quantum annealing – Gonzalez et al Physical Review Applied Nov 22

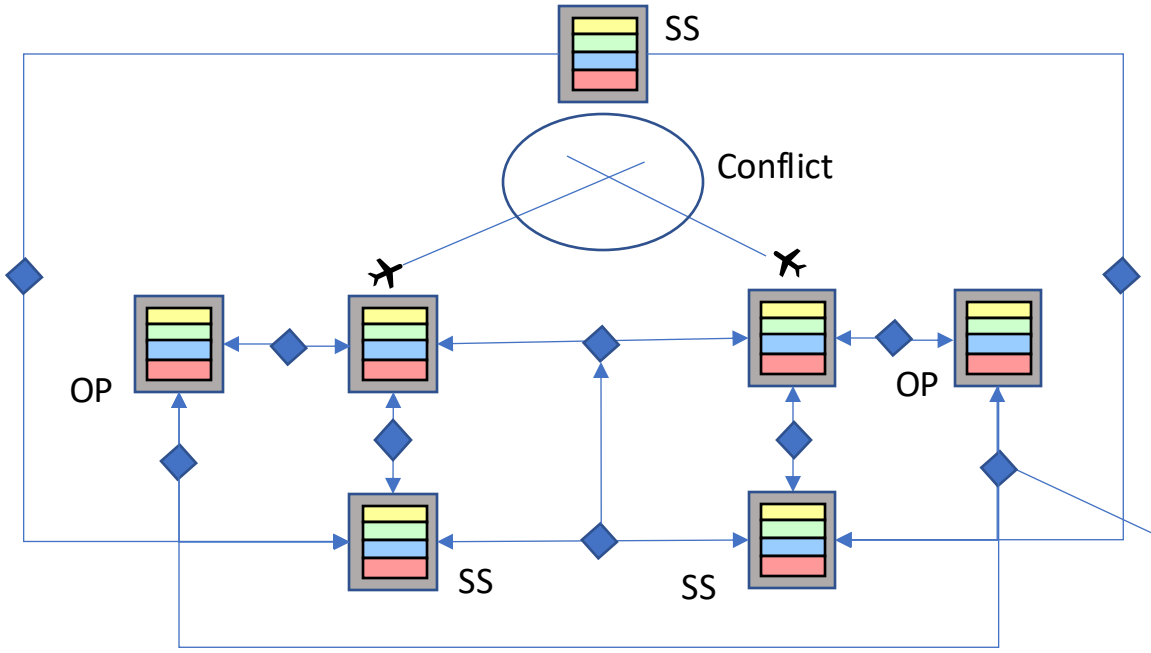
How can machine intelligence achieve human expertise?

Edge AI for conflict detection and distributed negotiation using credit mechanisms – Das et al Aviation 20, 22, SciTech 21

How can resilience to extreme uncertainty be achieved?

Path planning under extreme uncertainties – Zeng et al, ATM R&D seminar 21 and SciTech 2022

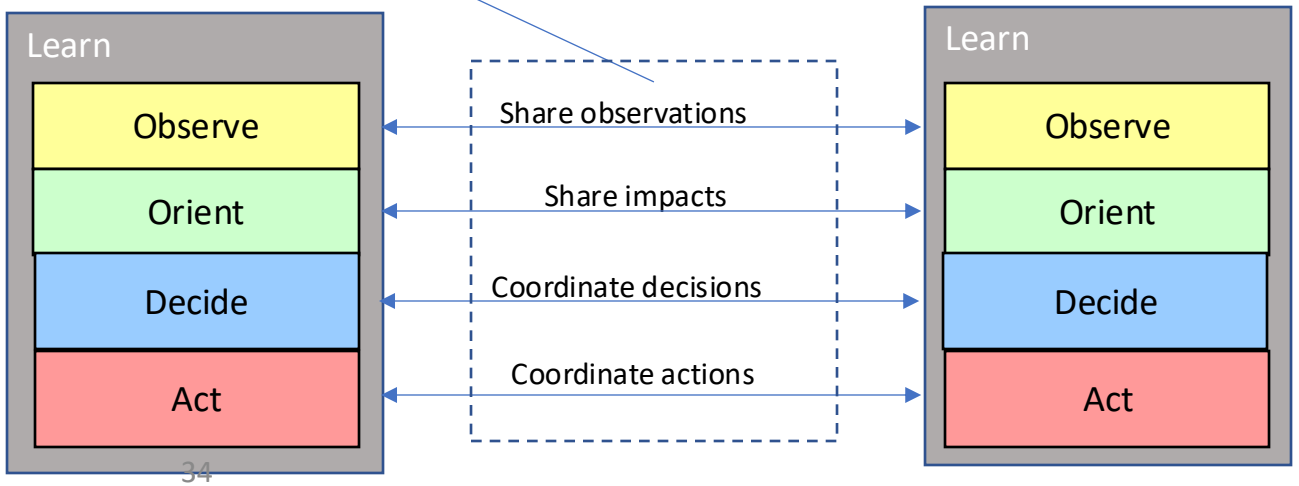
Autonomous Agents with Dynamic Coordination



Multi-agent system including vehicles, operators and service suppliers

Abstracting coordination mechanisms between distributed autonomous agents:

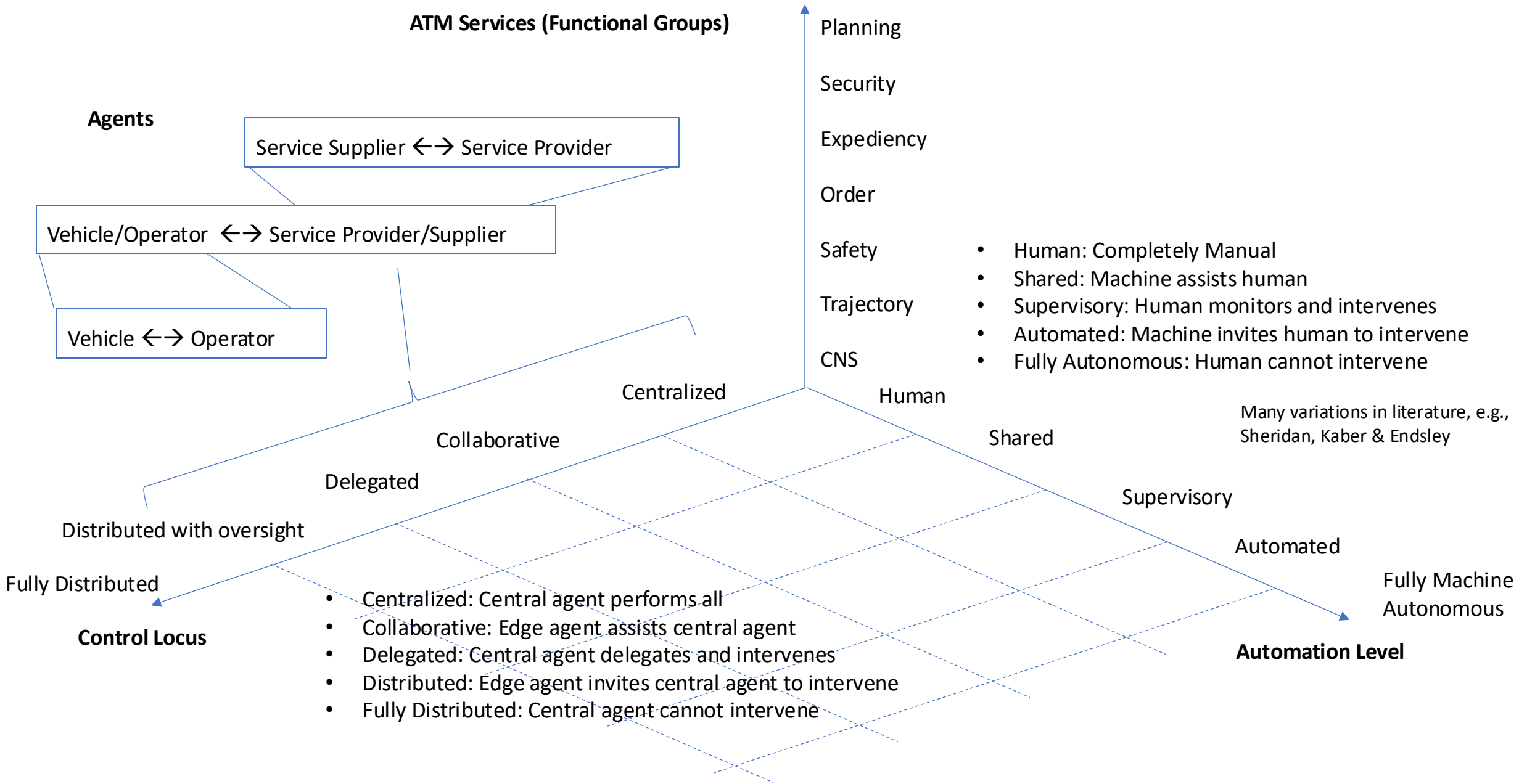
- Coordination mechanisms categorized by each cognitive phase
- Autonomous agents decide level of coordination with other agents across all cognitive phases
- Coordination level can be controlled dynamically based on situation
- Machine learning applied for each agent at all cognitive levels



Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Autonomy Dimensions and Levels

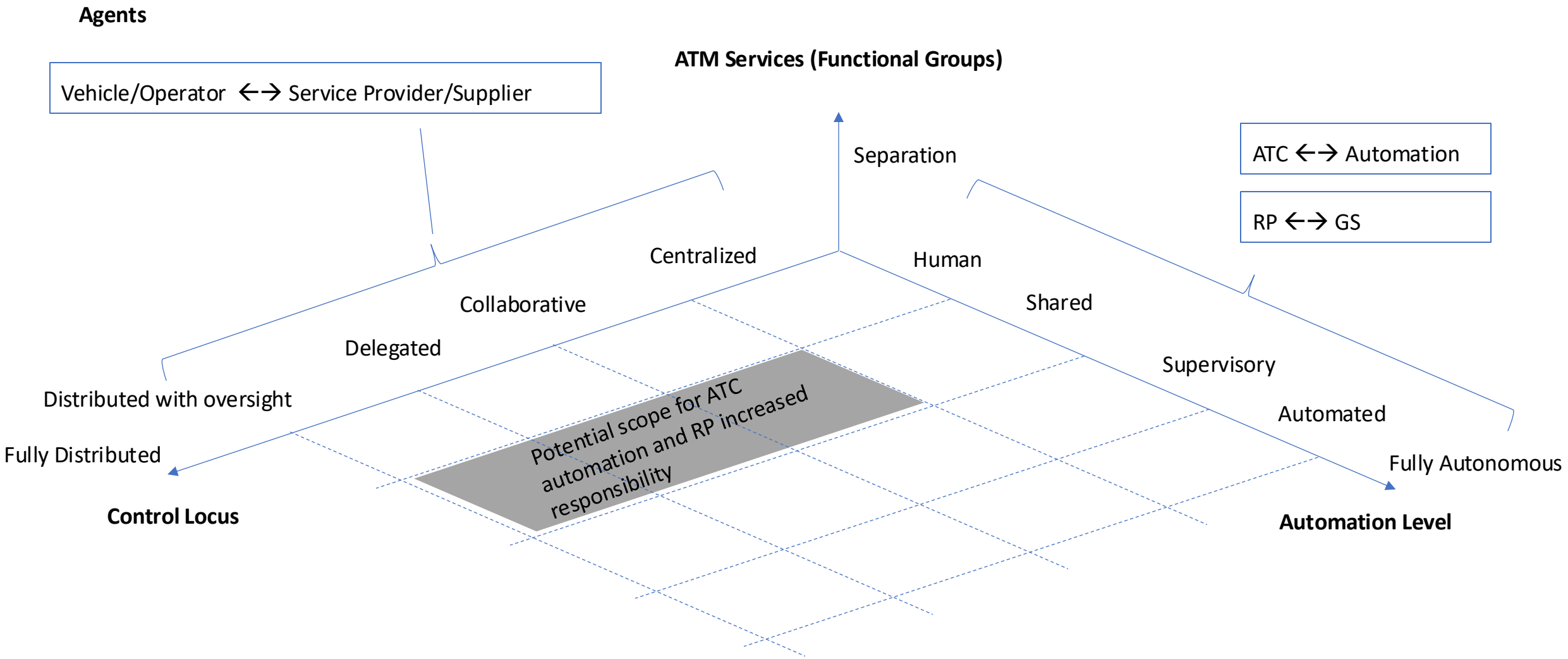


Levels of Autonomy

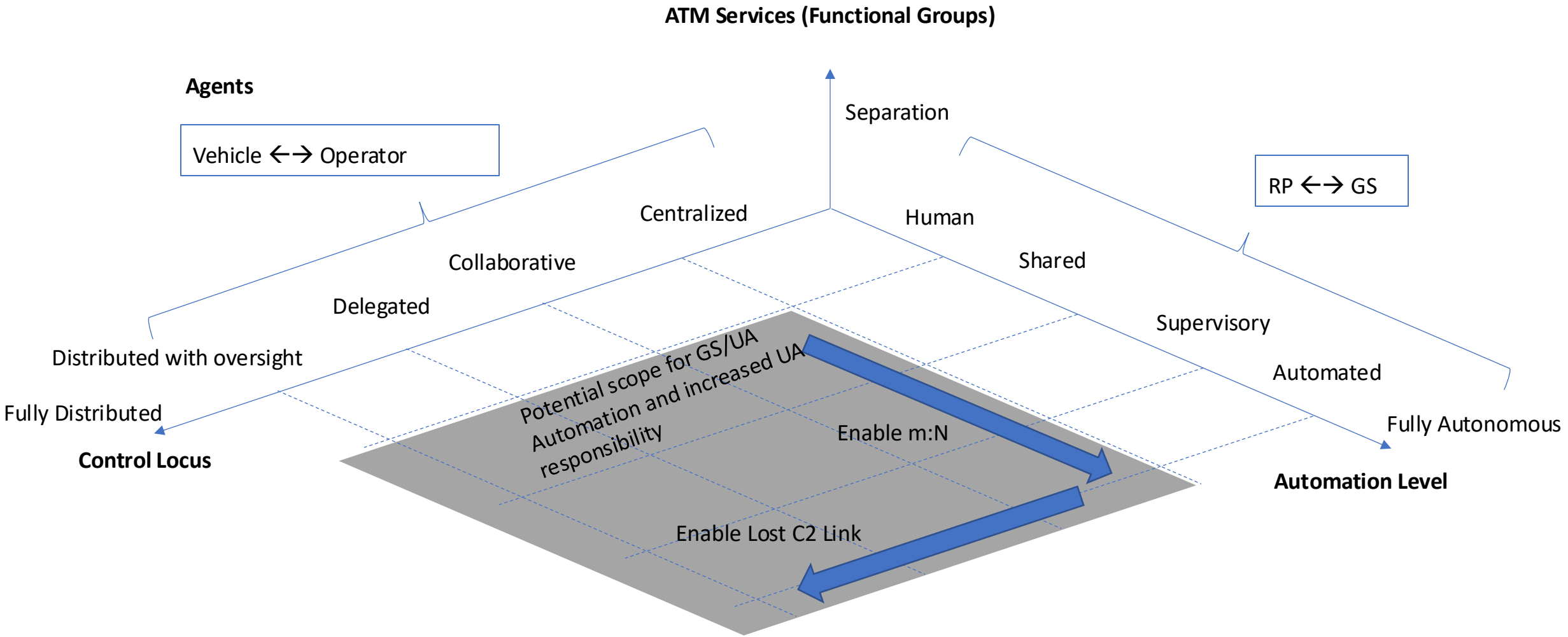
Term	Definition
Human Control	• The function is performed completely by the human.
Shared Control	• The human and the machine/automation perform the function in a cooperative manner (i.e., with decision support from automation). • The machine/automation can perform the function with human approval.
Supervisory Control	• The function is performed by the machine/automation with monitoring, teaching, and intervention from the human as needed. • The machine/automation can perform the function without human approval and will inform the human.
Automated Control	• The machine/automation performs the function independently without any involvement from the human, except when the machine decides.
Fully Machine Autonomous Control	• The machine/automation performs the function independently without any involvement from the human. • The machine/automation decides to perform the function. • The human is unable to take control of the system.

Note: May adjust to be more consistent with other terminology in literature.
For example: shared = human within the loop, supervisory = human on the loop, automatic = human over the loop, autonomous = human out of the loop

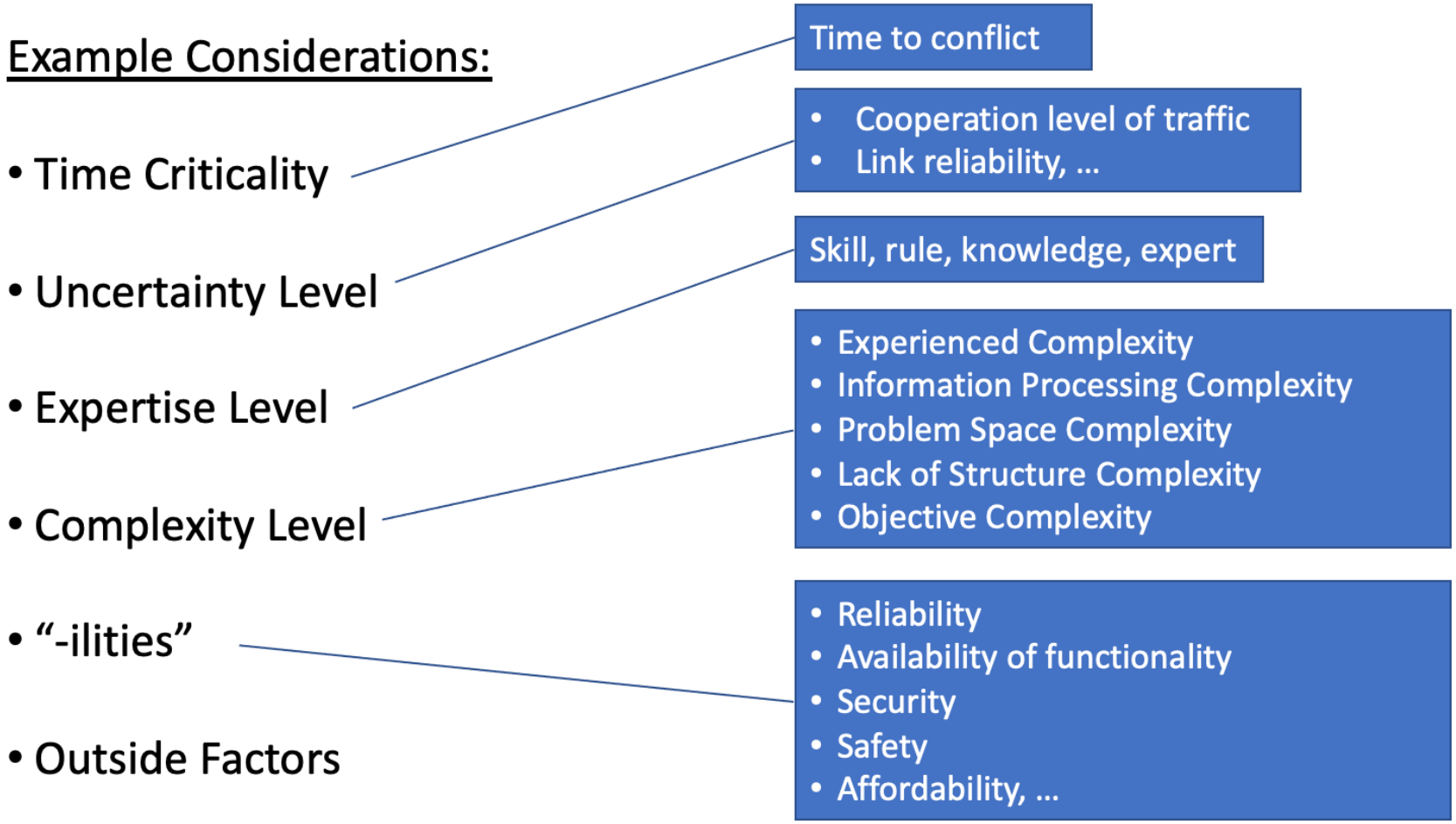
Autonomy Levels – Separation Example



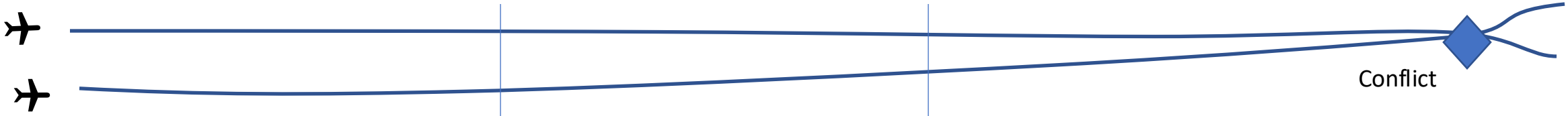
Autonomy Levels – Separation Example



Possible Functional Allocation Criteria



Dynamic Allocation Based on Time Criticality – Separation Example



Nominal 1:1

	ATC	AUT	RP	GS	UA
I			?	?	
I			?	?	
S			?	?	
A					

	ATC	AUT	RP	GS	UA
I					?
I					?
S					?
A					

	ATC	AUT	RP	GS	UA
I			?		
I			?		
S			?		
A			?		

Nominal m:N

	ATC	AUT	RP	GS	UA
I					?
I					?
S					?
A					

	ATC	AUT	RP	GS	UA
I					?
I					?
S	?	?			?
A					

	ATC	AUT	RP	GS	UA
I			?		
I			?		
S			?		
A			?	?	

Lost C2 Link

	ATC	AUT	RP	GS	UA
I					
I					
S	?	?			
A	?	?			

	ATC	AUT	RP	GS	UA
I					
I					
S	?	?	?	?	
A	?	?	?	?	

	ATC	AUT	RP	GS	UA
I			?	?	
I			?	?	
S					
A					

Primary Role

Assistive Role

No Role

Primary refers to authority (not always responsibility) – who is responsible when machine has authority?

Primary-Assistive relationship can be in, on, or over loop – can add more shades?

Is there need for additional gradual allocations in between?

What is an acceptable / optimal functional allocation?

