Safety Benefit Analysis of Conformance Monitoring for Situation Awareness in UTM

Min Xue[✧] **Vincent Kuo**[*]

José Ignacio de Alvear Cárdenas[✦]

Priyank Pradeep[◇] **Seungman Lee**[✧]

[✧] NASA Ames Research Center
[*] Metis Technology Solutions
[✦] San Jose Sate University Research Foundation
[◇] Universities Space Research Association

Moffett Field, CA

AIAA Scitech Conference, Jan. 10, 2025

Background & Motivation

Initial safety case was developed and published in the ASTM standard:

Strategic deconfliction (SD) can significantly mitigate UA to UA collision risk by two to three orders of magnitudes

Two key questions remain unanswered:

1) Can strategic deconfliction (SD) alone achieve the target level of safety?

2) Under what circumstances is conformance monitoring for situation awareness (CMSA) needed?

Outline

- Analysis Method
  - Assumptions in service modeling
  - Analysis model
  - Relationship Between Off-Nominal Flights and UA-to-UA Collision Risk
- Results: Conditions that require CMSA
  - Results driven by the risk of UA-to-UA collision
  - Results driven by the risk of ground injuries
- Conclusions

Assumptions in Service Modeling

Assumption 1: When the SD is applied and operational intent volumes are valid, the UA-to-UA collision probability or Mid-Air-Collision (MAC) risk can be reduced to zero.

$$P(MAC|(SD \cap Valid\_OIV)) = 0$$

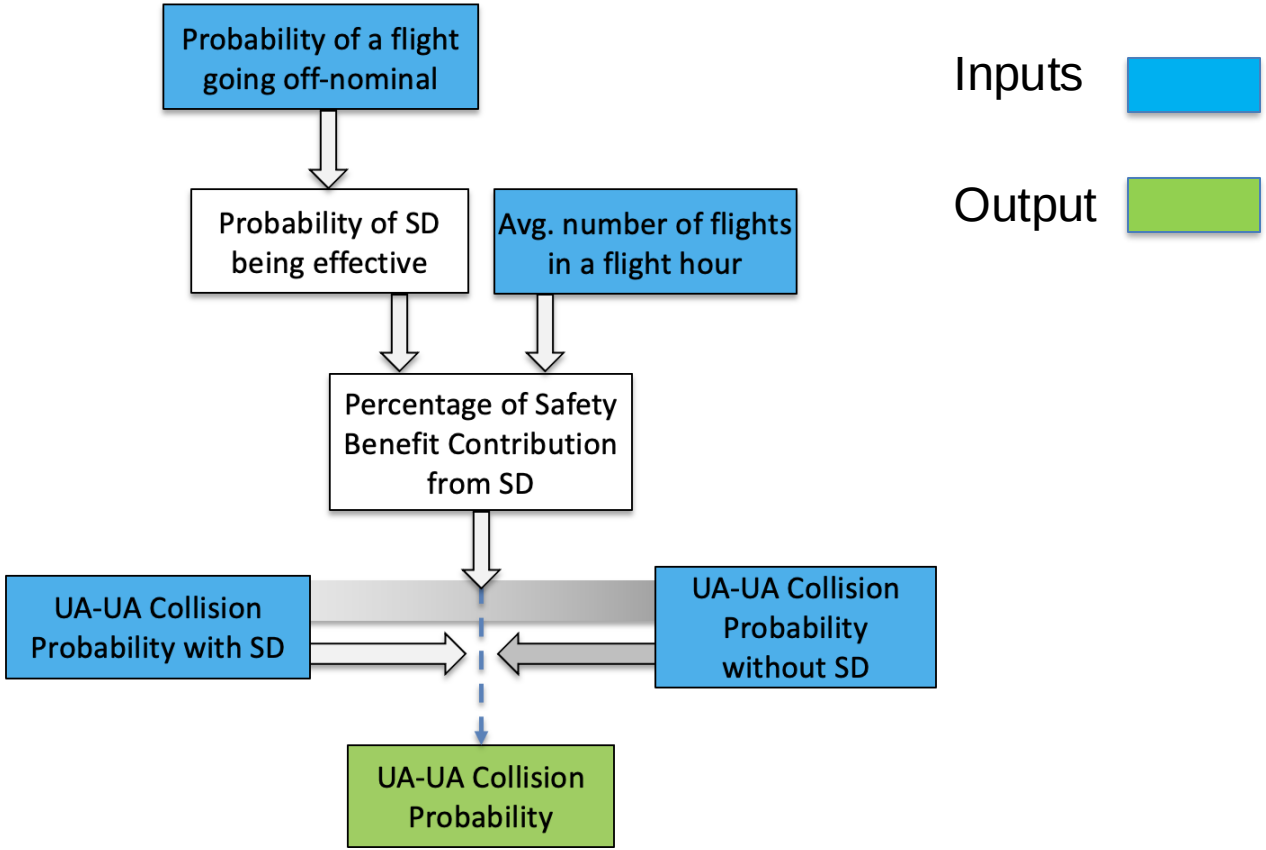
Assumption 2: When the CMSA service is active, there is no time delay between when a UA goes off-nominal and when the updated off-nominal operational intent volume.