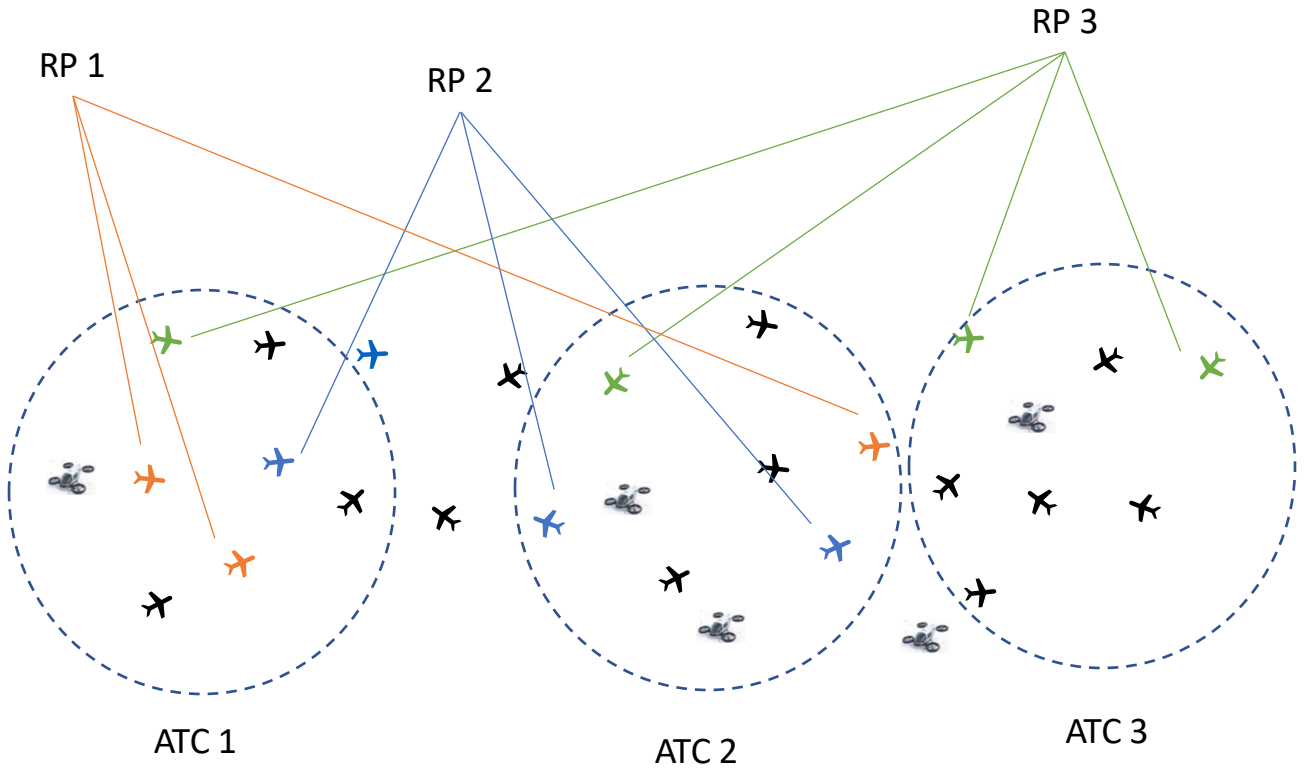
Back up / Old Slides

Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

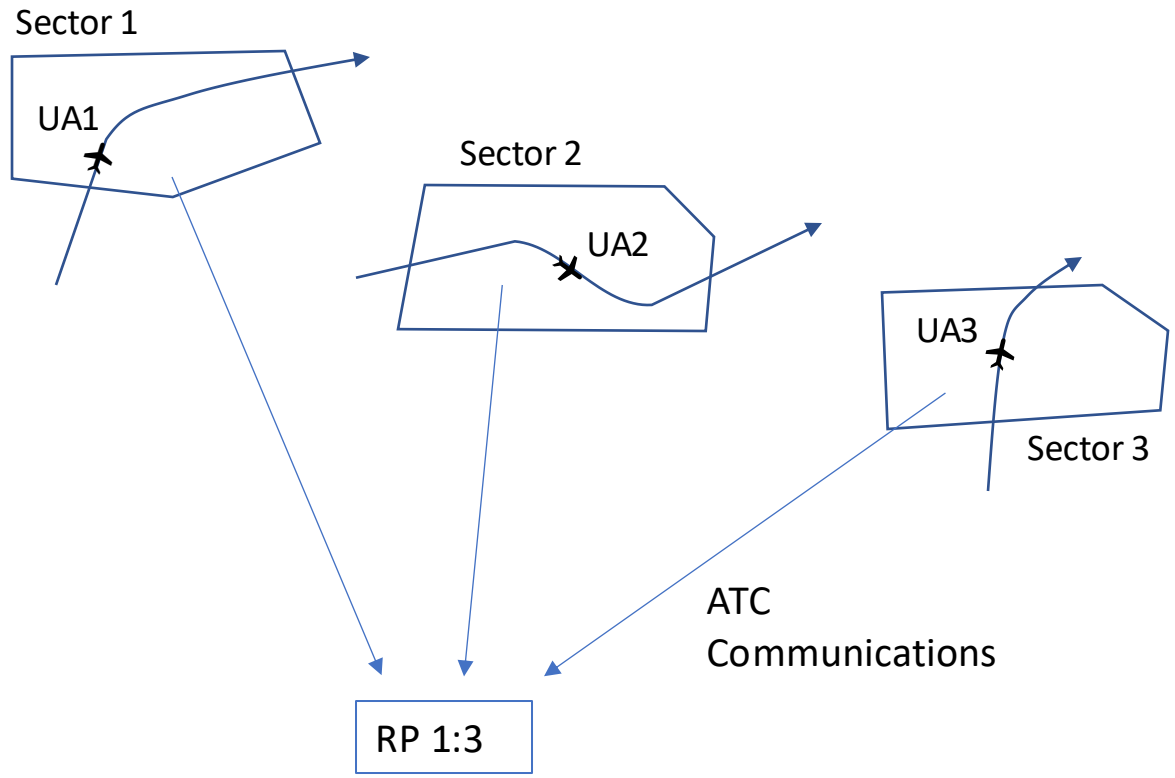
Dynamic UAS m:N supervisory control

- Multiple m:N ratios will exist in the NAS depending on airspace complexity, phase of flight, pilot workload, technological constraints (C2 link), communication constraints
- For example, 1:1 will be necessary for time-critical functions and under demanding environments while 1:many may be possible under less demanding airspace and conditions
- Dynamically transition between different m:N schemes
- Dynamically change m:N schemes based on changing conditions
- Hand-over process(es) will need to be established



Remote-Pilot Task Complexity: Inter-Maneuver Time

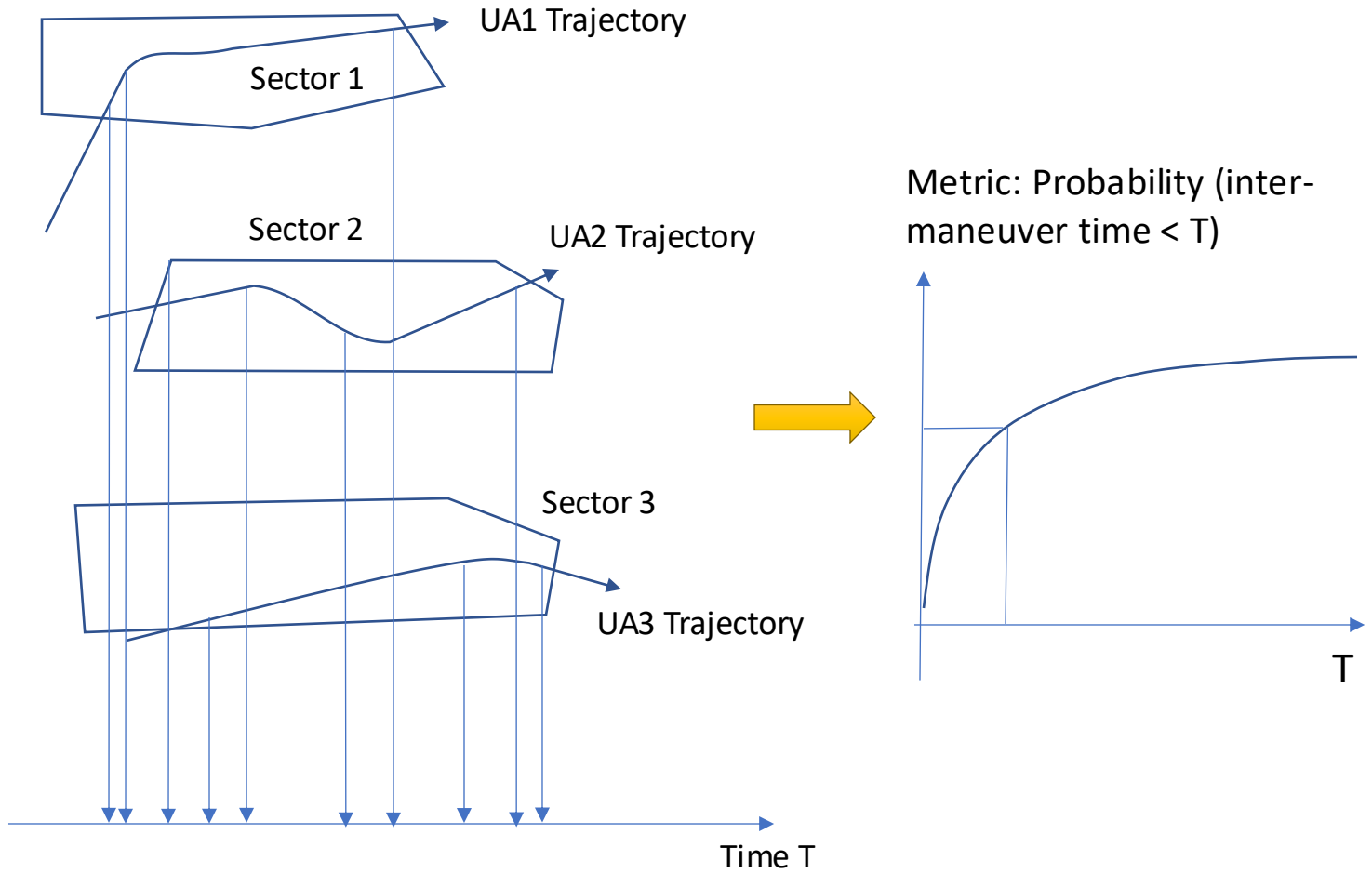
- Key issues / Questions
  - Remote pilot monitoring and responding to multiple controller frequencies simultaneously
  - Leads to high remote pilot workload, potential step-on communications and short time between controller clearances
  - Vehicles may involve different phases of flight (en route, arrival, departure), communication latencies (radio vs satellite), and conditions (densities, weather)
- Need to quantify remote pilot task (namely, maneuver / communication) load under different m:N schemes and conditions in order to assess feasibility



Idris and Dimitrova, Oral Presentation, INFORMS 2023 and SciTech 2024

Remote-Pilot Task Complexity: Inter-Maneuver Time

- Approach
  - Characterization of inter-maneuver times from historical track data to identify
    (1) observed times under current conditions and
    (2) expected times under m:N schemes
  - Inter-maneuver time computed between five events: sector entry, onset of altitude change, onset heading change, onset of speed change, and sector exit
  - Using maneuver events as proxy for communication events
  - Under different sector types and congestion levels

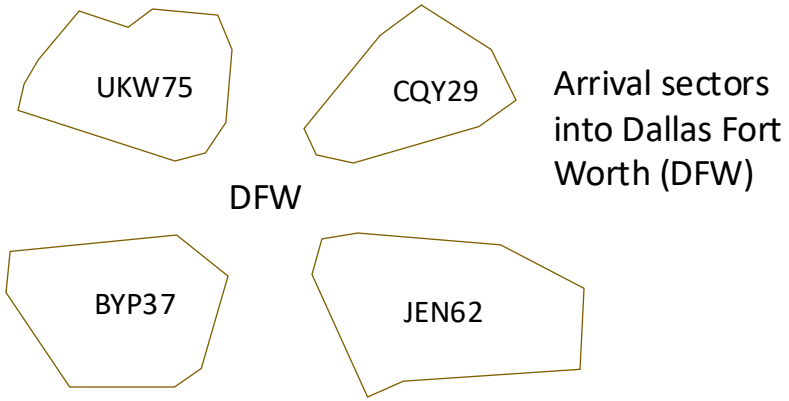


RP maneuver/handoff events under 1:3

Idris and Dimitrova, Oral Presentation, INFORMS 2023 and SciTech 2024

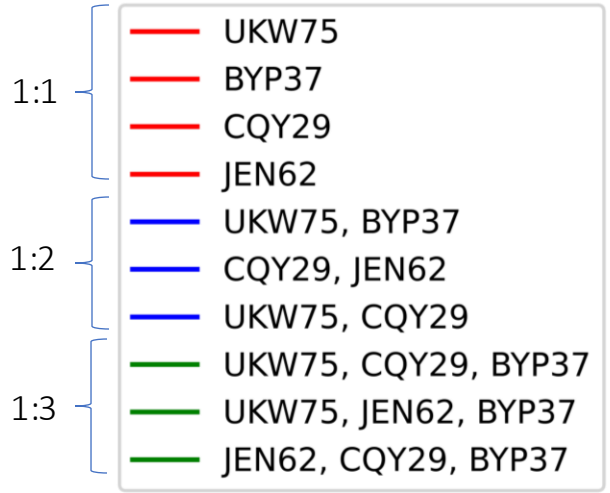
Remote-Pilot Task Complexity: Inter-Maneuver Time Preliminary Analysis

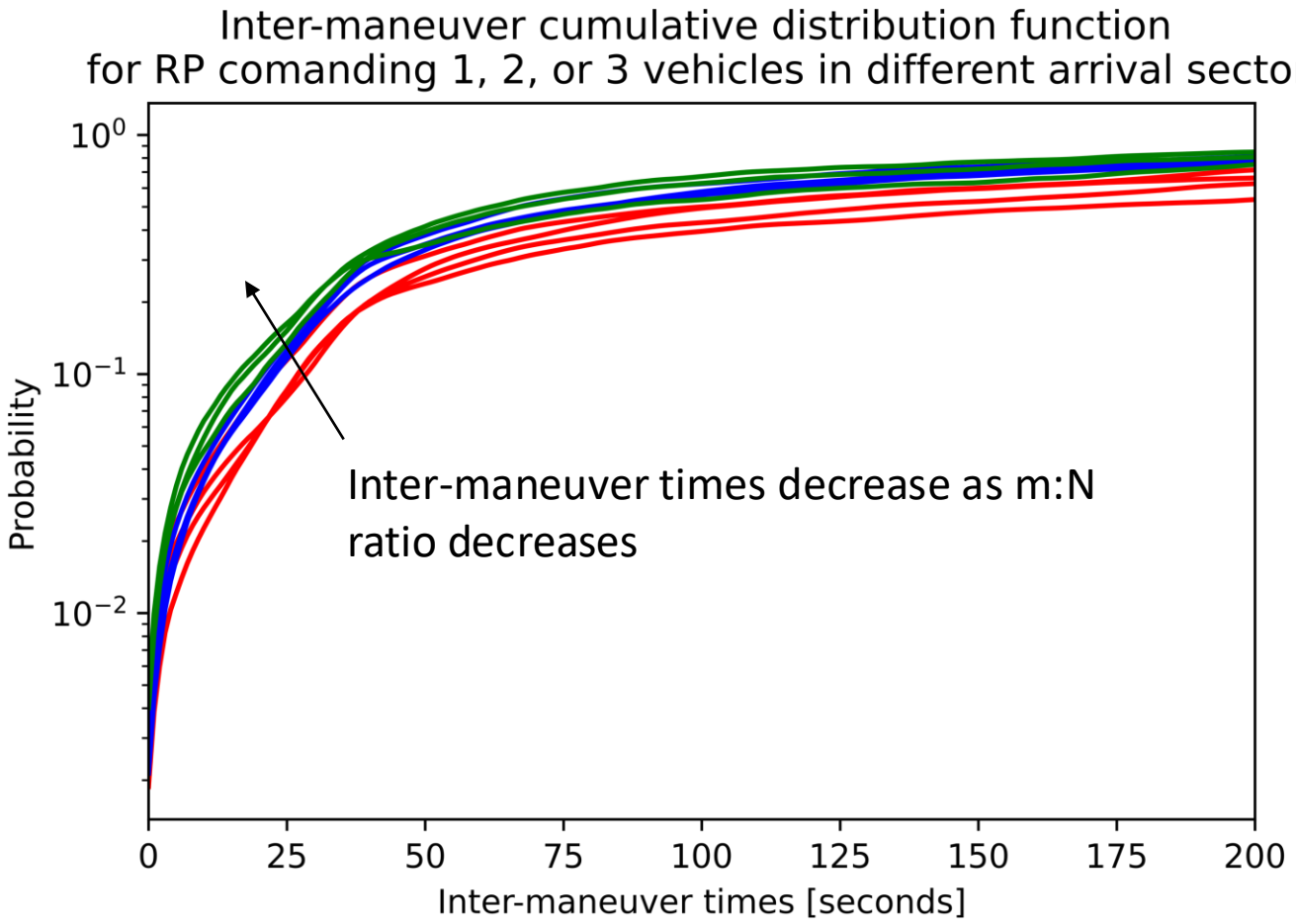
1:1, one RPA in each arrival sector
1:2, one RPA in each of two arrival sectors
1:3, one RPA in each of three arrival sectors



Arrival sectors into Dallas Fort Worth (DFW)

Sector	Daily aircraft minutes
UKW75	13,838
BYP37	15,422
CQY29	15,003
JEN62	4,958





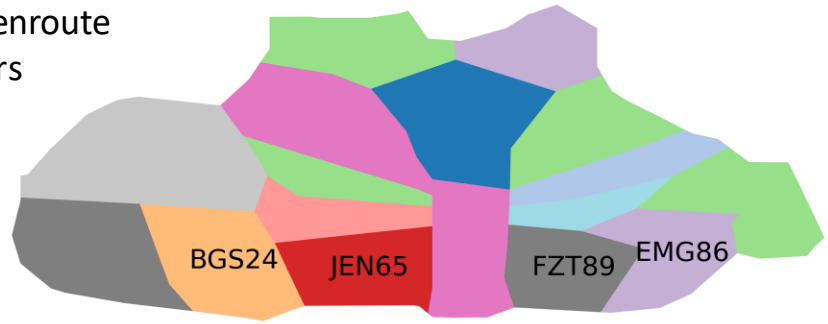
- One day – January 18, 2022
- Only altitude and heading maneuvers (no speed changes)
- Analysis in progress – numbers not final

Idris and Dimitrova, Oral Presentation, INFORMS 2023 and SciTech 2024

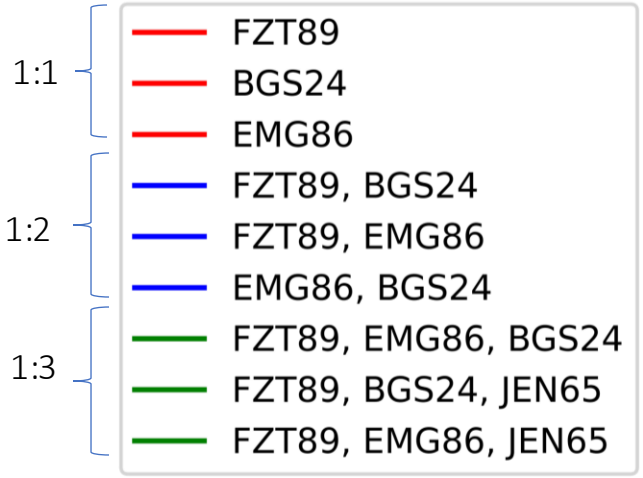
Remote-Pilot Task Complexity: Inter-Maneuver Time Preliminary Analysis

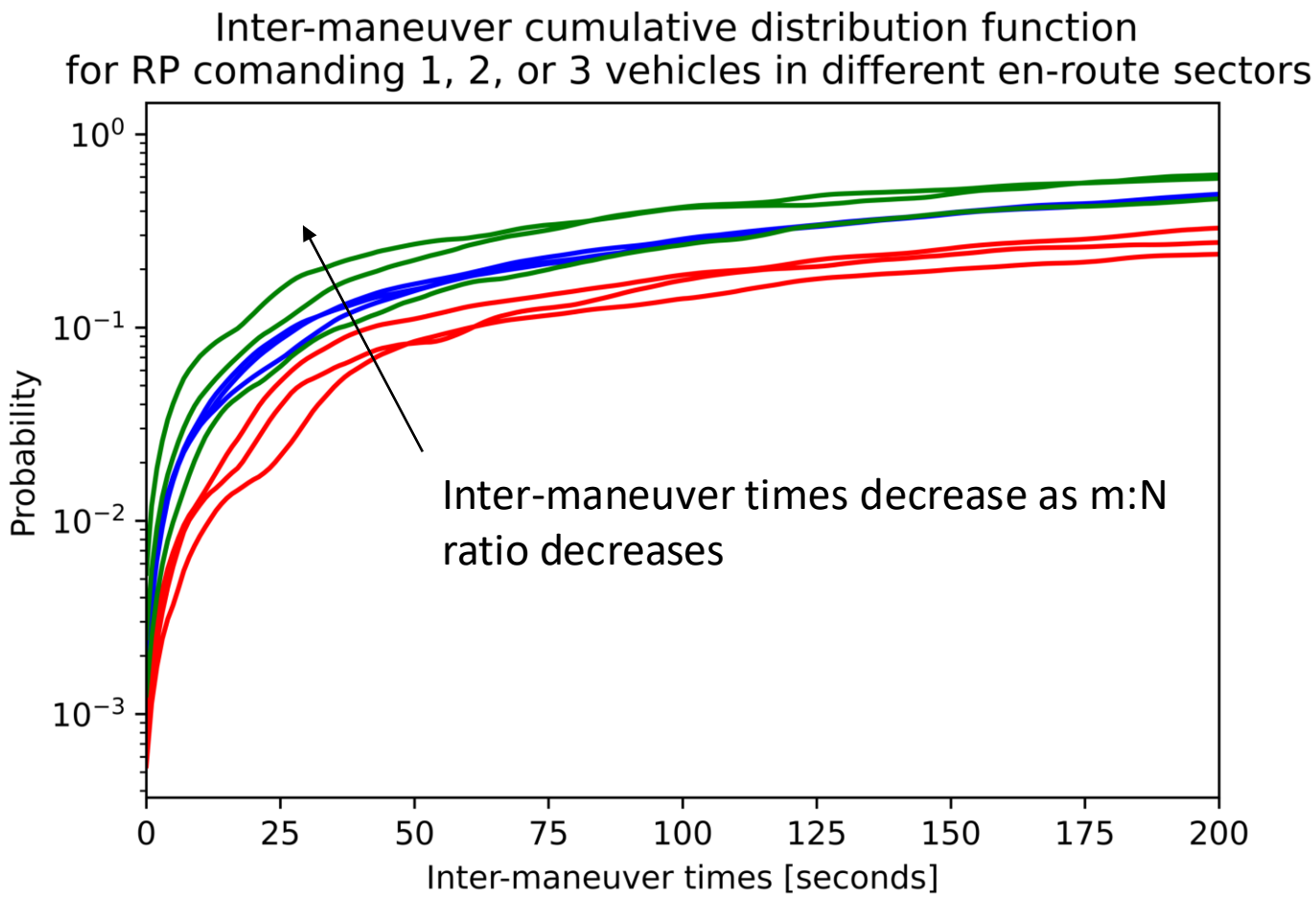
1:1, one RPA in each enroute sector
1:2, one RPA in each of two enroute sectors
1:3, one RPA in each of three enroute sectors

ZFW enroute sectors



Sector	Daily aircraft minutes
BGS24	4,969
JEN65	5,158
FZT89	16,185
EMG86	31,042



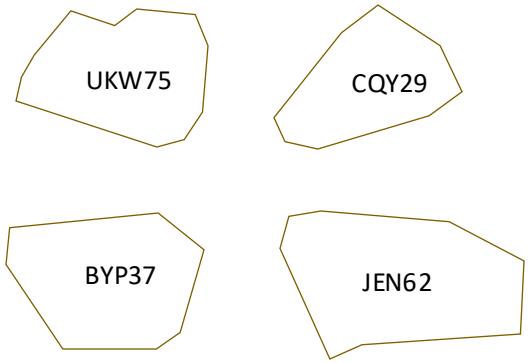


- One day – January 18, 2022
- Only altitude and heading maneuvers (no speed changes)
- Analysis in progress – numbers not final

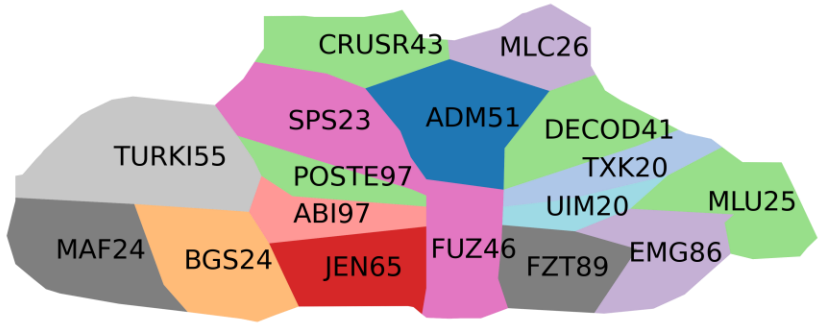
Idris and Dimitrova, Oral Presentation, INFORMS 2023 and SciTech 2024

Remote-Pilot Task Complexity: Inter-Maneuver Time Preliminary Analysis

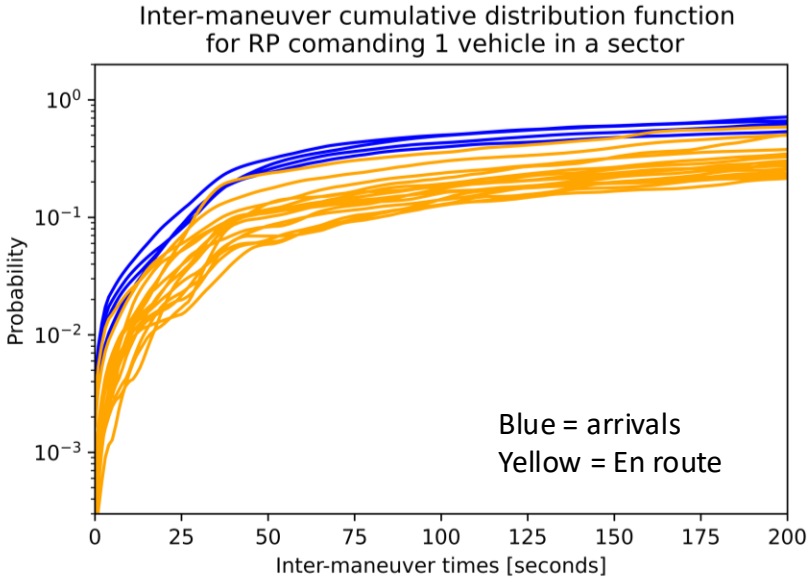
- Inter-maneuver times decrease as m:N ratio decreases
- Inter-maneuver times are smaller in arrival sectors than enroute sectors
- Analysis in progress – numbers not final

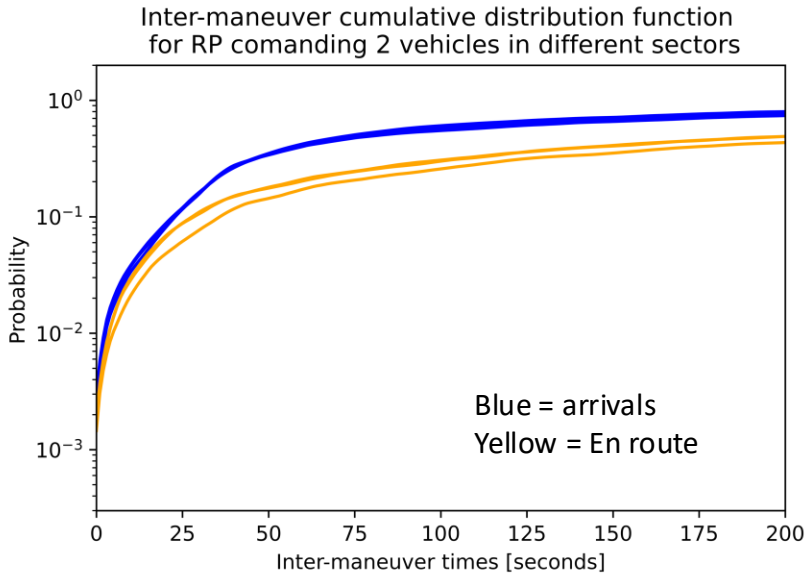


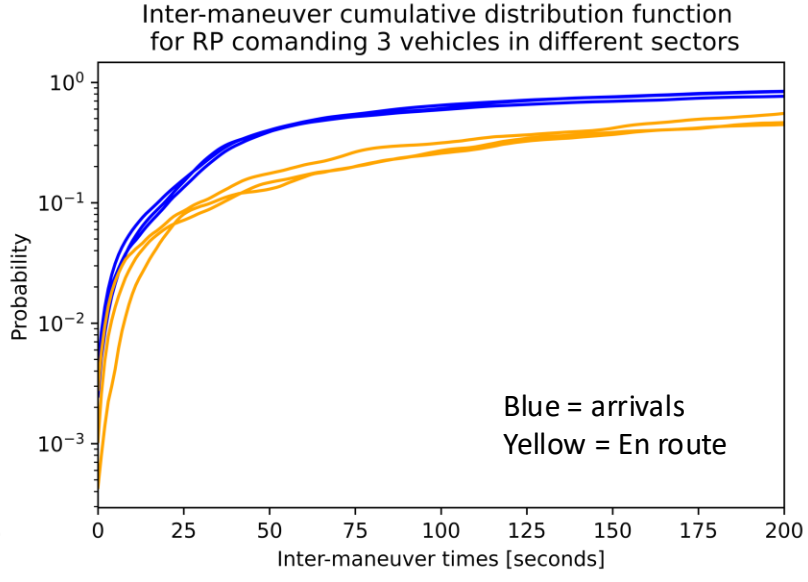
ZFW arrival sectors



ZFW enroute sectors



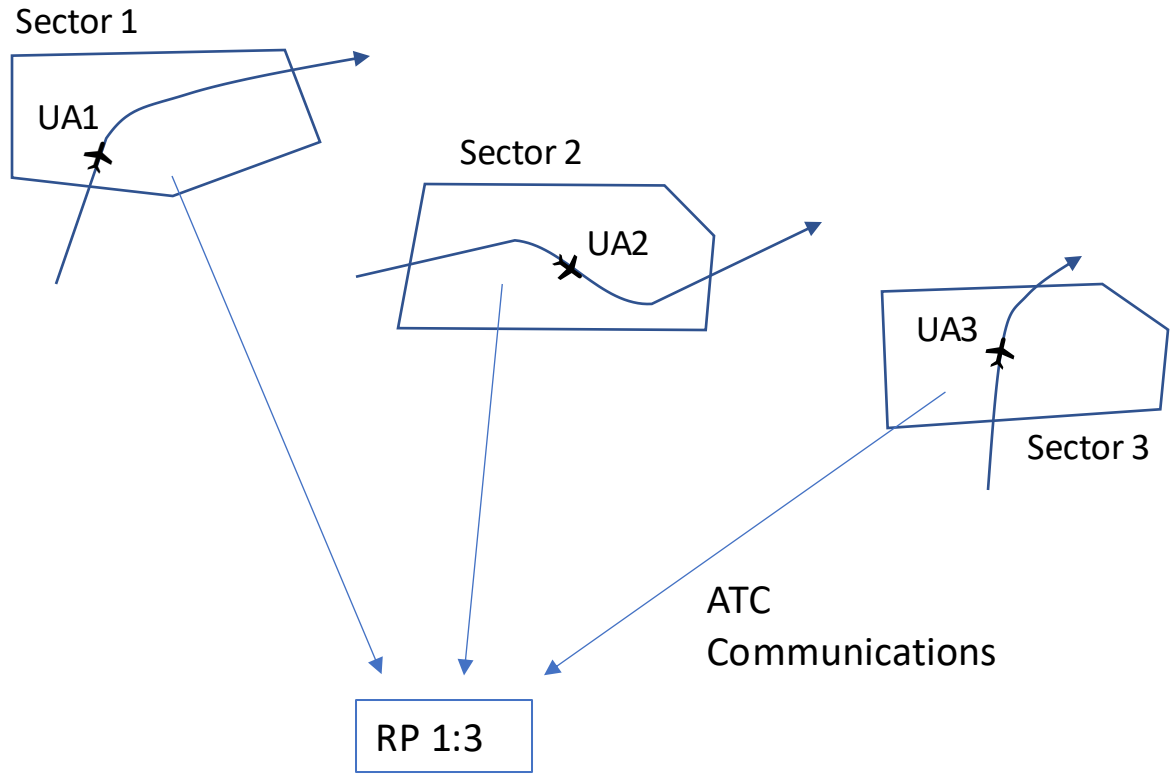




Idris and Dimitrova, Oral Presentation, INFORMS 2023 and SciTech 2024

Remote-Pilot Task Complexity: Inter-Maneuver Time

- Next Steps
  - Sensitivity to maneuver thresholds and other parameters
  - Validation of inter-communication time metrics using audio recording
  - Extending to other complexity metrics

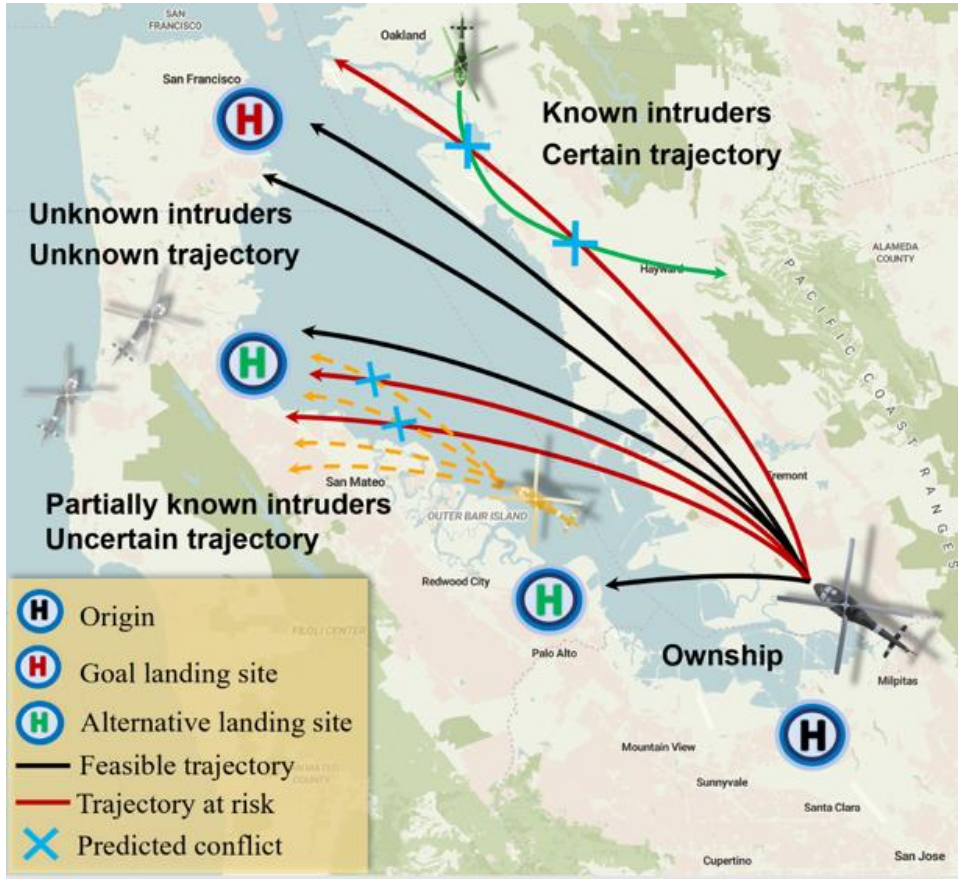


Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Trajectory Planning under Extreme Uncertainty

- **Motivation:** Autonomy needs to be assured and trusted under high uncertainty including unknown and unmodeled dynamics
  - It's difficult to characterize or bound the behavior of highly unpredictable events, or model unobserved and complex dynamics.
  - Ex: non-cooperative intruder traffic, flock of birds crossing the vehicle path
- **Research question:** How to plan a safe trajectory for an autonomous vehicle when there are external uncertainties, i.e., when the locations and future trajectories of weather systems and other vehicles are partially to completely unknown?
- **To answer the question**…
  - Two fundamental metrics
  - Four trajectory planning policies
  - Thirty-six different traffic scenarios that simulate operating environments with varying degrees of uncertainty ranging from moderate to extreme



Zeng, Idris and Clarke, "Trajectory Planning for Mission Survivability of Autonomous Vehicles in Moderately to Extremely Uncertain Environments", Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Trajectory Planning under Extreme Uncertainty

Metrics:

Metric |: Let L be a set of independent, feasible trajectories that are available to the vehicle for accomplishing the flight mission. $N_f = |L|$

A trajectory is feasible if the following constraints are satisfied:

- Vehicle dynamics
- Terminal constraints
- Conflict avoidance constraints

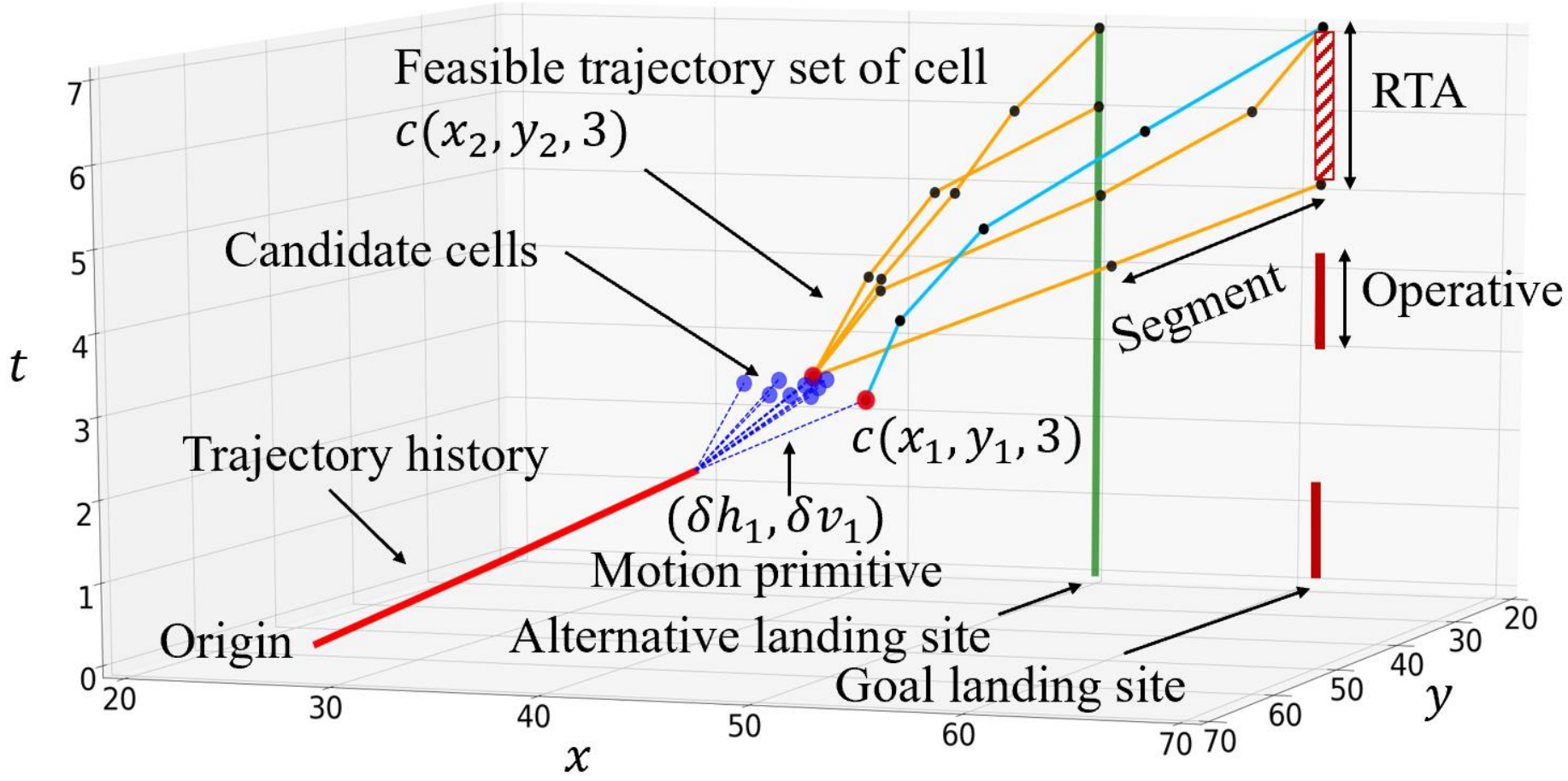
Metric II: The robustness of a trajectory P_l is defined as the likelihood that the trajectory l will remain feasible in the presence of disturbances. The robustness of a trajectory is expressed as:

$$P_l = (\prod_{i=0}^{T-1} p_i)\ \delta\mathrm{T}$$

where p_i is the probability that the trajectory segment l_i remains feasible, and $\delta\mathrm{T}$ is the probability that the corresponding landing site is available at time T

Trajectory Planning under Extreme Uncertainty

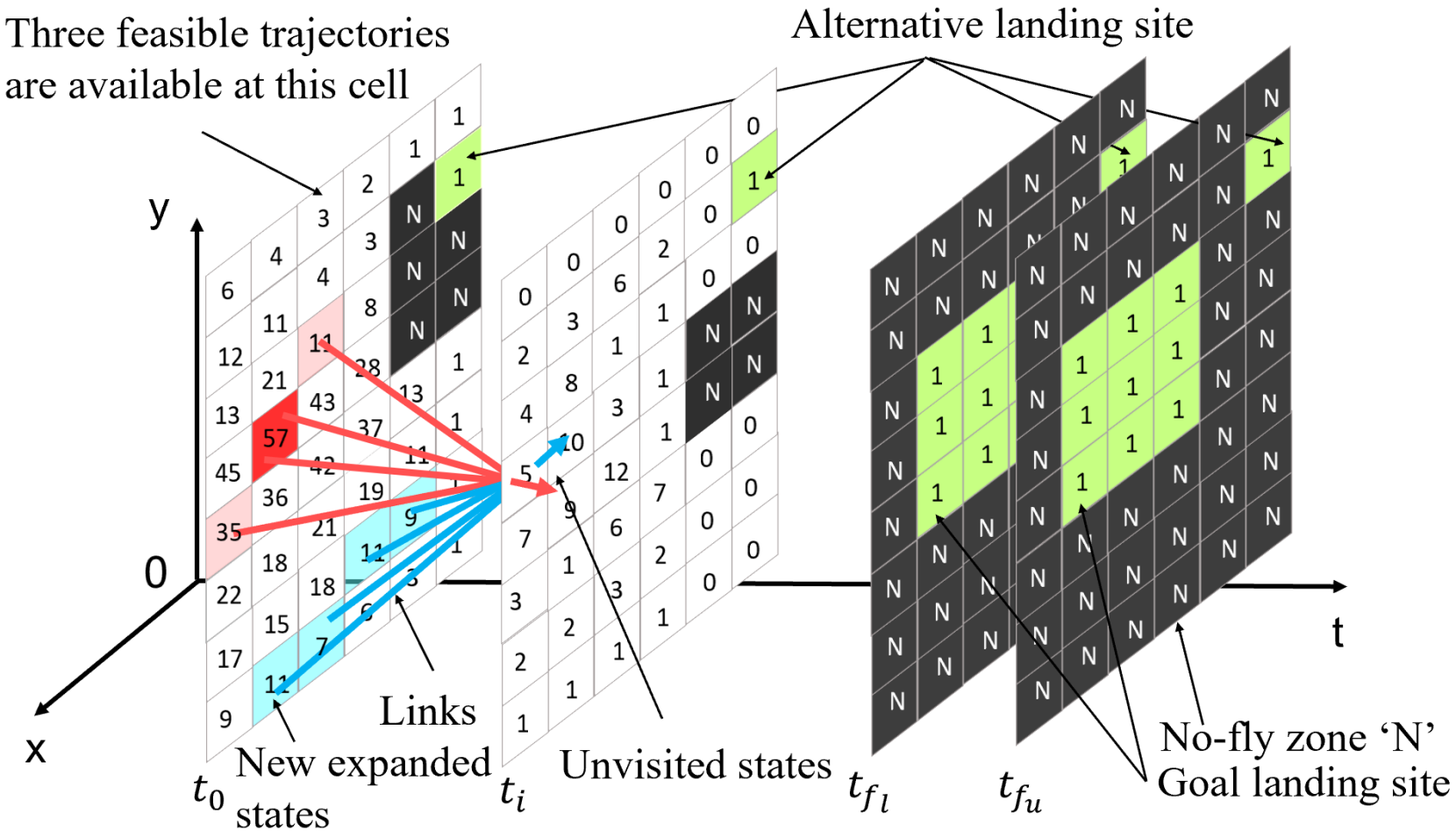
Discrete space-time domain



Trajectory Planning under Extreme Uncertainty

Estimating $N_f = |L|$ through backtracking

- Initialize the last step
- Backtrack the trajectory
- Prune via infeasibility
- Terminate at current state



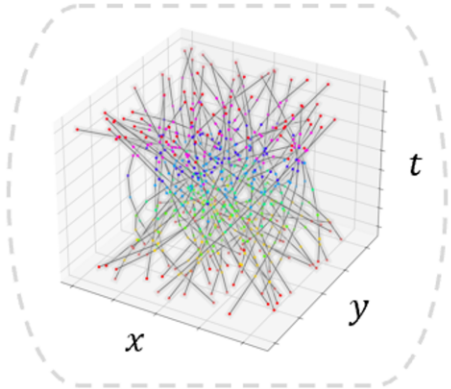
Trajectory Planning under Extreme Uncertainty

Estimating robustness P_l through MC simulation

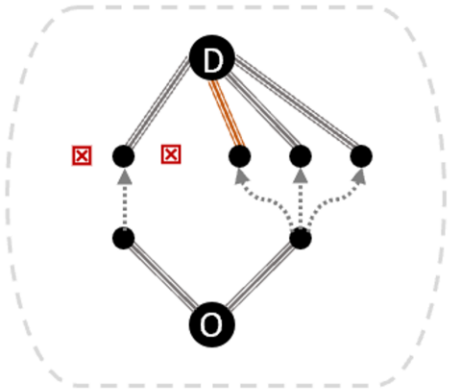
(a) Visualization of a traffic scenario in space and time

(b) Input trajectory segment is in orange

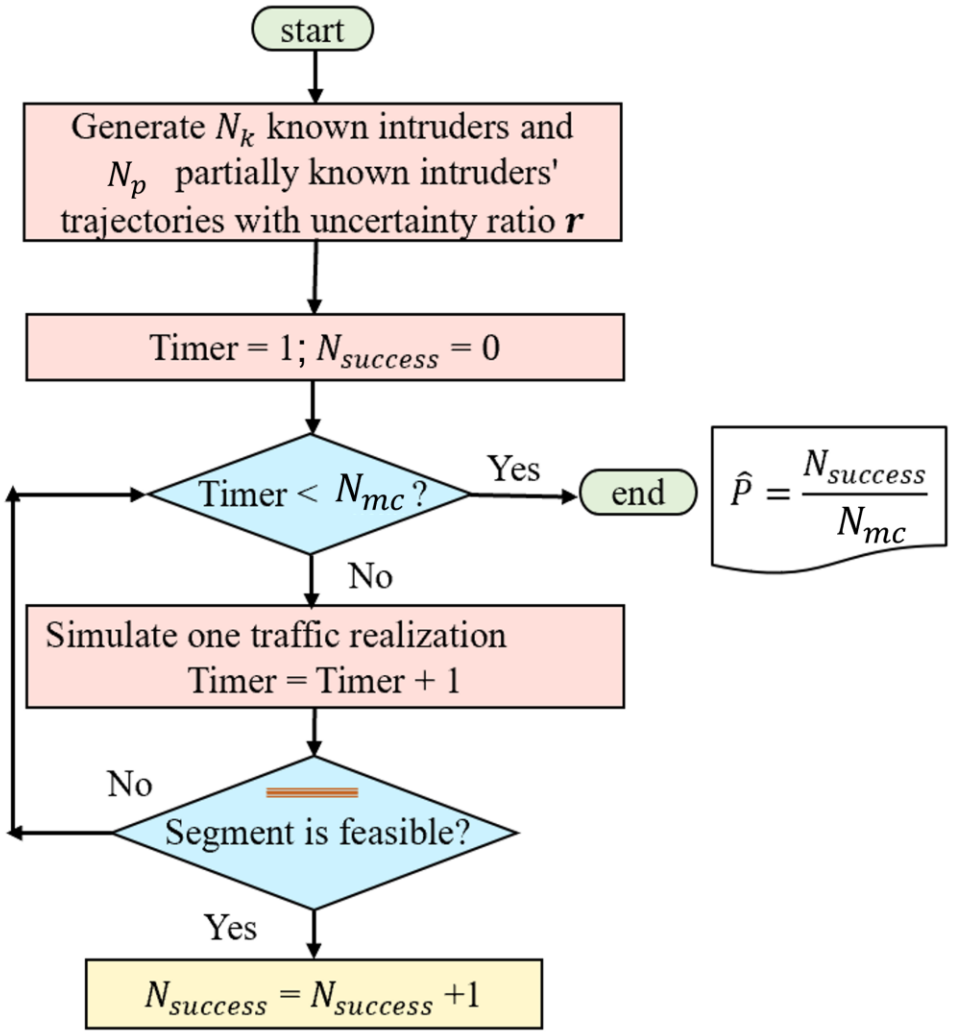
(Nmc : Maximum number of simulation runs.)



(a)



(b)



Trajectory Planning under Extreme Uncertainty

Control Policies:

$\boldsymbol{\pi_R}$ **: Maximize Mission Success** = Probability of having at least one feasible trajectory from cell to destination

$$P^{succed}(L) = 1 - \prod_{i=1, l_i \in L_g}^{n} (1 - P_{l_i}).$$

$L_g = \{l_1, l_2, \cdots, l_n\}$ is set of trajectories ending at destination g

$\boldsymbol{\pi_S}$ **: Maximize Mission Survivability** = Probability of having at least one feasible trajectory from cell to destination or to an alternate landing site

$$P^{survive}(L) = 1 - \prod_{i=1, l_i \in L}^{n} (1 - P_{l_i}).$$

$L = \{l_1, l_2, \cdots, l_n\}$ is set of trajectory ending at destination g or alternative landing sites

$\boldsymbol{\pi_{N_f}}$**: Maximize Trajectory Flexibility** = Number of feasible trajectories from cell to destination or alternate landing site

$\boldsymbol{\pi_{Avg(R)}}$**: Random selection** of trajectory from cell

Trajectory Planning under Extreme Uncertainty

Type of intruders

- Partially known intruders whose trajectories associate with an uncertainty radius r = 5 km. They are known to the ownship at the start of the flight mission.

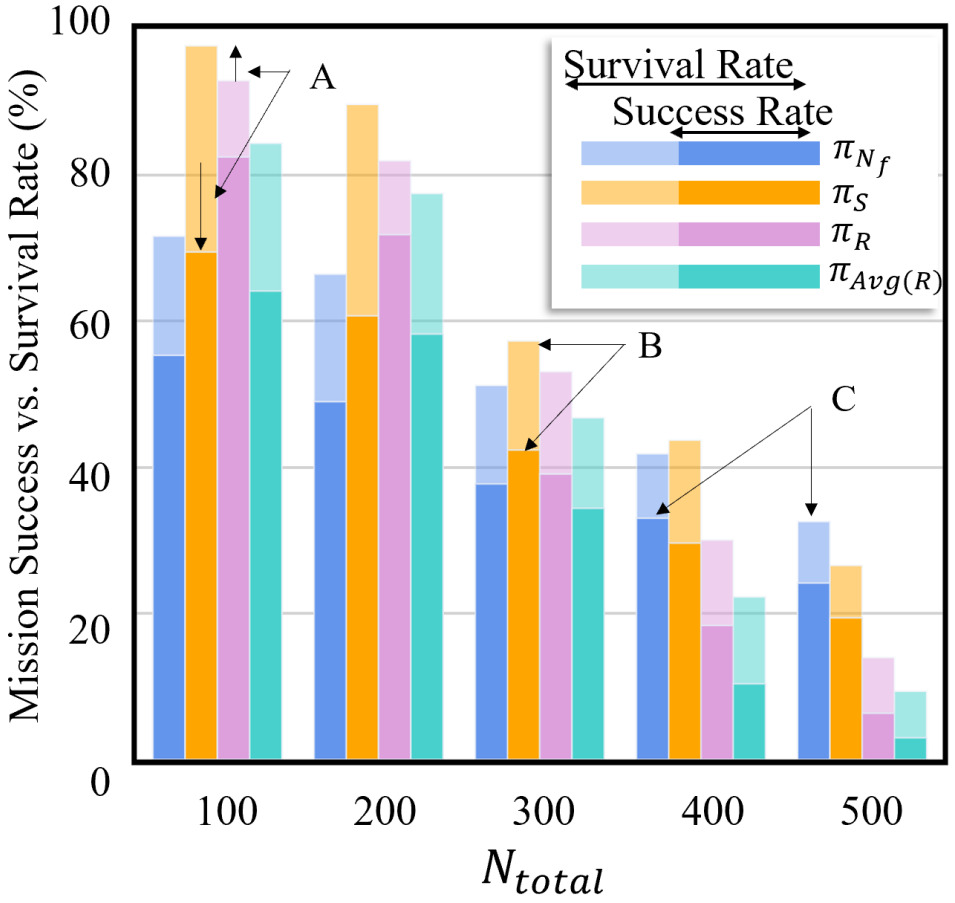
- Unknown intruders. They are unknown to the ownship until they appear in the environment based on a stochastic process. After that, they become completely known.