$$P(Valid\_OIV|CMSA) = 1$$

Assumption 2: the CMSA is assumed to include deconfliction services - whether strategic or tactical deconfliction, and the deconfliction process takes no time to ensure successful resolution of potential conflicts.

$$P(MAC|(CMSA \cap SD)) = 0$$

Analysis Approach

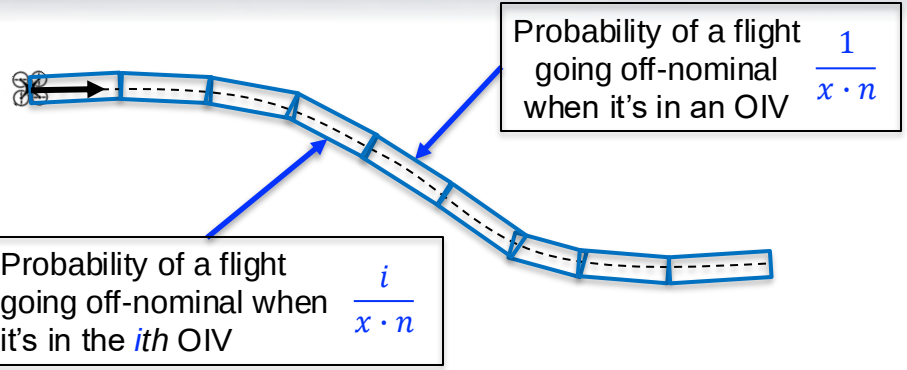


Step I: Probability of any OIV in a flight being invalid

- Probability of a flight going off-nominal: $\frac{1}{x}$

- Probability of the flight going off-nominal during any OIV is:

$$\frac{1}{x \cdot n}$$



- The probability of an operational intent volume (*i* th OIV of the total *n* OIVs in this flight) becomes invalid due to the flight going off-nominal is:

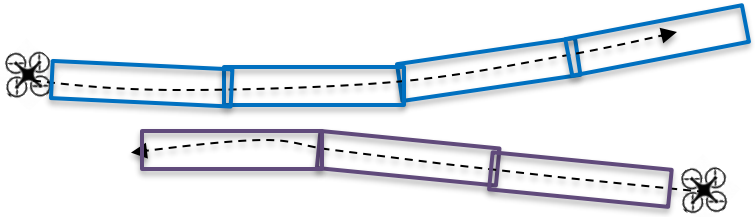
$$\frac{i}{x \cdot n}$$

- The probability of any operational intent volume (OIV) in a flight being invalid given the likelihood of the flight going off-nominal is then :

$$\text{P(invalid OIV exists in a flight)} = 1 - \prod_{i=1}^{n}\left(1 - \frac{i}{x \cdot n}\right) \approx \frac{1}{2x}$$