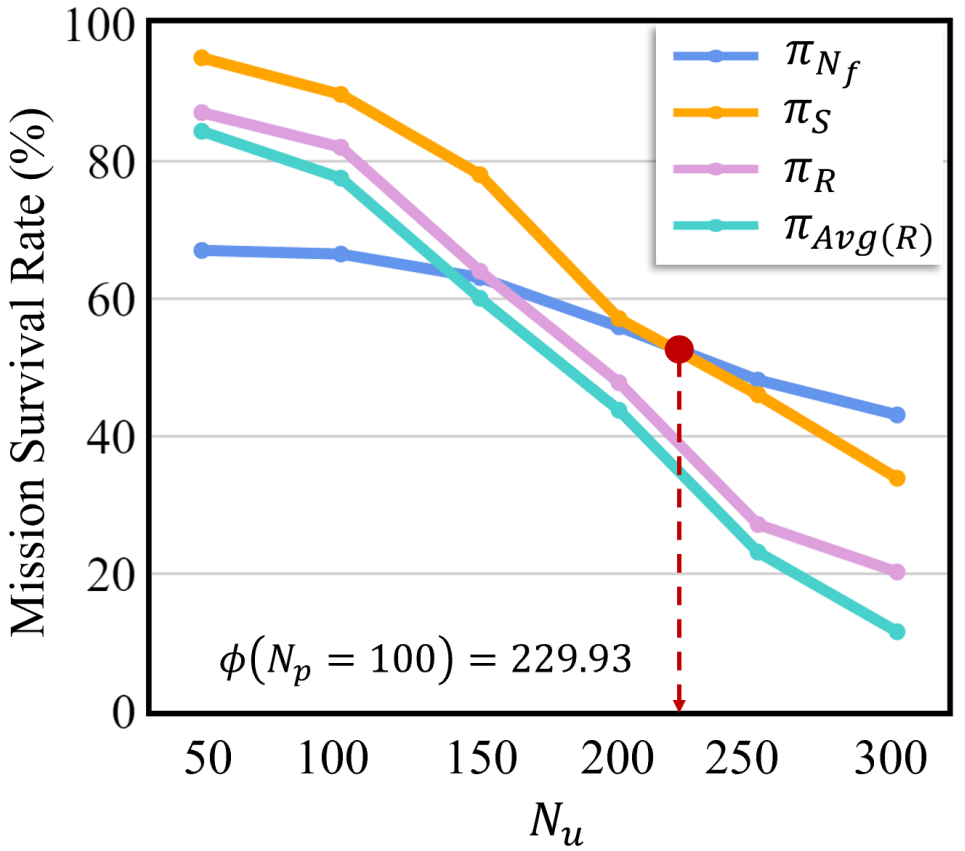
Number of intruders

Our experiment assesses 36 different traffic scenarios. Each scenario is characterized by the total number of partially known intruders Np 50; 100; 150; 200; 250; 300, and the total number of unknown intruders Nu 50; 100; 150; 200; 250; 300

Zeng, Idris and Clarke, "Trajectory Planning for Mission Survivability of Autonomous Vehicles in Moderately to Extremely Uncertain Environments", Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Trajectory Planning under Extreme Uncertainty

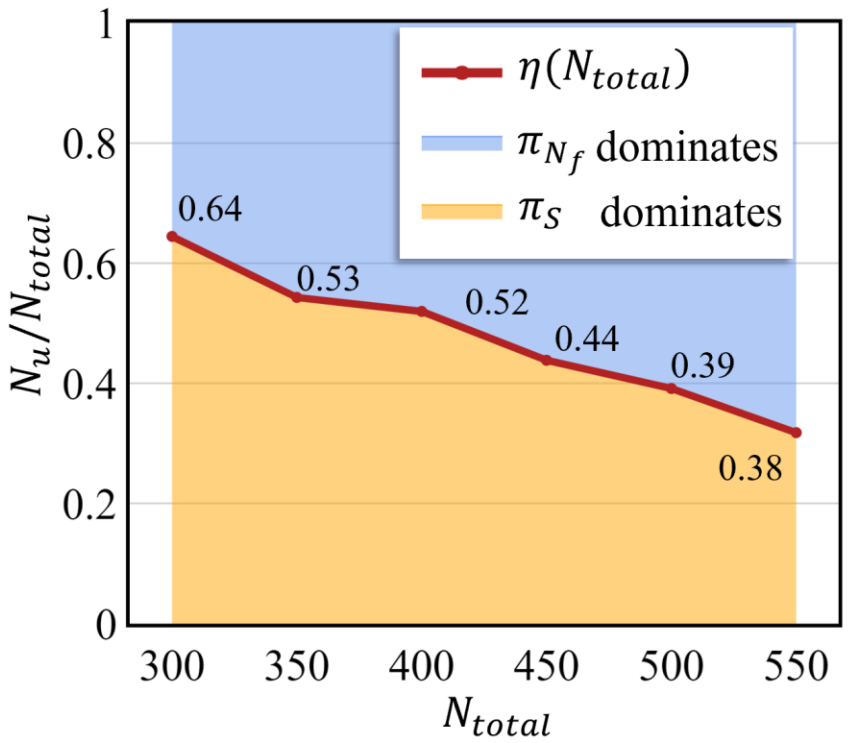


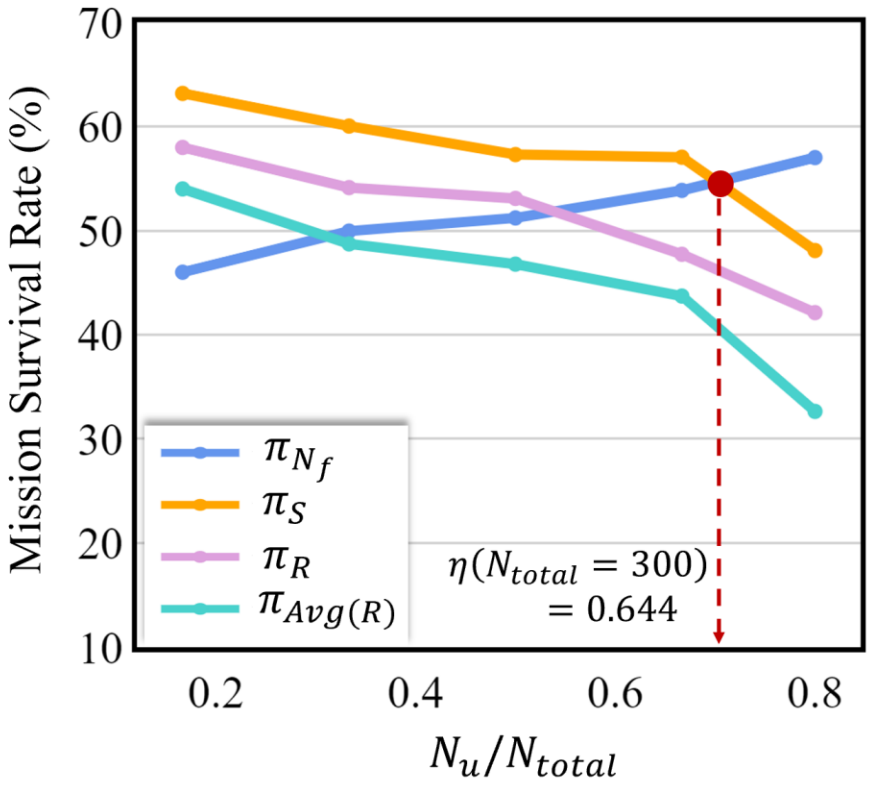


Zeng, Idris and Clarke, "Trajectory Planning for Mission Survivability of Autonomous Vehicles in Moderately to Extremely Uncertain Environments", Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Trajectory Planning under Extreme Uncertainty

- Maximizing the probability of having at least one trajectory to any of the valid landing site (Policy S) outperforms other policies when the vehicle is exposed to partially known uncertainty and moderate levels of unknown uncertainty.
  - Combines number and robustness of feasible trajectories
- Maximizing the total number of feasible trajectories (Policy N_f) yields the highest survival rates when operating environment is dominated by completely unknown events

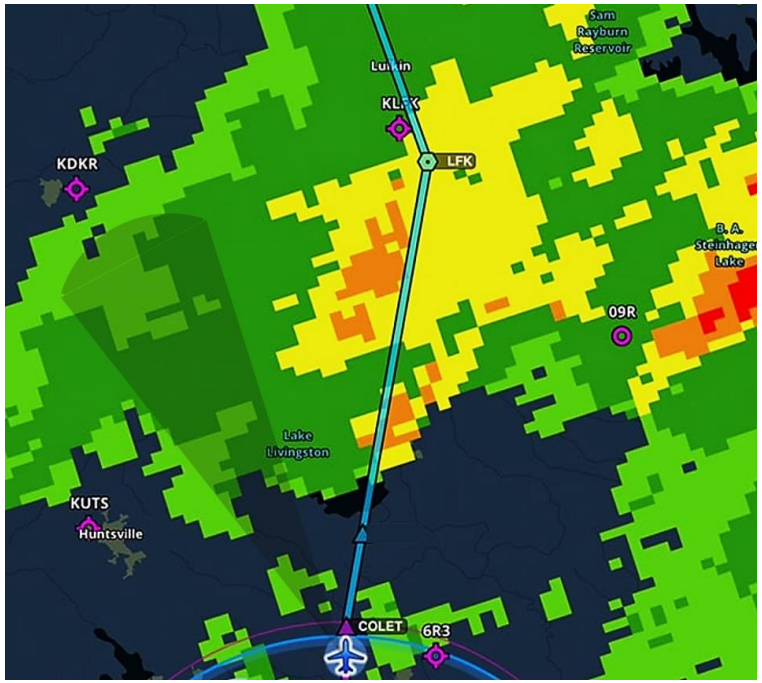




Zeng, Idris and Clarke, "Trajectory Planning for Mission Survivability of Autonomous Vehicles in Moderately to Extremely Uncertain Environments", Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)

Survivability Maps

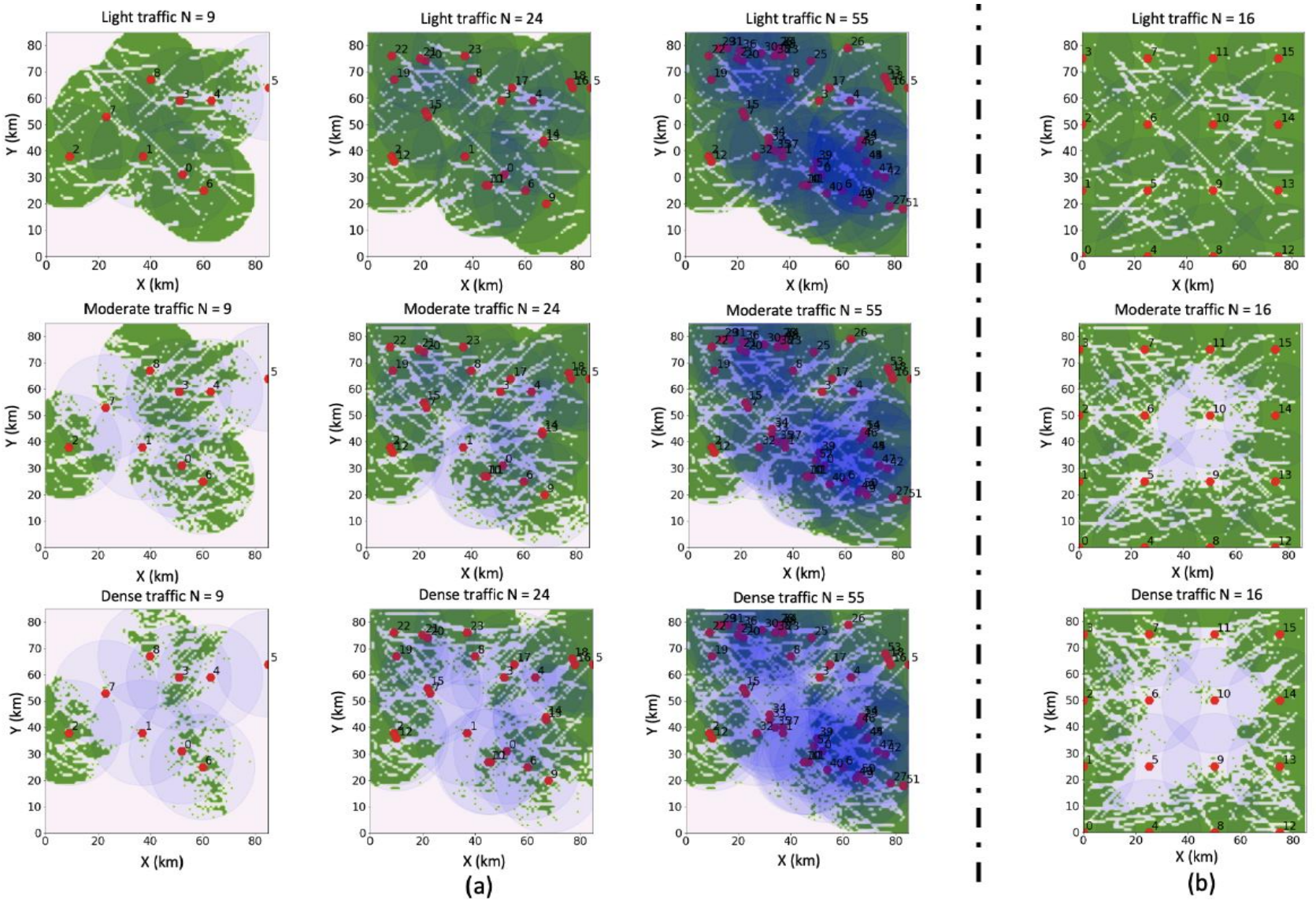
- Color represents probability of survival at each discrete cell (red lowest and dark green highest)
- Showed how survivability map depends on number of available ports (N), traffic congestions, vehicle maneuverability and vehicle lifetime



Zeng, Clarke and Idris, “A Methodology to Develop Survivability Maps for Autonomous Aerial Vehicles”, AIAA SciTech Forum 23-27 January 2023, National Harbor, MD & Online

Survivability Maps

- Color represents probability of survival at each discrete cell (red lowest and dark green highest)
- Showed how survivability map depends on number of available ports (N), traffic congestions, vehicle maneuverability and vehicle lifetime

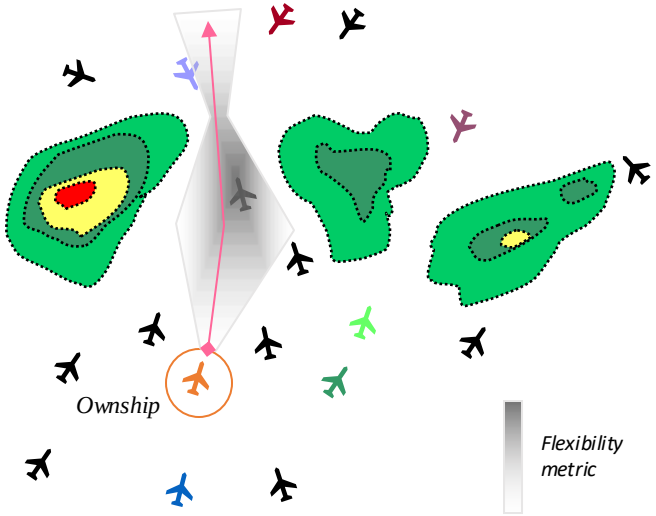


Zeng, Clarke and Idris, "A Methodology to Develop Survivability Maps for Autonomous Aerial Vehicles", AIAA SciTech Forum 23-27 January 2023, National Harbor, MD & Online

Flexibility for Complexity Mitigation

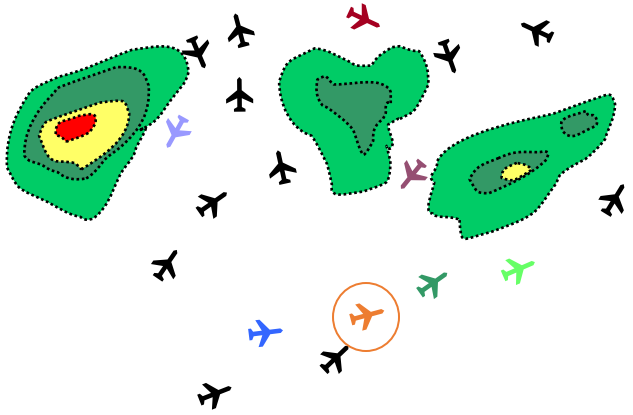
Flexibility preservation over flow management horizon: e.g. avoid congestion

Applicability of Trajectory Flexibility Prediction



Airborne flexibility function will question:
Do I have enough flexibility to safely proceed?
Can I modify my trajectory to increase my flexibility?
Do I need to avoid this airspace entirely and replan?

Trajectories Designed to Preserve Flexibility



Hypothesis:
If all aircraft apply flexibility preservation function, complexity automatically will be reduced

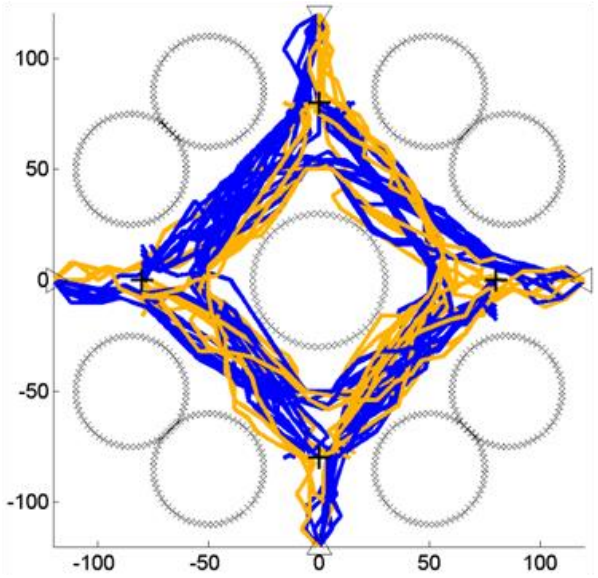
Idris H., Delahaye D., and Wing D., "Distributed Traffic Flexibility Preservation for Traffic Complexity Mitigation," 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa Valley, CA, 2009.

Flexibility for Complexity Mitigation

Preserving flexibility resulted in traffic pattern consistency and lower entropy measured by Lyapunov exponent

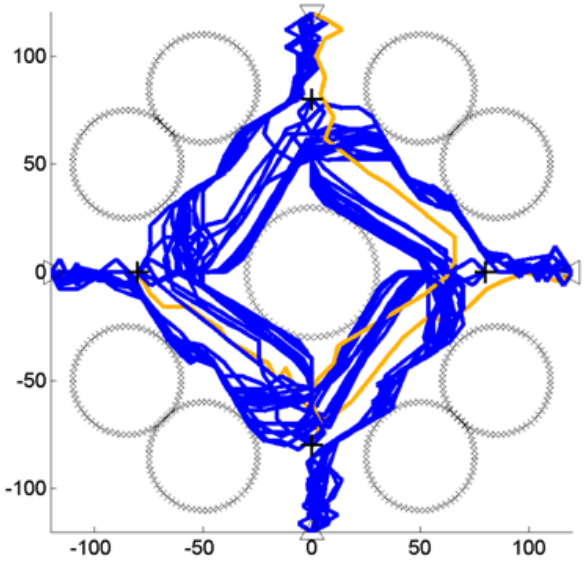
Shortest path with traffic avoidance

Pattern: 68% of aircraft counterclockwise (blue)



Maximum flexibility only

Pattern: 97% of aircraft counterclockwise (blue)



Scenario: Round about

- Four flows travel around round about
- Each aircraft meets an RTA at destination
- Each aircraft avoids hazards and preceding aircraft
- Each aircraft generates one trajectory upon entry (no dynamic planning) known exactly to other aircraft (no stochastic modeling)
- Origin to destination 200 nautical miles
- Speed range 240-360 knots with 10-knot increments
- Heading range +/- 60 degrees with 10-degree increments
- Separation zone set to 10 nautical miles to account for high uncertainty
- Time increment 2 minutes and grid cells 2x2 nautical miles

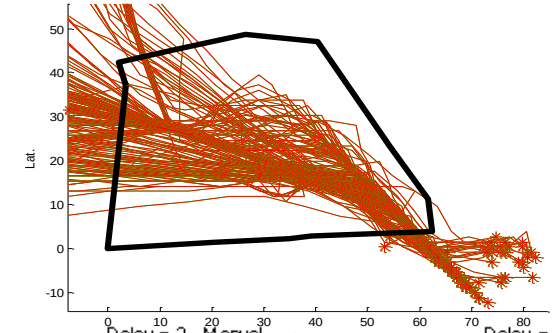
Idris H., Delahaye D., and Wing D., "Distributed Traffic Flexibility Preservation for Traffic Complexity Mitigation," 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa Valley, CA, 2009.

Airspace Capacity Estimation

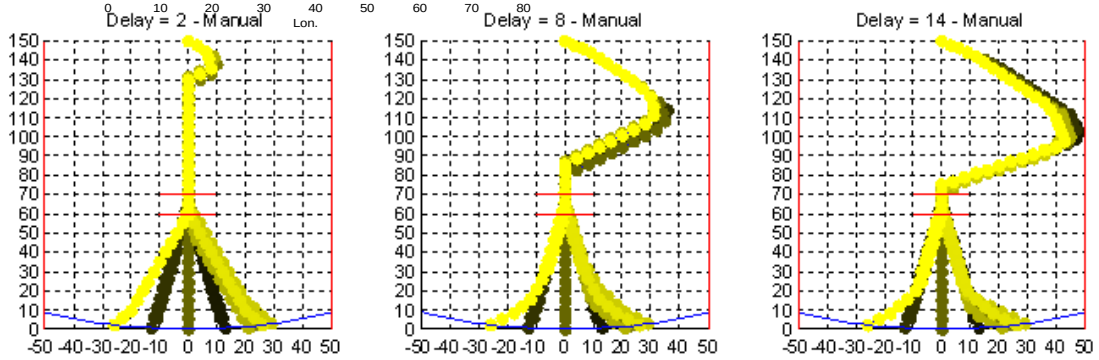
In this research two key elements were considered in order to derive generic capacity metrics

- (1) Tying airspace capacity to ability to mitigate risk of violating traffic management constraints
  - Any control scheme has to maintain safe and efficient operations
- (2) Accounting for cognitive factor in determining capacity
  - Airspace capacity is dependent on control strategy and its risk
  - Quantified risk tolerance in control strategy and related it to capacity
  - Control strategy may represent current or future control schemes: human control, automation control, automation assisted control, static or dynamic configuration of airspace and flow structures, etc.

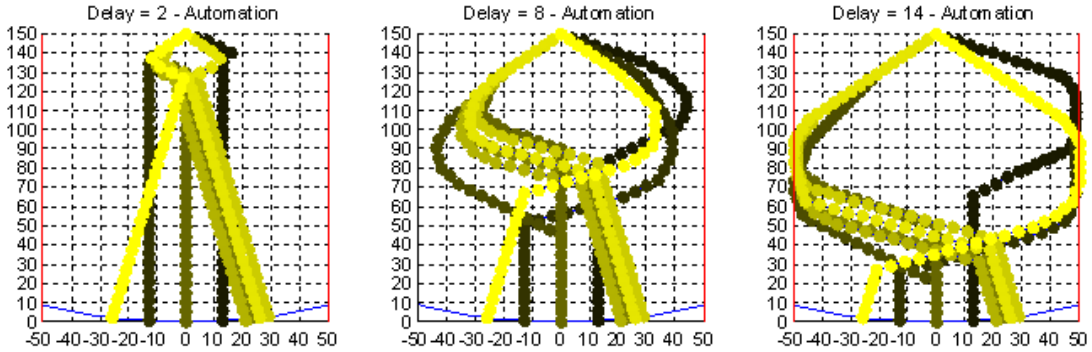
Flexibility versus Capacity Analysis



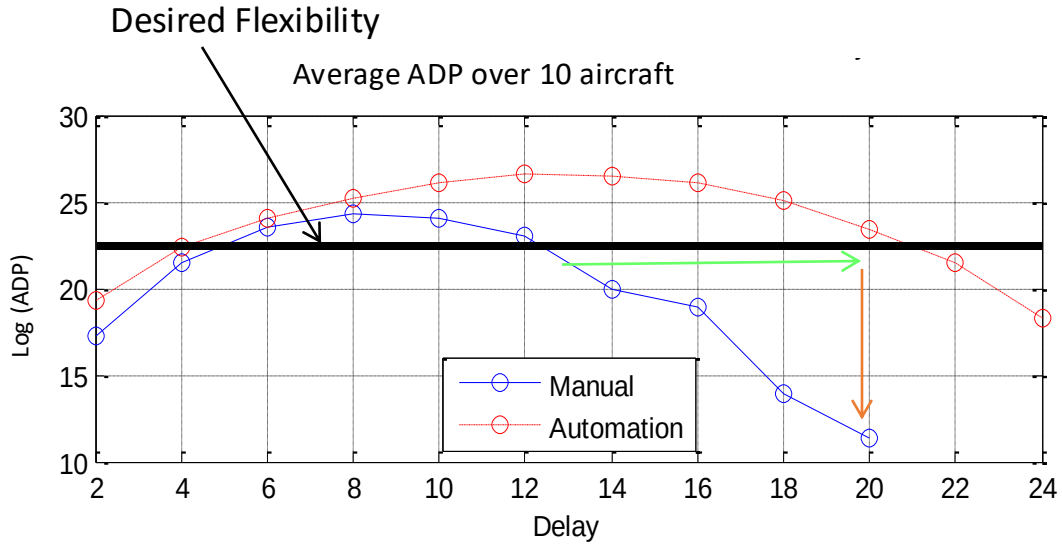
Manual Delay Strategy



Automation Delay Strategy



- Maximum delay capacity can be inferred at zero flexibility
- More delay can be absorbed with automation relative to human strategy because of increased degrees of freedom
- Automation strategy achieves higher flexibility at similar capacity limits - Automation considers more solutions to mitigate risk
- Automation failure can result in extreme low flexibility to handle increased capacity with human strategy



Idris H. and Shen N., "Estimating Airspace Capacity Based on Risk Mitigation Metrics," Presented at the 10th USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL, 2013.

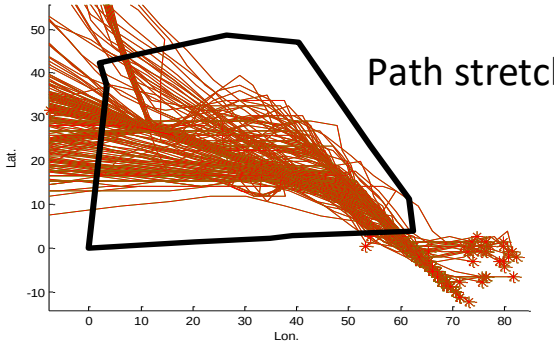
Flexibility versus Capacity Analysis

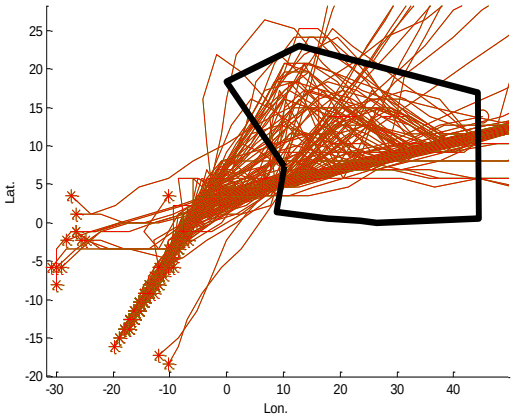
- Controller switching to holding aircraft indicates reaching capacity limit of path stretch control strategy as perceived by controllers
- Larger sector ZAU74 switched to holding at higher ADP relative to smaller sector ZAU26 - Controllers may not use all available sector area for path stretch before holding

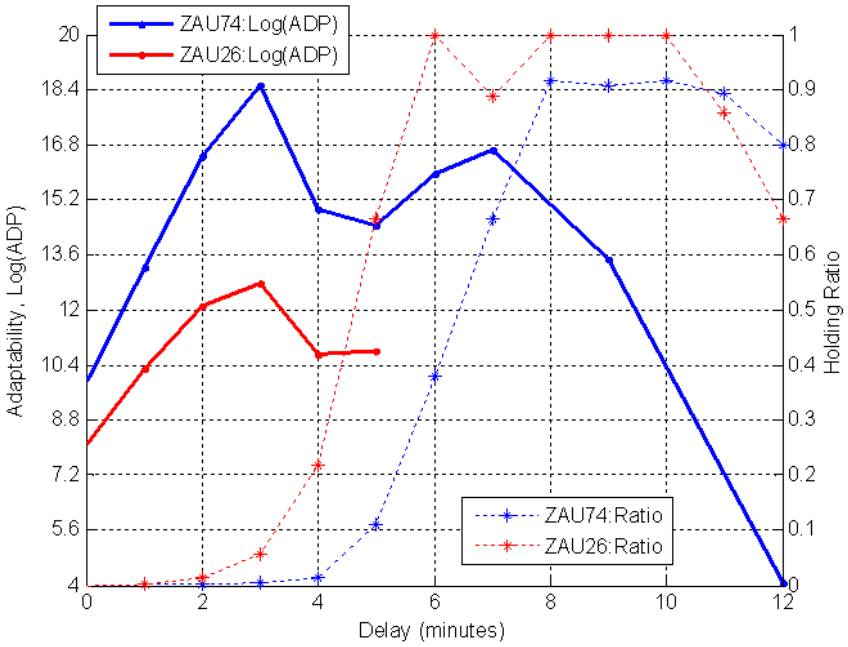
ZAU74

ZAU26

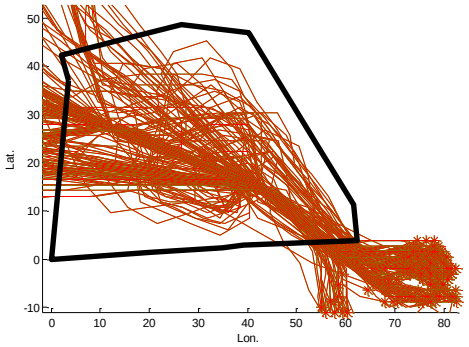
Path stretching

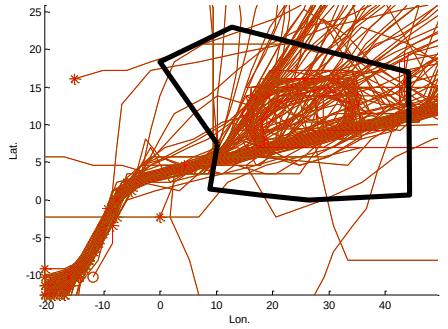






Holding patterns

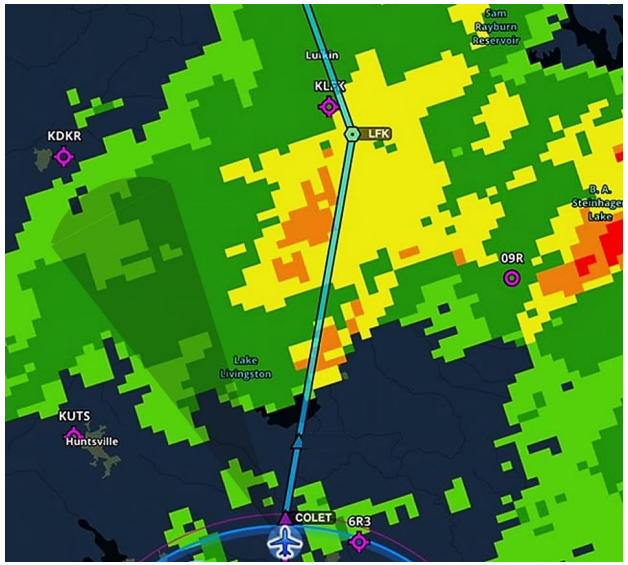




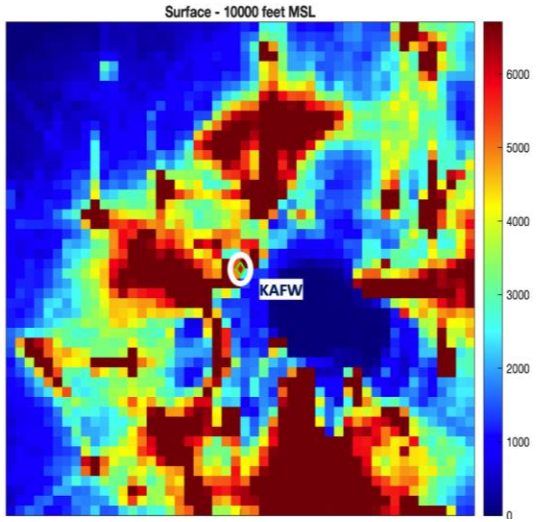
Idris H. and Shen N., "Estimating Airspace Capacity Based on Risk Mitigation Metrics," Presented at the 10th USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL, 2013.

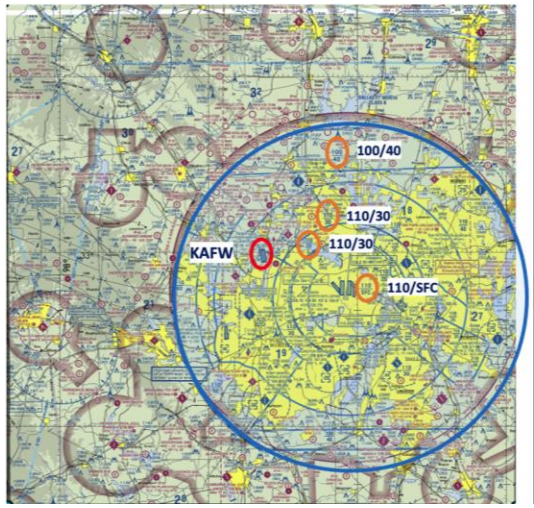
Next Steps

- Building flexibility and survivability metrics/maps for Lost C2 Link contingency management accounting for risk from VFR traffic



+





Zeng, Clarke and Idris, "A Methodology to Develop Survivability Maps for Autonomous Aerial Vehicles", AIAA SciTech Forum 23-27 January 2023, National Harbor, MD & Online

Characterization of VFR traffic patterns and uncertainties – identifying spatial and temporal concentrations and gaps of VFR traffic (Bulusu, et al AIAA Aviation Forum 2023)

- Collaborating with DLR on applying flexibility and survivability metrics for quantifying safety hazards such as loss of thrust

References

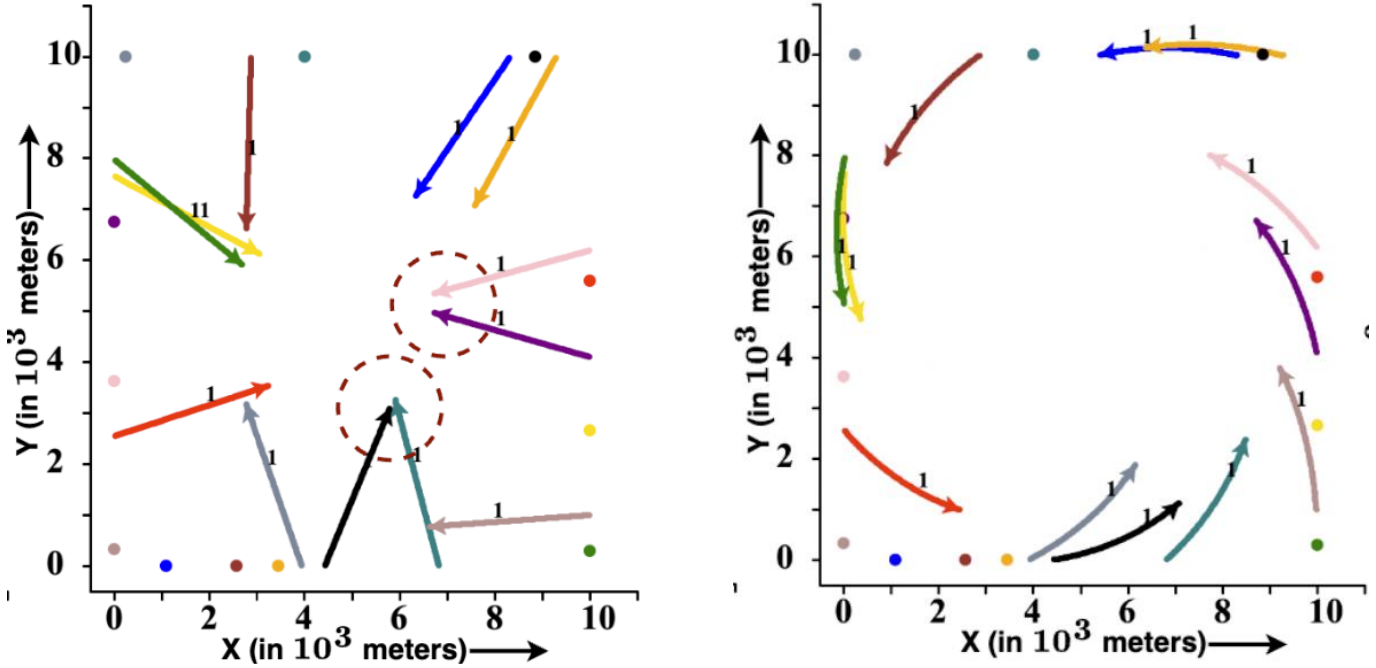
- Idris H. and Shen N., "Estimating Airspace Capacity Based on Risk Mitigation Metrics," Presented at the 10th USA/Europe Air Traffic Management Research and Development Seminar, Chicago, IL, 2013.
- Shen N. and Idris H., "Tradeoff between Airspace Capacity and Risk Mitigation," Presented at the AIAA Guidance Navigation and Control (GNC) conference, Boston, MA, 2013.
- Idris H., Shen N., and Wing D., "Complexity Management Using Metrics for Trajectory Flexibility Preservation and Constraint Minimization," Presented at the Aviation Technology, Integration and Operations (ATIO), Hampton, VA, 2011.
- Idris H., Shen N., and Wing, D., "Improving Separation Assurance Stability through Trajectory Flexibility Preservation," presented at the Aviation Technology, Integration and Operations (ATIO), Fort Worth, TX, 2010.
- Idris H., "Organizing Metroplex Traffic based on Speed Segregation and Trajectory Flexibility," presented at the 27th Congress of the International Council of the Aeronautical Sciences (ICAS), Nice, France, 2010.
- Idris H., and Vivona R., "Metrics for Traffic Complexity Management in Self-Separation Operations," Air Traffic Control Quarterly, Volume 17, Number 1, 2009.
- Idris H., Delahaye D., and Wing D., "Distributed Traffic Flexibility Preservation for Traffic Complexity Mitigation," 8th USA/Europe Air Traffic Management Research and Development Seminar, Napa Valley, CA, 2009.
- Idris H, Shen N., El-Wakil T., and Wing D., "Analysis of Trajectory Flexibility Preservation on Traffic Complexity," Presented at the AIAA Guidance Navigation and Control (GNC) Conference, Chicago, IL, 2009.
- Idris H, El-Wakil T., and Wing D., "Trajectory Planning by Preserving Flexibility: Metrics and Analysis," Presented at the AIAA Guidance Navigation and Control (GNC) Conference, AIAA-2008-7406, Honolulu, HI, 2008.
- Idris H., Wing D., Vivona R., and Garcia-Chico J.L., "A Distributed Trajectory-Oriented Approach to Managing Traffic Complexity," Presented at the 7th AIAA Aviation Technology Integration and Operations (ATIO) Conference, AIAA-2007-7731, Belfast, Northern Ireland, 2007.
- Idris H., Vivona R., Garcia-Chico J.L., and Wing D., "Distributed Traffic Complexity Management by Preserving Trajectory Flexibility," Presented at the 26th Digital Avionics Systems Conference, Dallas, TX, 2007.

Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Motivation

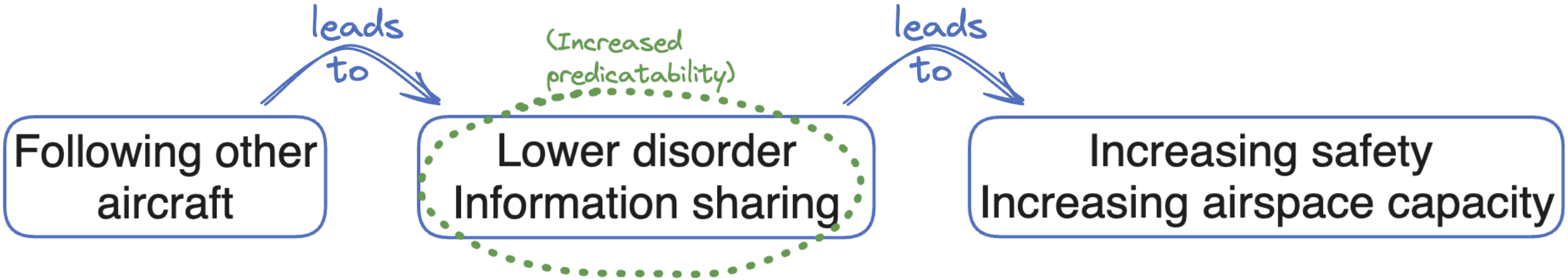
- Several characteristics of “good” multi-agent autonomous systems such as safe, efficient, timely, expedient, have been studied
- One that is identified but less explored is “order” or “chaos”
- Pilots follow traffic patterns; controllers maintain orderly traffic



Motivation

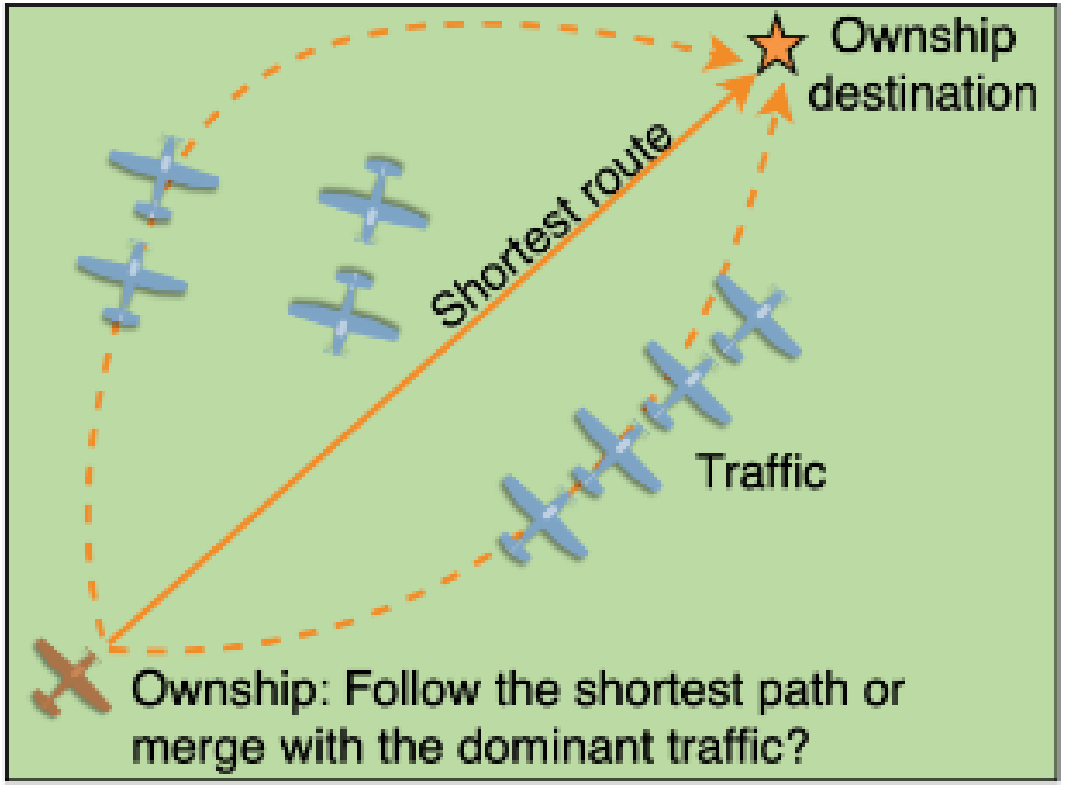
- Overall, an orderly behavior could be following other aircraft to:
  - Lower disorder
  - Share information

- Orderly behavior may result in **increased safety and airspace capacity**



Research Question

- When should an ownship follow aircraft as opposed to going its own way?
  - Which factors affect this decision?
  - How do we measure the ultimate benefits?
  - How do we optimize the transition to and from “following” behavior?
- Overall, when and how does structure emerge dynamically through autonomous decisions without being imposed a priori?



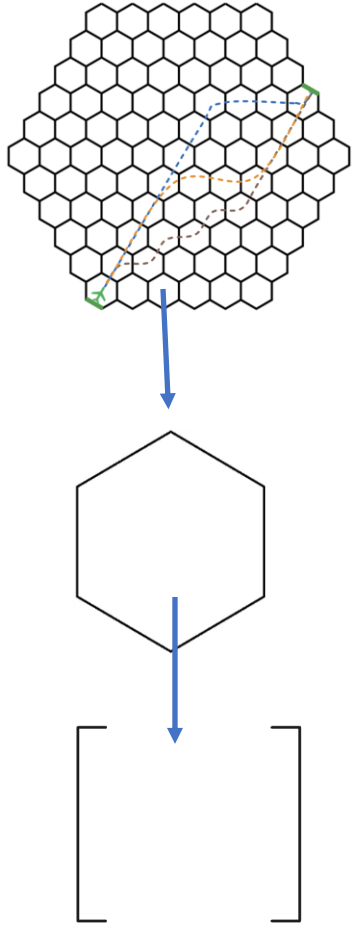
Anahita Jain, Husni Idris and J-P Clarke, submitted to ICRAT 2024

Concept

- By observing the flow of traffic over time, build a traffic entropy/disorder map of the airspace
- The map is used by an ownship to decide whether to follow traffic or not
- Currently, we are measuring disorder only in terms of the direction of traffic (“directionality”) and the number of aircraft in a direction
  - In the future, we plan on incorporating other traffic “similarity” characteristics (such as speed, equipage, …)
- Currently traffic information has constant value over time
  - In the future, we plan to discount older traffic information

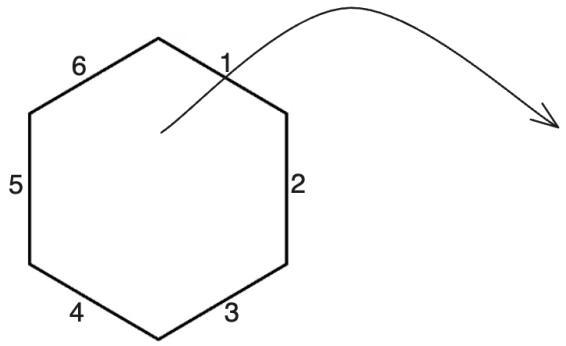
Problem Formulation

1. Divide the airspace into a hexagonal grid/map
2. Each cell in this map has a cost (utility) function associated with it. This cost is dependent on 2 factors:
   - Unimpeded transit between cell entry-exit – denoted U
   - Historic traffic through the cell along different directions – denoted T
3. A gain constant, k_t, weighs the "pull/attraction" an ownship undergoes from cells with traffic
4. A repulsion model is used to ensure minimum separation
5. Using Dijkstra's algorithm, an ownship finds the least costly path through cells to reach its destination



Approach – U matrix

- Each cell has a 6x6 unimpeded matrix associated with it
- The U matrix contains the cost of unimpeded (by traffic) transit between each entry-exit pairing in a cell

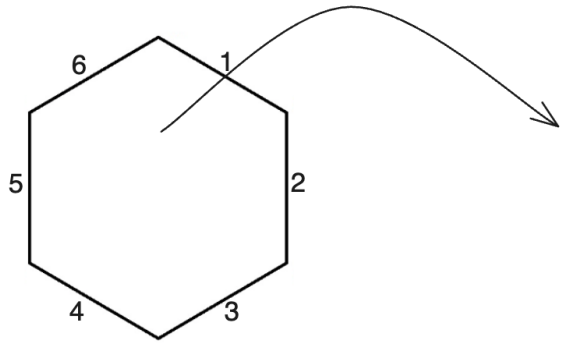


$$U = \begin{bmatrix} u_{1,1} & u_{1,2} & u_{1,3} & u_{1,4} & u_{1,5} & u_{1,6} \\ u_{2,1} & u_{2,2} & u_{2,3} & u_{2,4} & u_{2,5} & u_{2,6} \\ u_{3,1} & u_{3,2} & u_{3,3} & u_{3,4} & u_{3,5} & u_{3,6} \\ u_{4,1} & u_{4,2} & u_{4,3} & u_{4,4} & u_{4,5} & u_{4,6} \\ u_{5,1} & u_{5,2} & u_{5,3} & u_{5,4} & u_{5,5} & u_{5,6} \\ u_{6,1} & u_{6,2} & u_{6,3} & u_{6,4} & u_{6,5} & u_{6,6} \end{bmatrix}$$

where each element can be individually adjusted based on winds, weather, and other factors, not including traffic impacts

Approach – T matrix

- Each cell has a 6x6 traffic matrix associated with it
- This matrix keeps track of all traffic transitions between each entry-exit pairing



$$T = \begin{bmatrix} t_{1,1} & t_{1,2} & t_{1,3} & t_{1,4} & t_{1,5} & t_{1,6} \\ t_{2,1} & t_{2,2} & t_{2,3} & t_{2,4} & t_{2,5} & t_{2,6} \\ t_{3,1} & t_{3,2} & t_{3,3} & t_{3,4} & t_{3,5} & t_{3,6} \\ t_{4,1} & t_{4,2} & t_{4,3} & t_{4,4} & t_{4,5} & t_{4,6} \\ t_{5,1} & t_{5,2} & t_{5,3} & t_{5,4} & t_{5,5} & t_{5,6} \\ t_{6,1} & t_{6,2} & t_{6,3} & t_{6,4} & t_{6,5} & t_{6,6} \end{bmatrix}$$

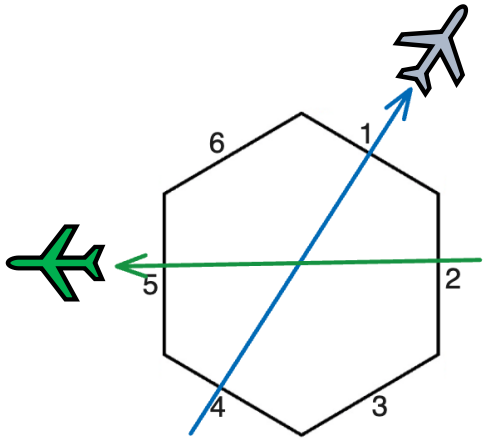
where the duration of the observation period may be adjusted and/or weighted based on age

Approach – T matrix

- Every time an aircraft transits in and out of a cell, the associated traffic matrix is updated for the respective entry-exit pairing
- Discounting by time can be used to favor more recent traffic patterns

e.g., in the beginning at t_0 the cell has no entries

$$T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$



then at t_1 if the cell sees two aircraft traverse it in directions 4-1 and 2-5

the traffic matrix updates to

$$T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Approach – Cost matrix

- Then the matrix containing the transition cost between each entry-exit pairing of a cell is