Step II: Percentage of the safety contribution from SD

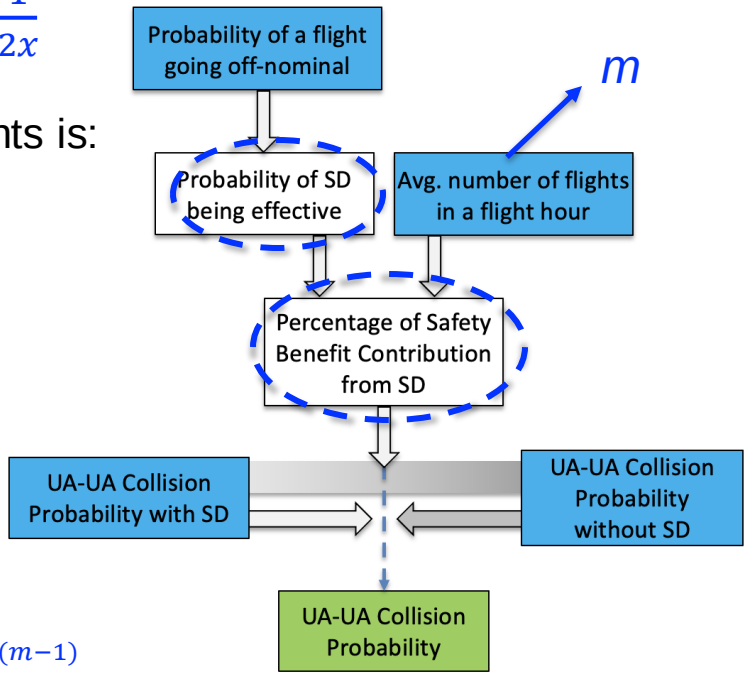
- The probability of all OIVs in a flight being valid: $1 - \frac{1}{2x}$
- The probability of SD being effective given any two flights is:



$$P(\text{effective\_SD}|\text{any two flights}) = \left(1 - \frac{1}{2x}\right)^2$$

- Assuming the number of flights in a flight hour is m,

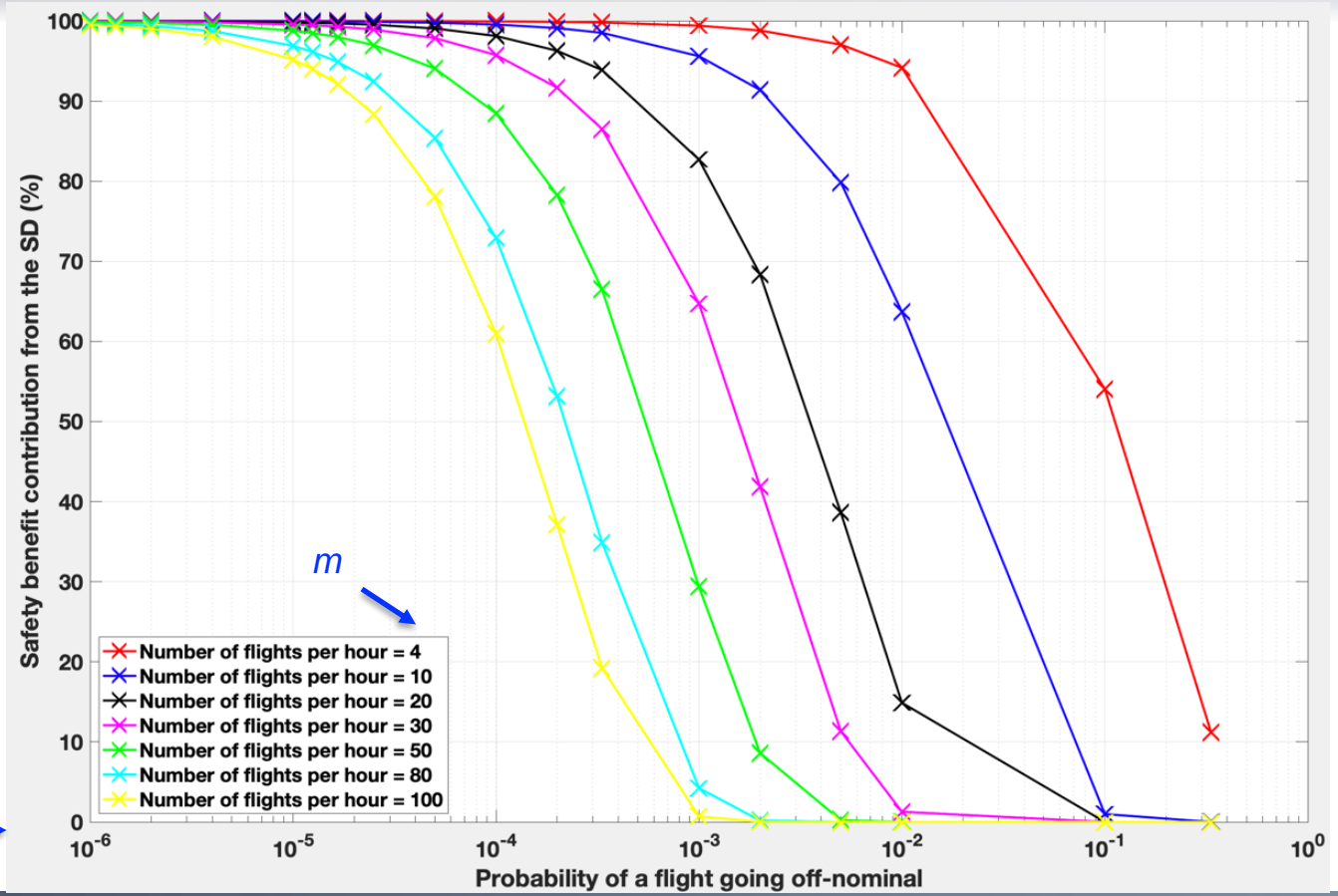
$$P(\text{effective\_SD}|m \text{ flights}) = \left[\left(1 - \frac{1}{2x}\right)^2\right]^{C_m^2} = \left(1 - \frac{1}{2x}\right)^{m(m-1)}$$