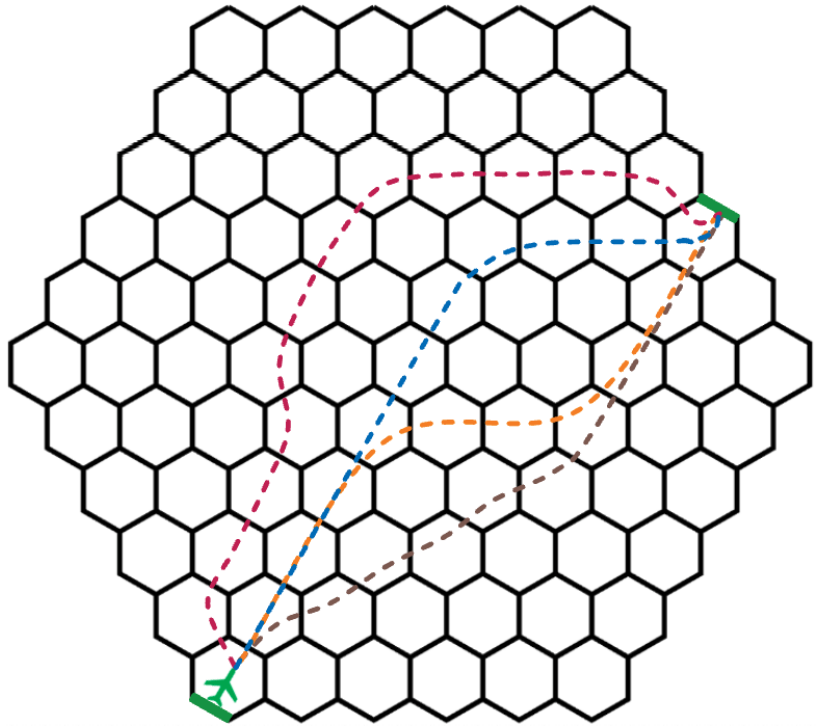
$$C = U + \left[\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} - k_t \frac{T}{\sum_{N,X} t_{N,X}} \right]$$

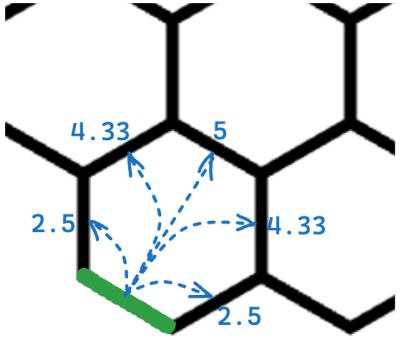
where the traffic gain, k_t, is an adjustable parameter and $\sum_{N,X} t_{N,X}$ is the grand sum of matrix T

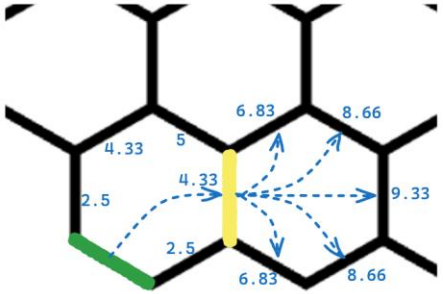
- This traffic gain weighs how costly cells with traffic are and therefore **by varying this gain, we can vary how attractive traffic is to an ownship**

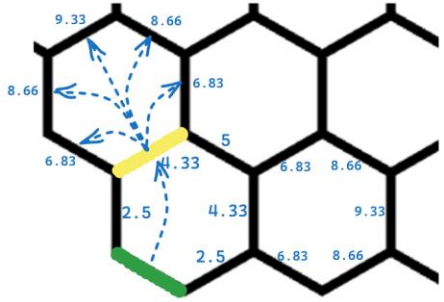
Path planning

- There are many different paths with different costs an ownship can take to get to the destination as are shown in the map
- To find the least costly path of transit between cells, an ownship uses Dijkstra's algorithm for path-planning



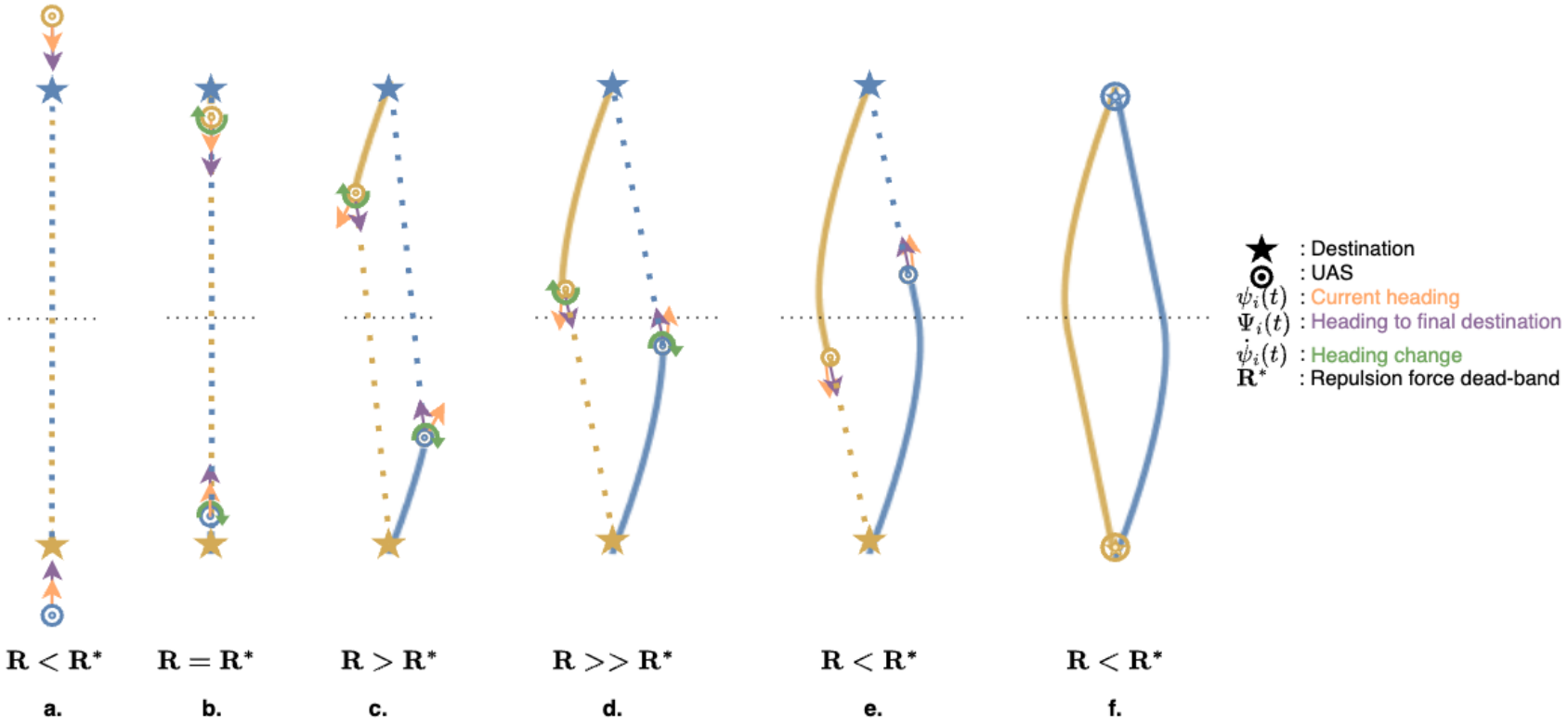






Repulsion algorithm

$$R_i(t) = \sum_{j=1}^{N} \left[\frac{k_r}{|r_{ij}(t)|^2} + k_{\dot{r}} \max\left(0, -\frac{\dot{r}_{ij}(t) \cdot r_{ij}(t)}{|r_{ij}(t)|}\right) \right], \forall j \neq i$$



Jain, Anahita, John-Paul Clarke, and Fanruiqi Zeng. "Non-Communicative Negotiation-Free Collision Avoidance." *AIAA AVIATION 2023 Forum*. 2023

Entropy Metric

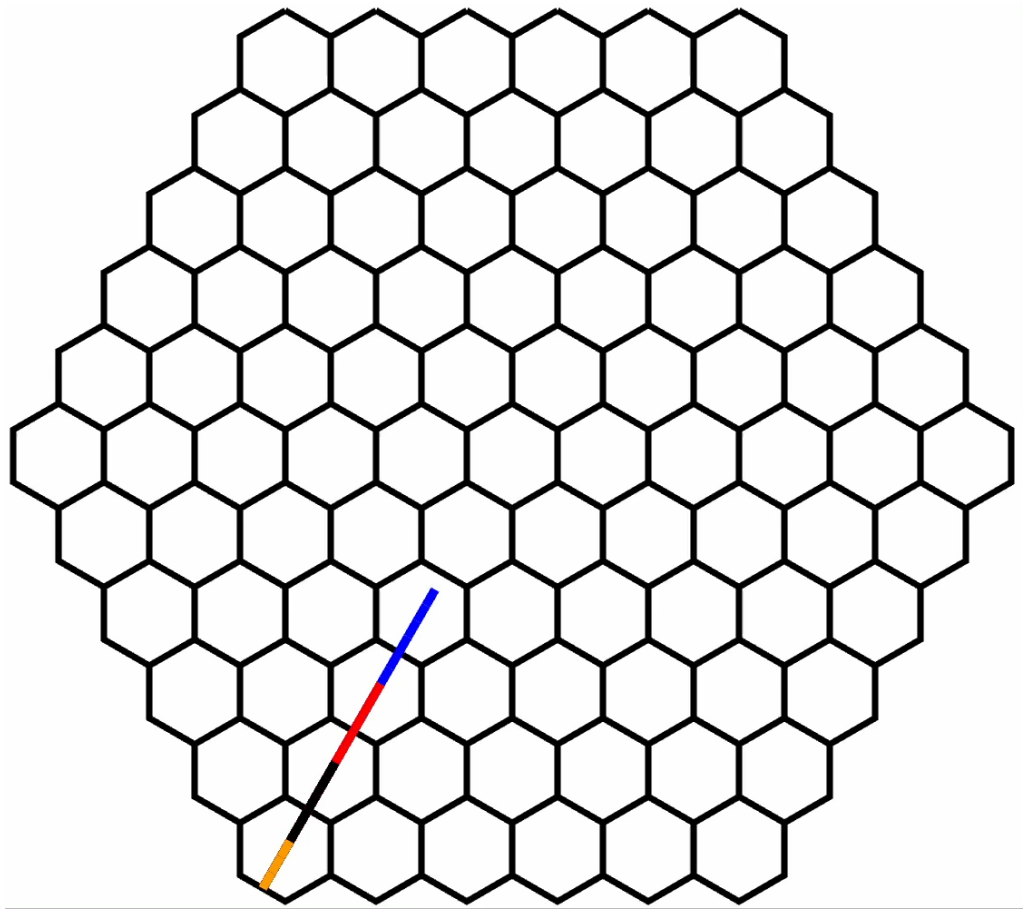
- In general, entropy is defined as the lack of order (“disorder”) in a system
- In information theory, the entropy of a random variable is the average level of “information”, “surprise”, or “uncertainty” inherent to the variable’s possible outcomes
- For a discrete random variable X that is distributed as $p: \mathcal{X} \to [0, 1]$ the entropy is $\mathrm{H}(X) := -\sum_{x \in \mathcal{X}} p(x) \log p(x) = \mathbb{E}[-\log p(X)]$

Currently only measuring entropy in directionality (consistency in traffic direction)

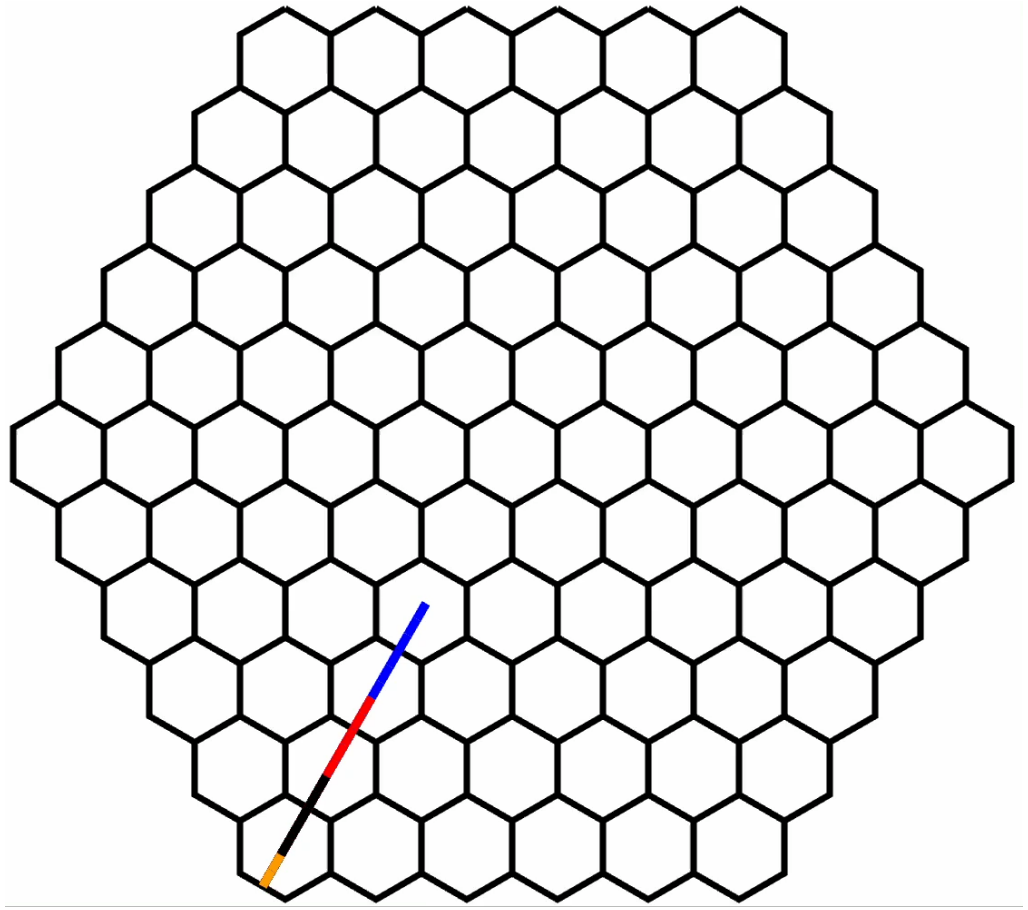
$$T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{H(T)} = \tfrac{1}{2} \log(1/2) \times 2$$

Simulation – Single Ownship

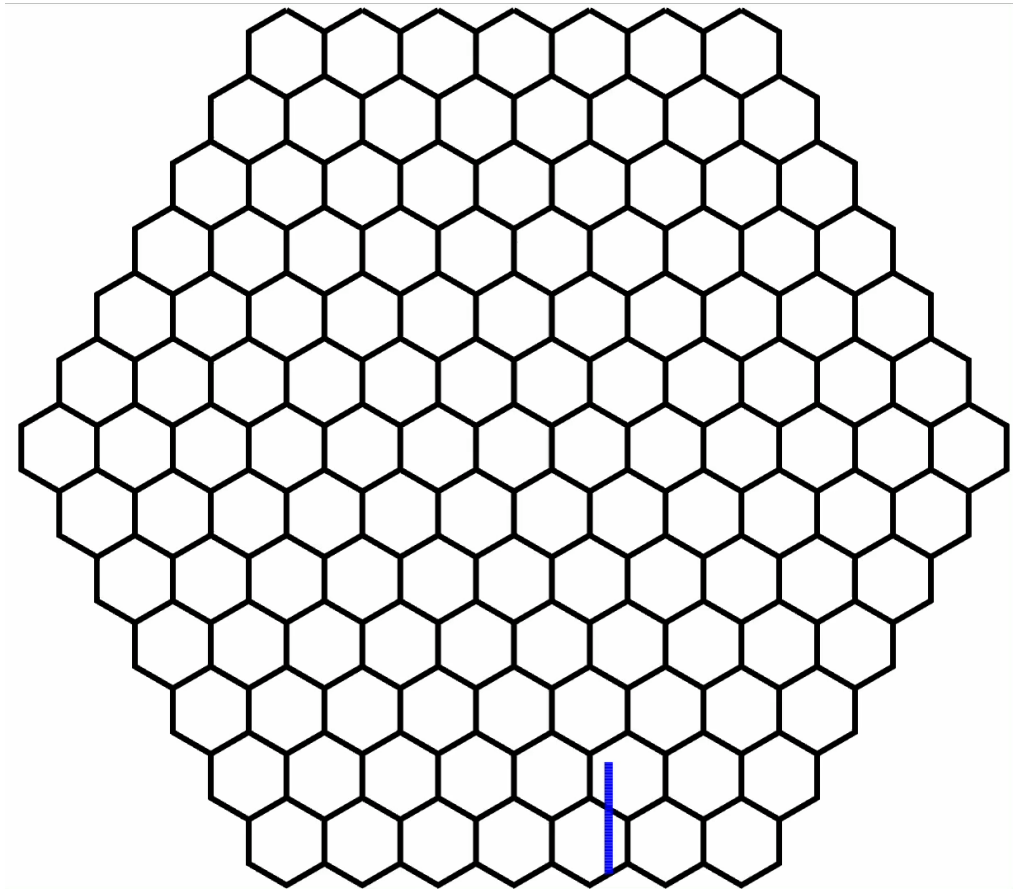


Trajectory of ownship (orange) when cells with traffic are not less costly

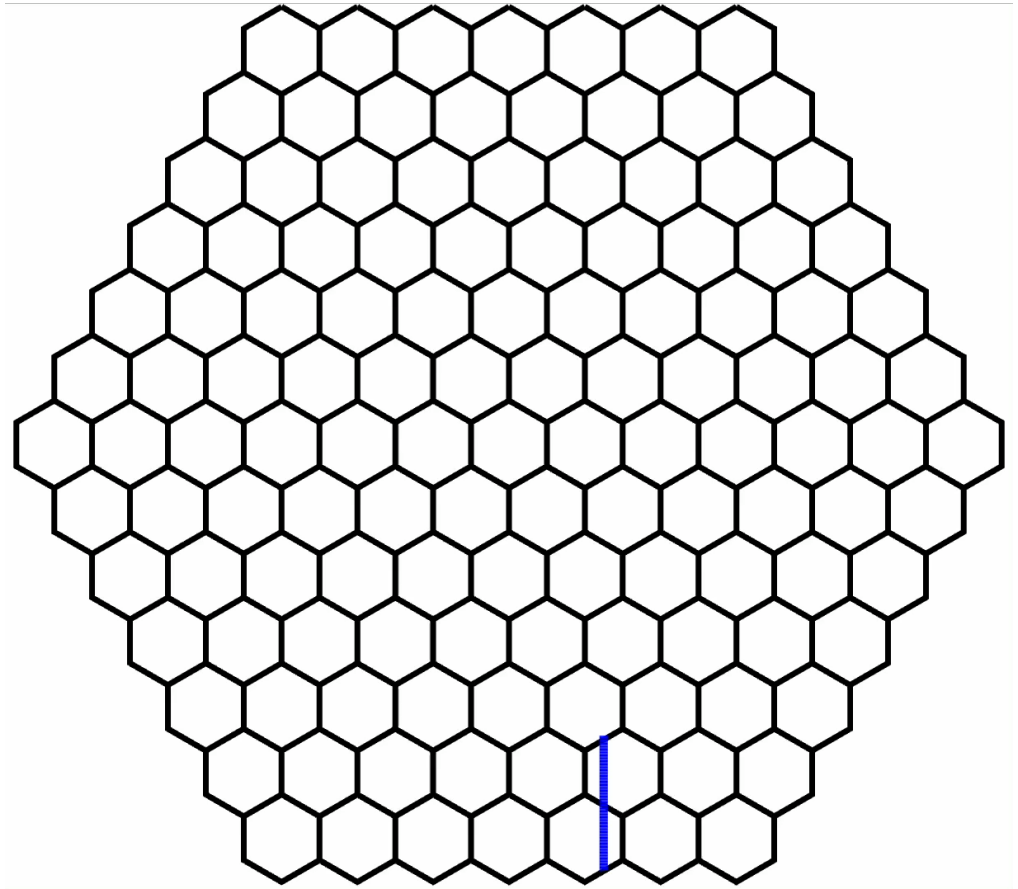


Trajectory of ownship (orange) when cells with traffic are less costly

Simulation – All Ownship

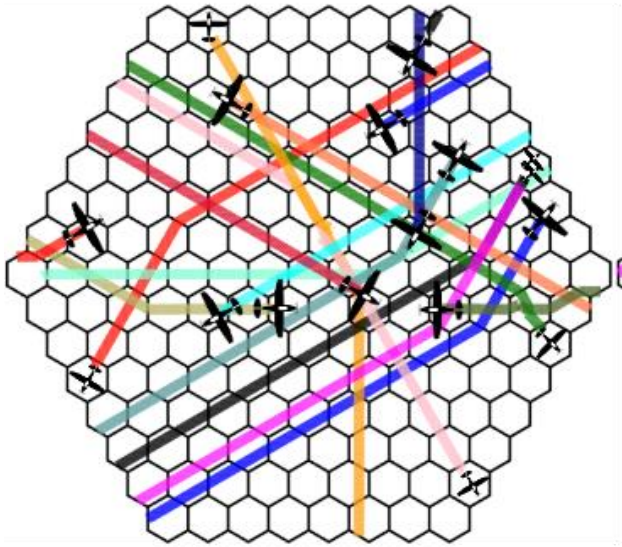


Trajectory of ownship when cells with traffic are not less costly

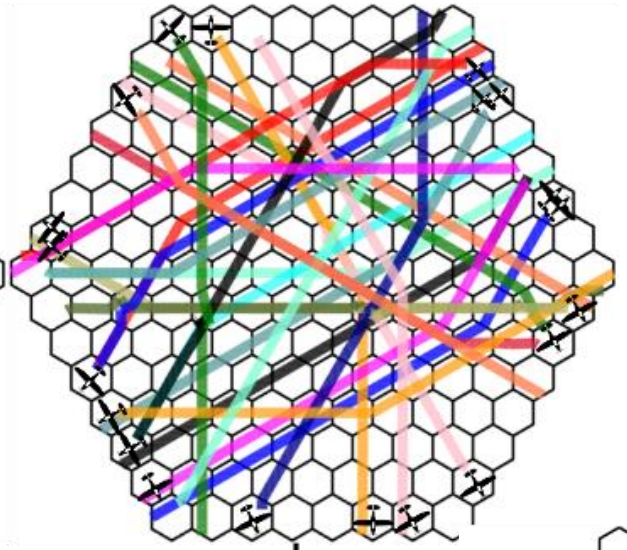


Trajectory of ownship when cells with traffic are less costly

Results – Emergence of Structure



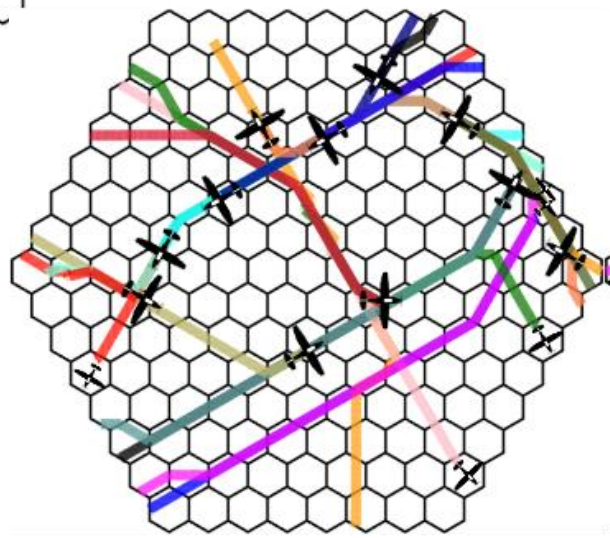
a.



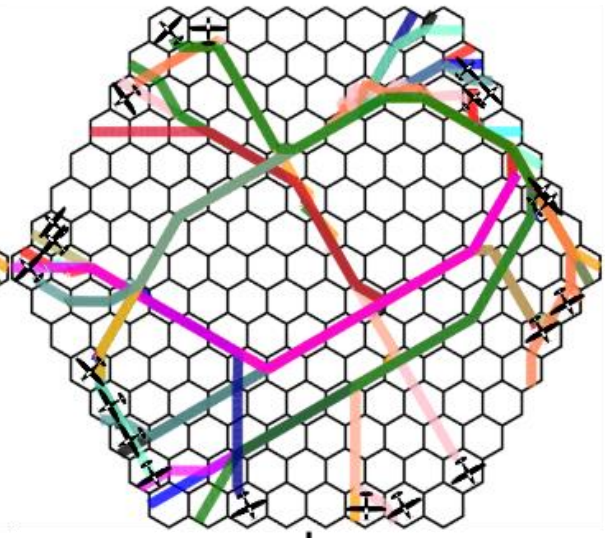
b.

Without following

With following

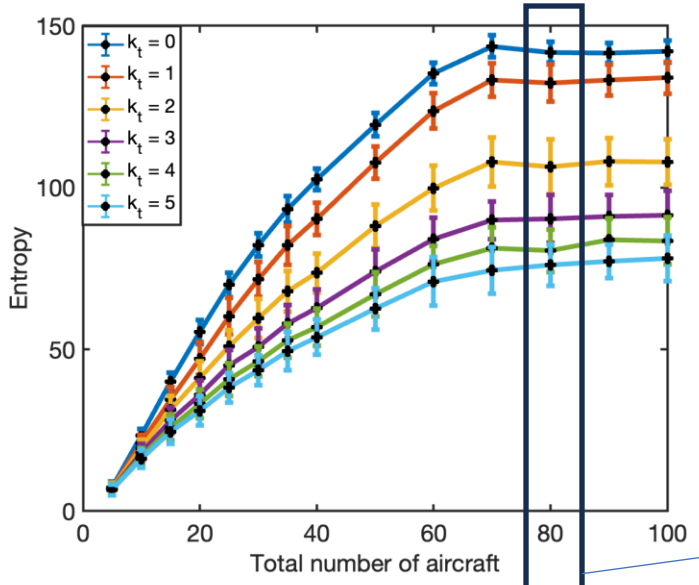


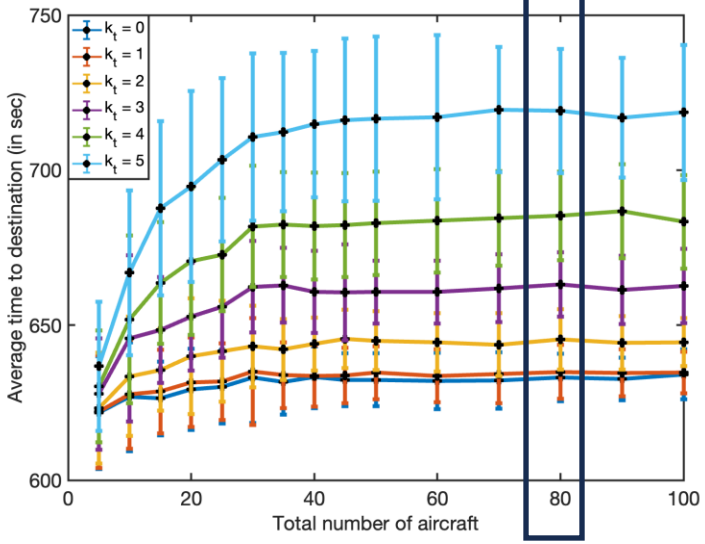
c.

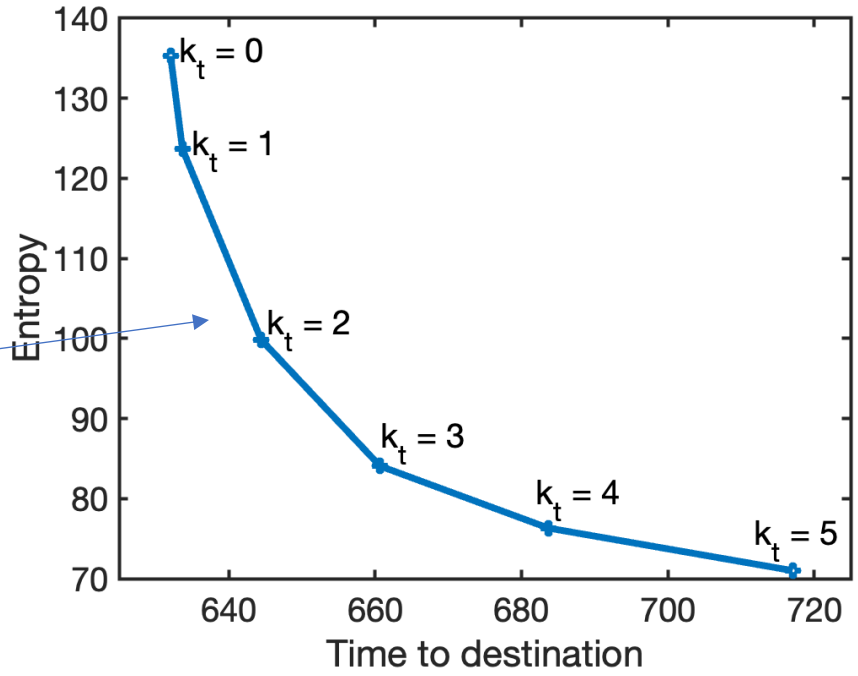


d.

Preliminary Results – Tradeoff between Entropy and Time at Low Traffic Density







Next Steps

- Analyze tradeoff between entropy and time under high traffic densities
- Discount traffic pattern information by time
- Extend to predictive traffic maps based on traffic intent information and its uncertainty
- Extend to speed degree of freedom
- Apply to real traffic scenarios such as integration with historical VFR traffic patterns

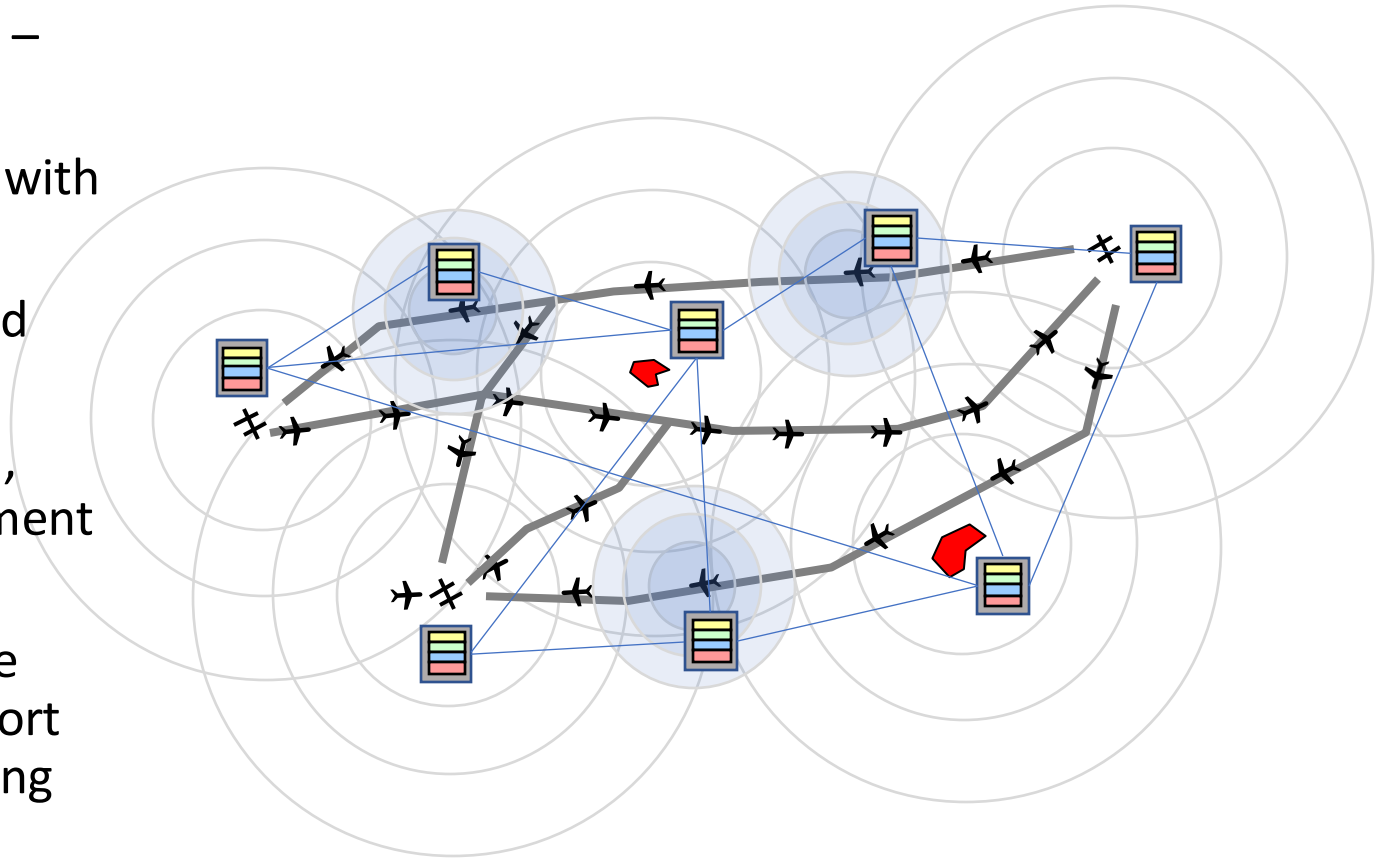
Outline

- Motivation for Autonomy
- Use Cases: Auto-Cargo and Urban Air Mobility
- Autonomy Framework and Gaps
- Dynamic Functional Allocation
- Metrics and Models for Collective Autonomy
  - Task complexity for multi-vehicle operations
  - Flexibility and survivability under extreme uncertainty
  - Entropy, convoy operations, dynamic structure emergence
  - Delay propagation in closed network models

Integrated Network Management

Motivation

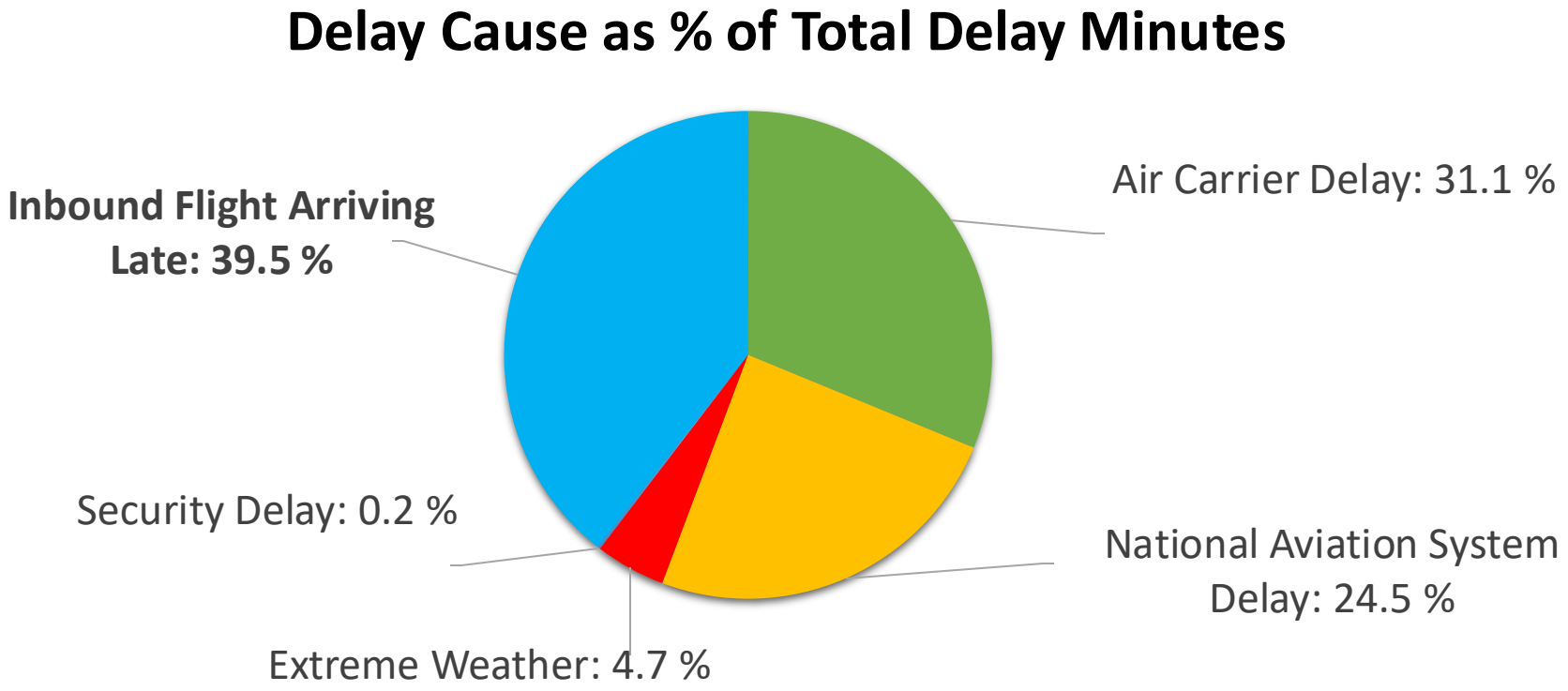
- Account for connectivity of vehicle, crew, passengers, and other propagation factors – Focus here is on vehicle connectivity
- Model system as closed network of nodes with vehicles circulating through
- Vehicle-oriented rather than flight-oriented perspective
- Integrate operator fleet management (e.g., routing/connectivity) with traffic management (e.g., node scheduling)
- Mitigate delay propagation through vehicle turnaround and during flight – airlines report ~40% of delays due to inbound flight arriving late



Idris H., Chin C., and Evans A., "Integration of Network Scheduling Using Accrued Delay Across Vehicle Connectivity," Journal of Air Transportation, Vol. 29, No. 1, January–March 2021

Motivation: Network Delay Propagation

Late arriving aircraft from inbound flight are major source of delay



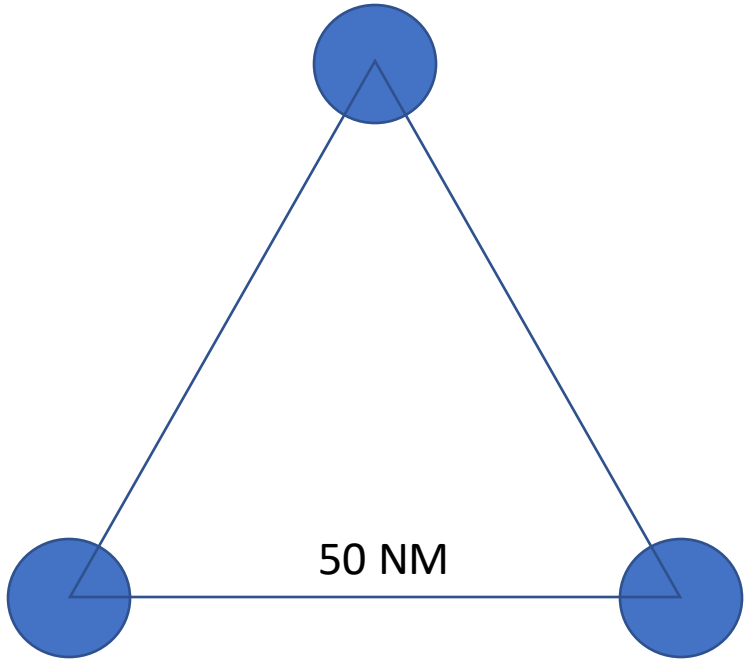
Source: Airline Service Quality Performance (ASQP), May 2017- May 2018

Accrued Delay Concept

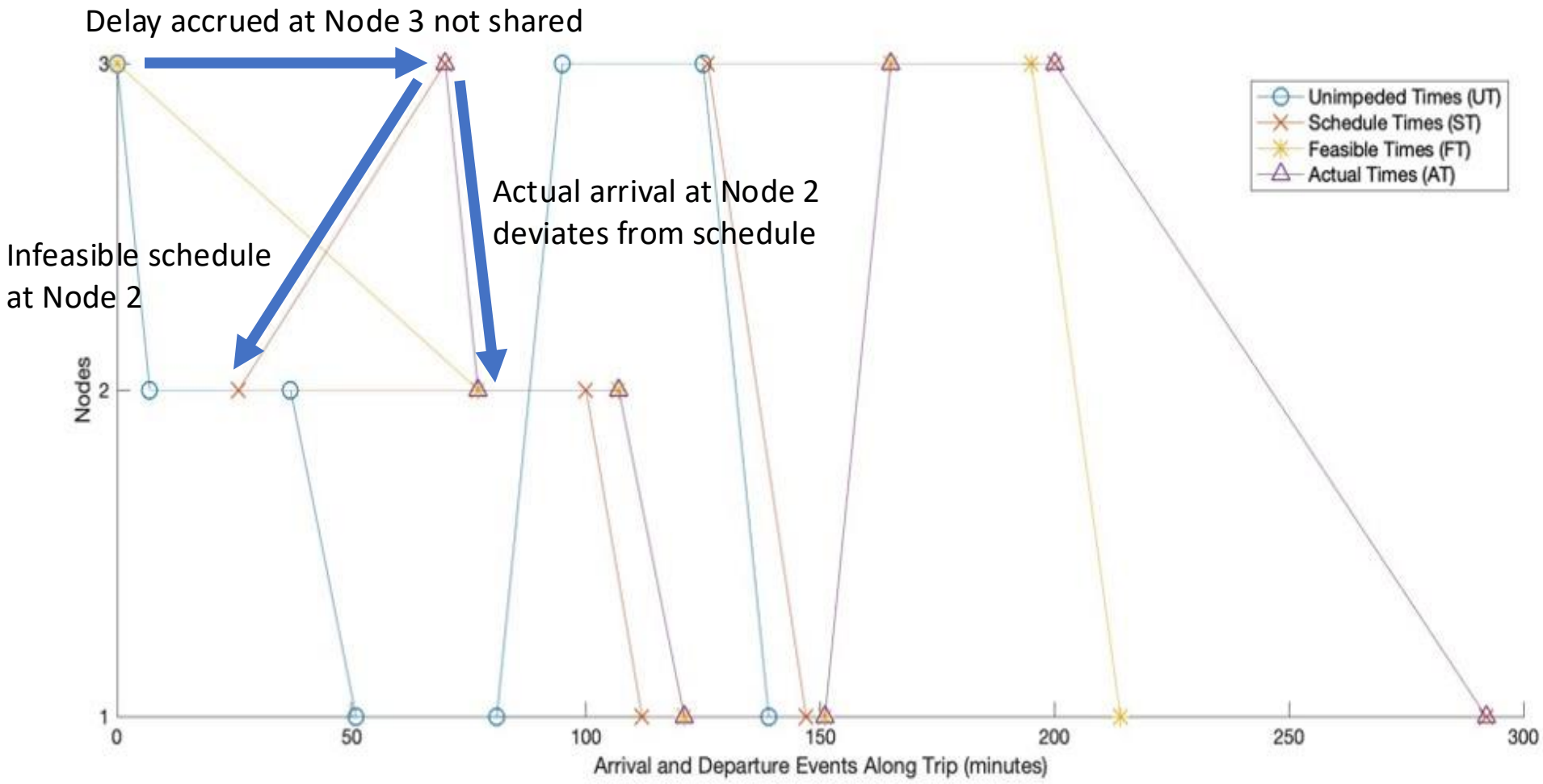
- **Accrued delay** is a continuous measurement of delay
  - As it propagates from previous flight legs due to aircraft, crew, or passenger connectivity
  - As it accumulates throughout progress of flight due to weather and congestion
- Uses and Benefits:
  1. Improve feasibility of schedule: Schedule based on feasible times of arrival that account for network delay propagation
  2. Improve delay distribution variance: Schedule while prioritizing by accrued network delay to mitigate delay propagation

Closed Network Simulation Scenario

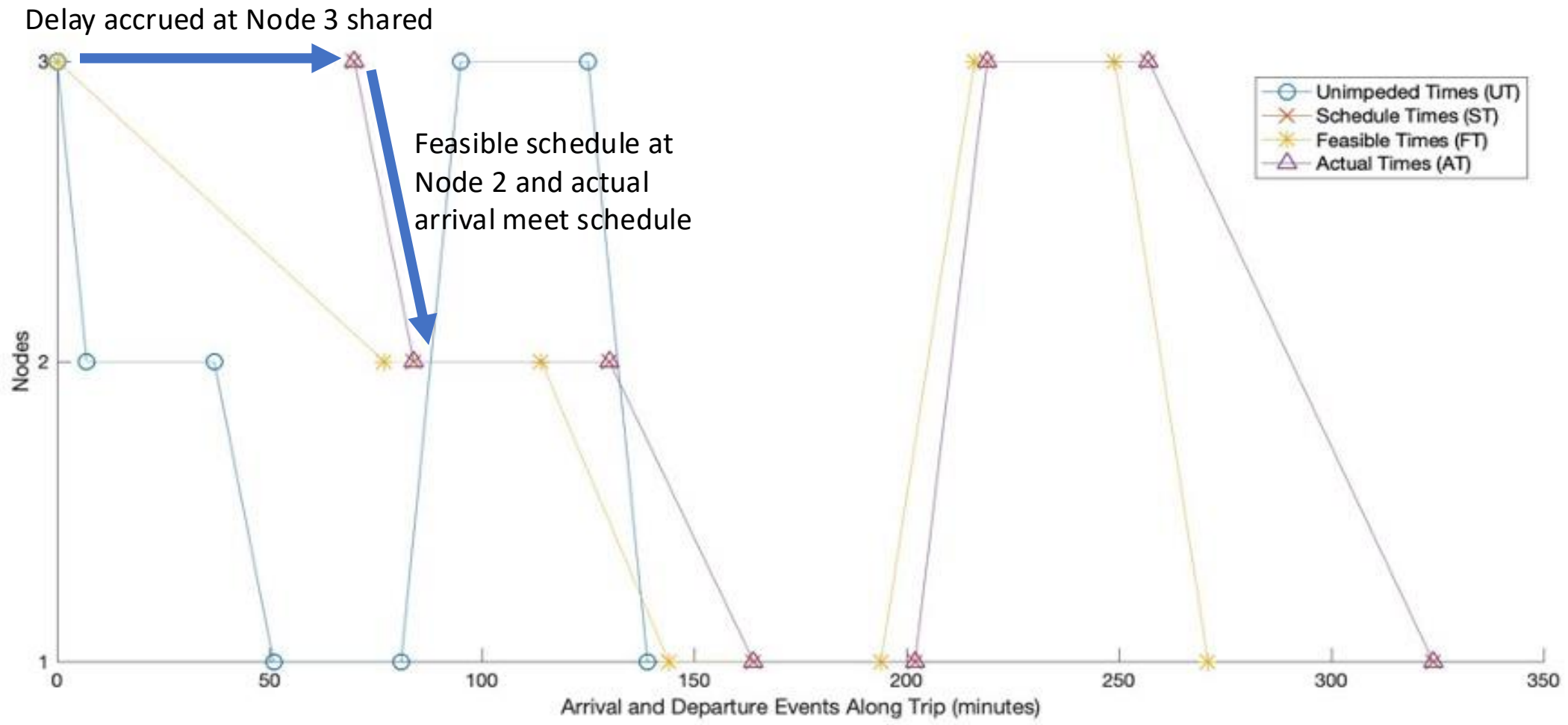
- Three nodes fully connected
- Distributed node scheduling without explicit coordination
- Investigate implicit coordination induced through updating and sharing accrued delay
- Vehicle trips modeled as series of nodes (e.g., 5) – stays constant during scenario
- Vehicles modeled with travel speed (160-240 knots) and turnaround times (35-45 min.)
- Node capacities set as minimum time separation between consecutive operations (e.g., 10 min.)
- Assuming arrivals and departures at nodes are independent



Infeasible Schedule FCFS by Unimpeded Times



Feasible Schedule FCFS by Feasible Times



Prioritizing by accrued delay

1. Schedule FCFS based on FT's
2. Rank by expected AD = ST - UT
3. Swap flights with highest AD with earlier ST's only if variance of AD is reduced

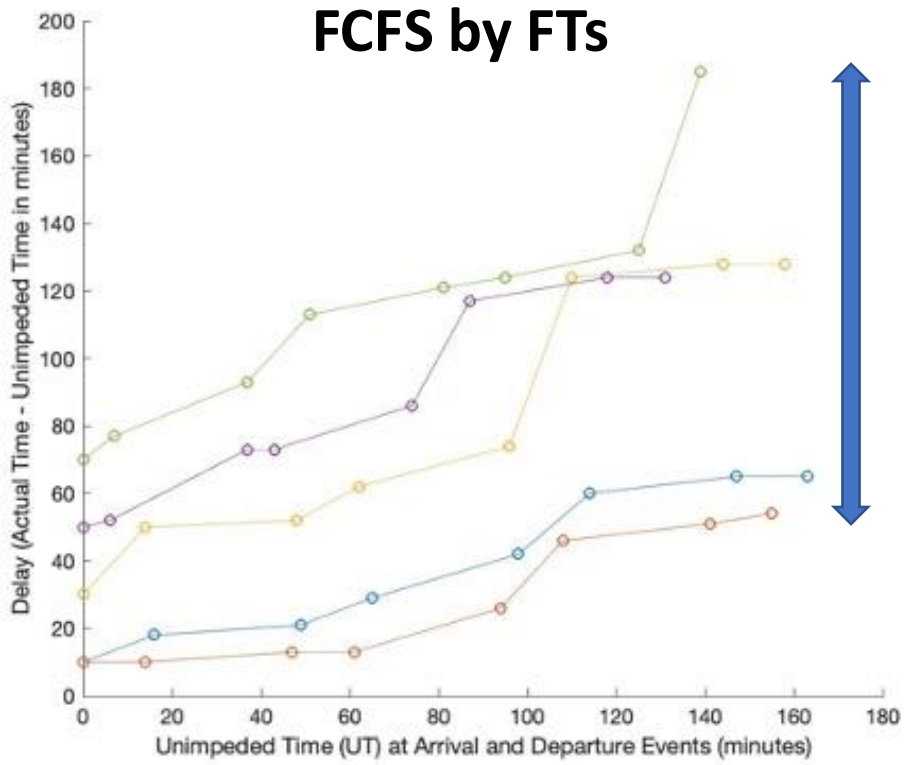
	Test Schedule 0: Baseline					
Vehicle	**UT**	**FT**	**ST**	**AD**	**New ST**	**New AD**
A	7:00	7:00	7:02	2	7:02	2
B	7:01	7:02	7:04	3	7:04	3
C	7:02	7:03	7:06	4	7:08	6
D	7:02	7:04	7:08	6	7:10	8
E	7:00	7:05	7:10	10	7:06	6
	Total Delay: 25 minutes for AD and New AD Standard Deviation: 3.2 for AD down to 2.5 minutes for New AD					

UT = Unimpeded time
FT = Feasible time
ST = Scheduled time
AD = Accrued delay = ST – UT

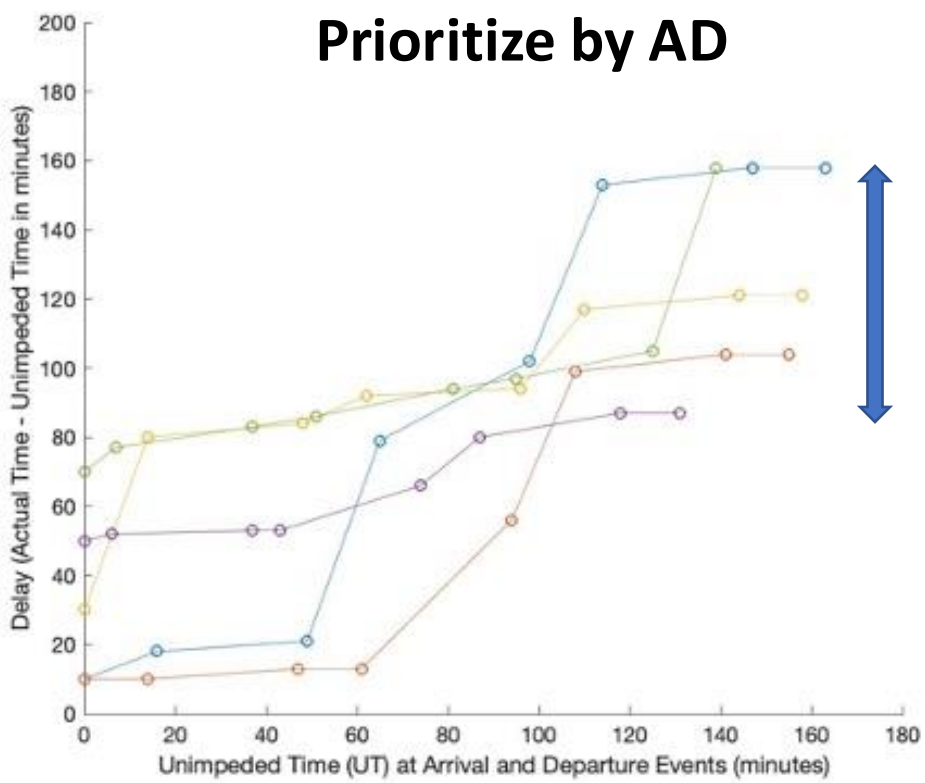
Example Trips with Accrued Delay Prioritization

Example Trips

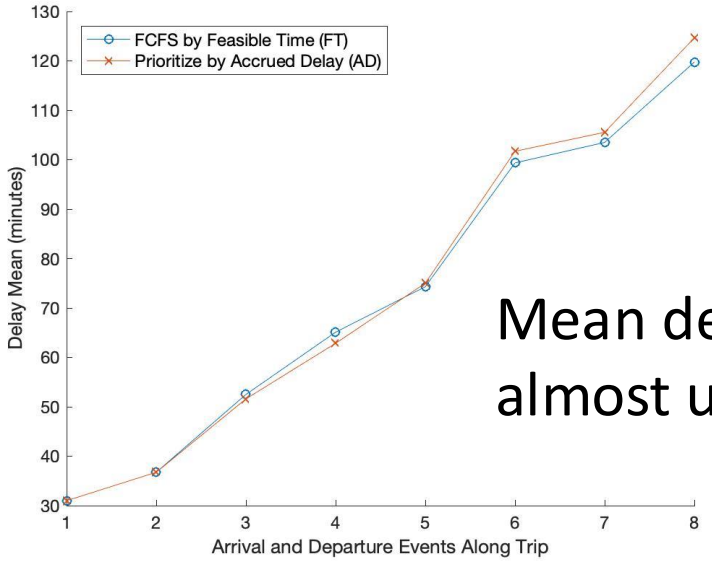
FCFS by FTs



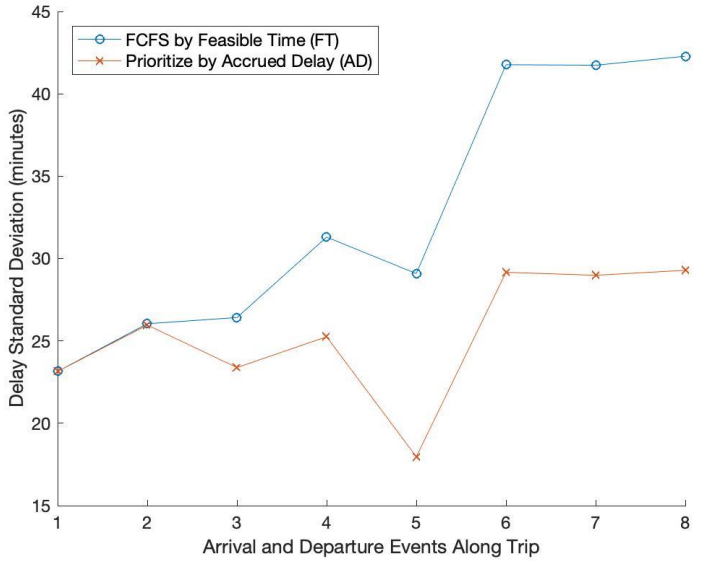
Prioritize by AD



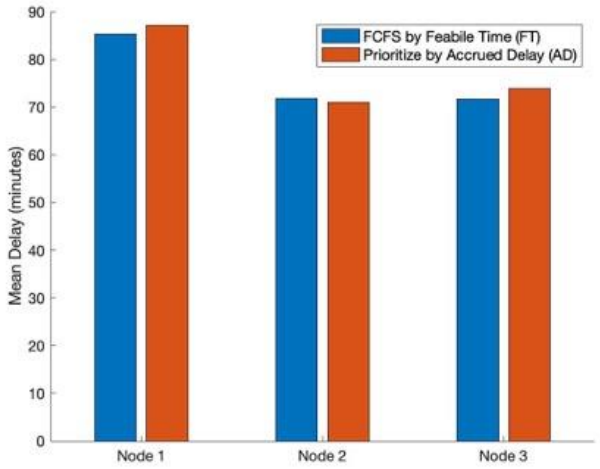
Accrued Delay Impact on Variance

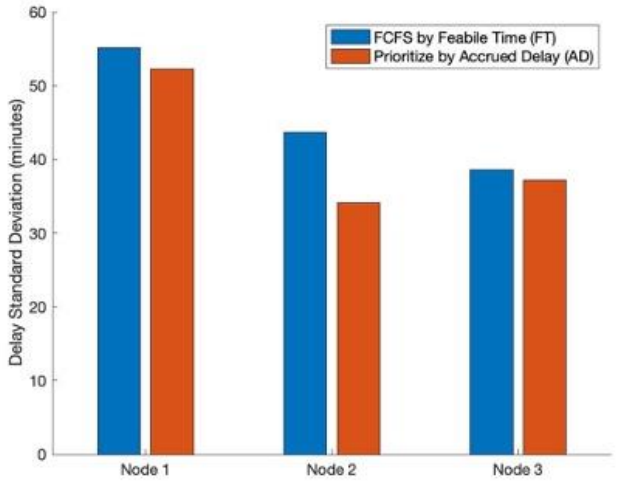


Mean delay almost unchanged



Delay variance reduced along trip and at nodes





Summary

- Updating expected times using accrued delay improved schedule feasibility
- Prioritization by accrued delay reduced delay variance along vehicle trips and at network nodes
- Effects more pronounced when:
  - Feasible expected times are updated more frequently
  - There is high variance in initial delay
  - Lower demand-to-capacity ratios
- Caveat: Models used in initial analysis are deterministic and heuristic – should be extended to include uncertainties

Considerations and Extensions

- Vehicle-oriented perspective is useful in reducing delay propagation – may require
  - Supporting data to keep track of vehicle connectivity and delay propagation though turnaround
  - Participation of operators by providing information about vehicle trips and vehicle swapping
  - Models of operator behaviors in vehicle routing management
- Extension to other connectivity-related delay propagation such as passenger and crew connectivity
- Vehicle, passenger, and operator orientation are steps to integrating operator fleet management with traffic management
- Closed network models may be critical for urban air mobility (UAM) with high volume, short flights, ride sharing and on-demand mobility

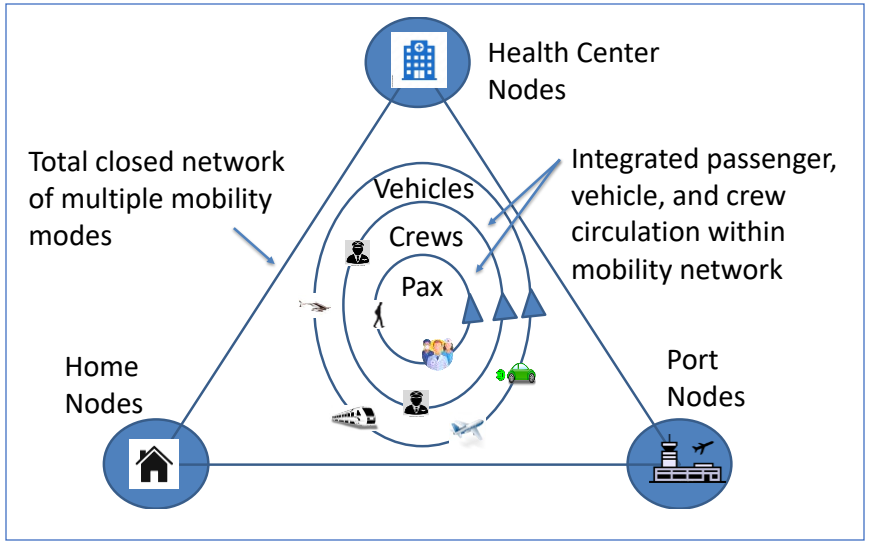
Passenger-Oriented Total Mobility through Digital Transformation

Vision (end state): Cut down end-to-end travel time for people and goods (referred to generally as *passengers*) through:

- A **passenger-oriented paradigm** to enable faster mobility that is accessible by all people, end to end (rather than port to port), and that is also safer, more efficient and cleaner
- A **total mobility paradigm** that integrates among modes of mobility to achieve end to end objectives
- **Digital transformation** that establishes an agile research and development process that cuts down the time to reach end to end mobility solutions

Strategy: Start with a particular use case such as **delivery of health services**, and conduct research-to-implementation that will cut down end-to-end travel time for passengers by a NASA-set target ratio. Generalize to other use cases

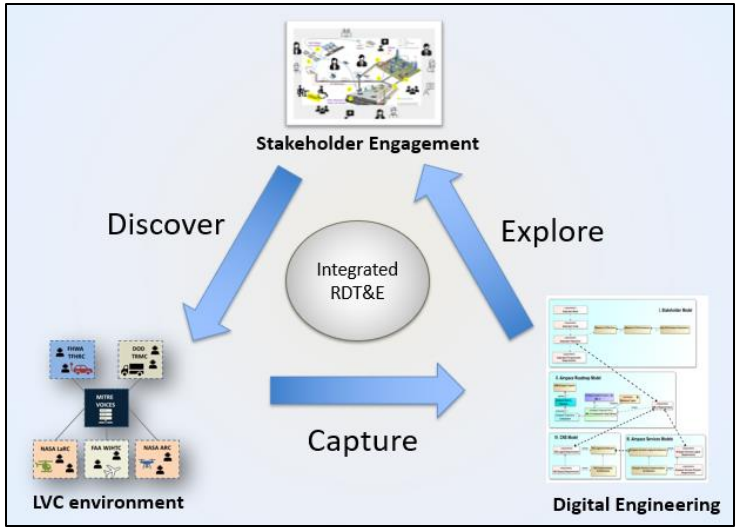
Passenger-Oriented Total Mobility System



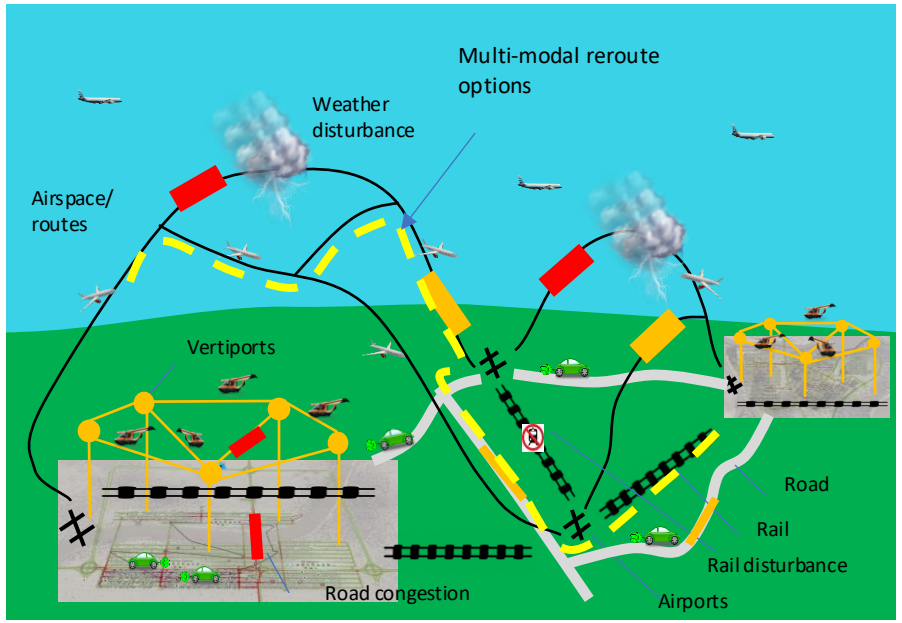
R&D Maturing Goals and Requirements

Tailored and Timely R&D support

Digitally Transformed Agile SE Process



Initial Use Cases / Prototypes

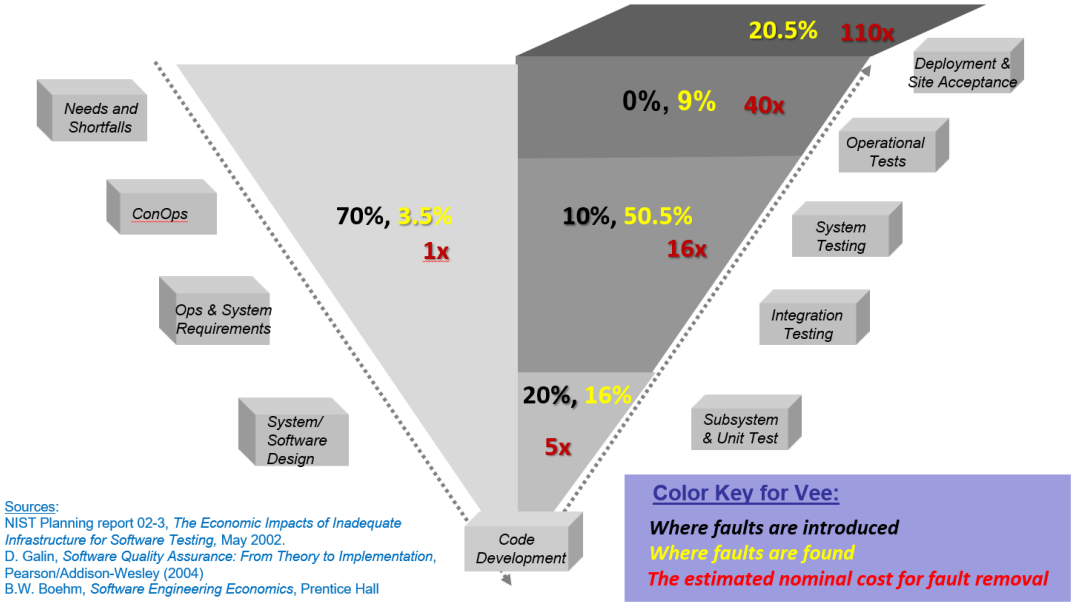


Mobility Use Case:
Passenger-Oriented Total Mobility

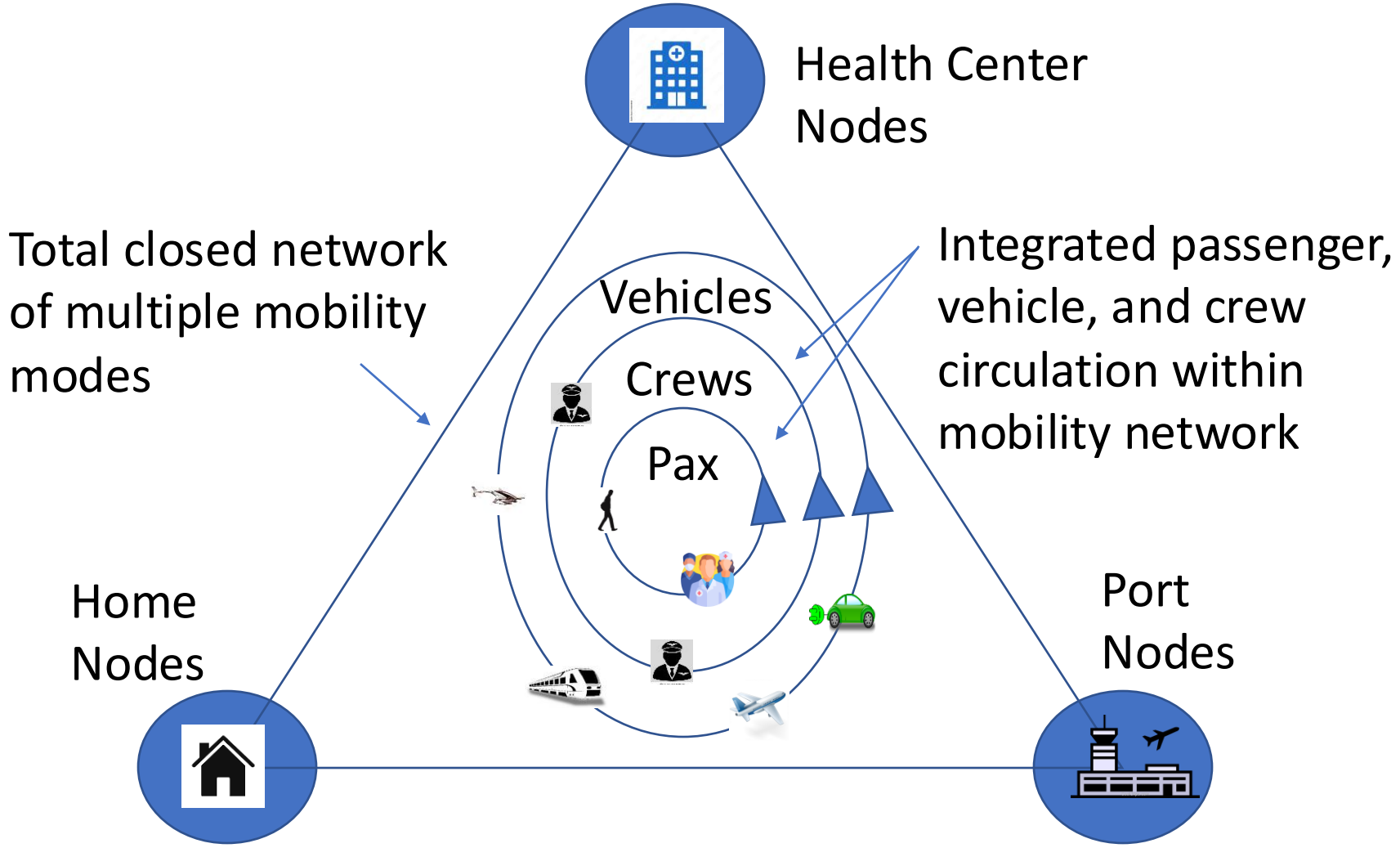
- Provision of health services to and between two hard-to-access regions (remote underserved) within the US
- Focus is on the timeliness of end-to-end health-related mobility between the two regions
- Integrated aviation solutions reduce the time that it takes today (e.g., by alleviating multi-modal mobility choke points)

Digital Transformation Use Case:
System Engineer supporting the Researcher

- Digital knowledge management and creative stakeholder engagement work together to identify requirements for experiment design and execution[1]
- Focus is on the time it takes to advance system maturity
- Integrated RDT&E reduces time and improves tech transfers, at lower cost



1. See *Automated Research Workflows for Accelerated Discovery, National Academies, 2022*


Health Center Nodes
Total closed network of multiple mobility modes
Integrated passenger, vehicle, and crew circulation within mobility network
Vehicles
Crews
Pax
Home Nodes
Port Nodes

Total Mobility
Barriers and Needs

- **Lack of integration** within and between modes of mobility leads to stove-piped solutions which fail to deliver as desired because of interoperability issues
  - **Need a total mobility perspective** to ensure solutions are viable when integrated into the total eco-system
  - **Need a passenger-oriented perspective** to move people (and goods) end to end faster, safer and more efficiently
    - How can we achieve **interoperable mobility** modes to increase the options available? (+ Information and transportation experts)
    - How can we optimize the options across modes and achieve **robust and resilient mobility** to disruptions and disasters (+ operations research experts)
    - How can we achieve **seamless mobility** to the passenger, and along the way to the operator, vehicle, and service provider? (+ policy, procedure, and information experts)
    - How can we achieve **cost-effective mobility**, even free or subsidized (+ economists)
    - How can **autonomous mobility** ensure scalability reducing human role (+ autonomy experts)

- **Lack of timely research** that converges to a solution leads to obsolescence as the operating environment diverges beyond original assumptions
  - **Need agile R&D** approach (faster, better, and cheaper) to ensure total mobility converges before problem diverges
  - **Need resilient project management** approach that adapts to the unknowns uncovered along the way
  - **Need efficient system engineering** approach that is synchronized with the evolving operating environment and can cut quickly through the problem space
  - **Need up front investment** in change management through agile and digital transformation

Total Mobility
Barriers and Needs

- **Detailed barriers will be identified as part of the initial effort, but some initial thoughts are:**

  - **Language barrier** – different modes often use different languages, taxonomies, data fabrics
  - **Heterogeneity barrier** – at many levels: vehicles, technologies, services, operators, architectures, …
  - **Security barrier** – different levels of securities for aviation versus other modes
  - **Private-public integration barrier** – hinders seamless transfer and mobility
  - **Cost barrier** – different cost point for aviation versus other modes
  - **Organizational barrier** – stove piping at organizational level among others
  - **Accessibility barrier** – difficulty in transfer between nodes
  - Others TBD

Total Mobility
Barriers and Needs

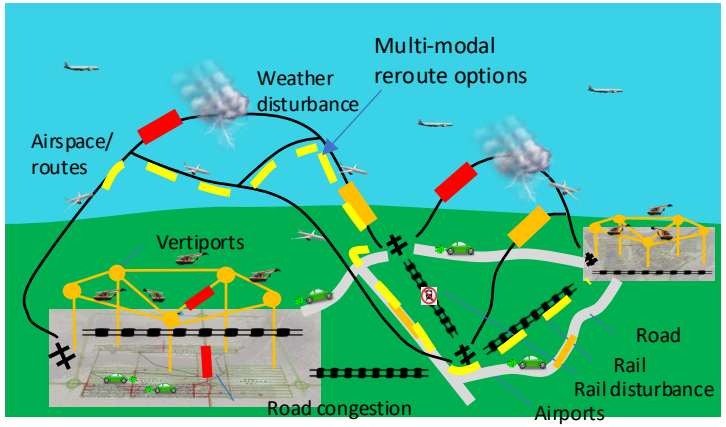
- **Lack of integration** within and between modes of mobility leads to stove-piped solutions which fail to deliver as desired because of interoperability issues
  - **Need a total mobility perspective** to ensure solutions are viable when integrated into the total eco-system
  - **Need a passenger-oriented perspective** to move people (and goods) end to end faster, safer and more efficiently

- **Lack of timely research** that converges to a solution leads to obsolescence as the operating environment diverges beyond original assumptions
  - **Need agile R&D** approach (faster, better, and cheaper) to ensure total mobility converges before problem diverges
  - **Need resilient project management** approach that adapts to the unknowns uncovered along the way
  - **Need efficient system engineering** approach that is synchronized with the evolving operating environment and can cut quickly through the problem space
  - **Need up front investment** in change management through agile and digital transformation

Passenger-Oriented Total Mobility

Opportunity:
Aviation rarely operates without other modes of mobility to move people (and packages) from end to end. New vehicles such as flying cars promise to use multi-modal infrastructures competing as well as complementing other mobility modes. NASA should lead the way to improve the passenger mobility achieved by the transportation system –the vision is **a passenger-oriented paradigm to enable faster mobility that is accessible by all people, anywhere to anywhere**, and that is also safer, more efficient and cleaner.
Use Case: pick two hard-to-access points "anywhere" within the US and globally; ask how long it takes people to travel between them; **set a target to cut travel time by certain percentage** (say half); and identify how aviation can help achieve this by alleviating choke points – with new vehicles, more access for vehicles, and the focus here **better integration between aviation and other mobility modes**

- How can we achieve **interoperable mobility** modes to increase the options available? (+ Information and transportation experts)
- How can we optimize the options across modes and achieve **robust and resilient mobility** to disruptions and disasters (+ operations research experts)
- How can we achieve **seamless mobility** to the passenger, and along the way to the operator, vehicle, and service provider? (+ policy, procedure, and information experts)
- How can we achieve **cost-effective mobility**, even free or subsidized (+ economists)
- How can **autonomous mobility** ensure scalability reducing human role (+ autonomy experts)



"Wicked-Wild" Idea:
Improve total everywhere-to-everywhere mobility through a passenger-oriented perspective as opposed to traditional flight/trip -oriented perspectives. Start by identifying barriers and defining concepts for **the simplest use case of few interconnected remote areas**. Models and metrics represent the circulation of passengers, vehicles (air and ground), operators/crews, and services (airspace and surface), in a **miniature but complete closed eco-system** that can be scaled up to more complex systems. Follow by deriving guidelines and technologies to improve interoperability and total mobility and scaling to more complex networks.