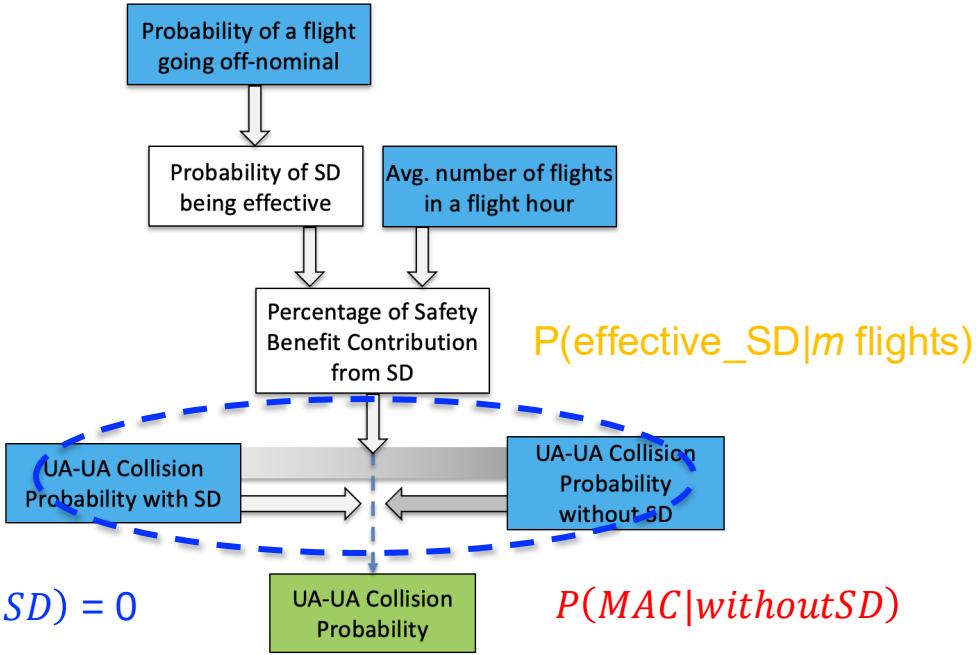
Relationship between off-nominal flights and effective SD

P(effective_SD|*m* flights)

$$= \left(1 - \frac{1}{2x}\right)^{m(m-1)}$$



Relation between UA-to-UA collision risk and off-nominal flights (I)



P(UA-UA Collision Risk) = $P(MAC|SD)$ · P(effective_SD|*m* flights) + $P(MAC|withoutSD)$ · (1 – P(effective_SD|*m* flights))

Relation between UA-to-UA collision risk and off-nominal flights (II)

P(UA-UA Collision Risk) = $P(MAC|SD)$ · P(effective_SD|*m* flights) +$P(MAC|withoutSD)$ · (1 − P(effective_SD|*m* flights))

Target UA-to-UA collision

$P(MAC|SD) = 0$

$P(MAC|withoutSD)$

⇒ P(effective_SD|*m* flights)

⇒ Probability of off-nominal flights

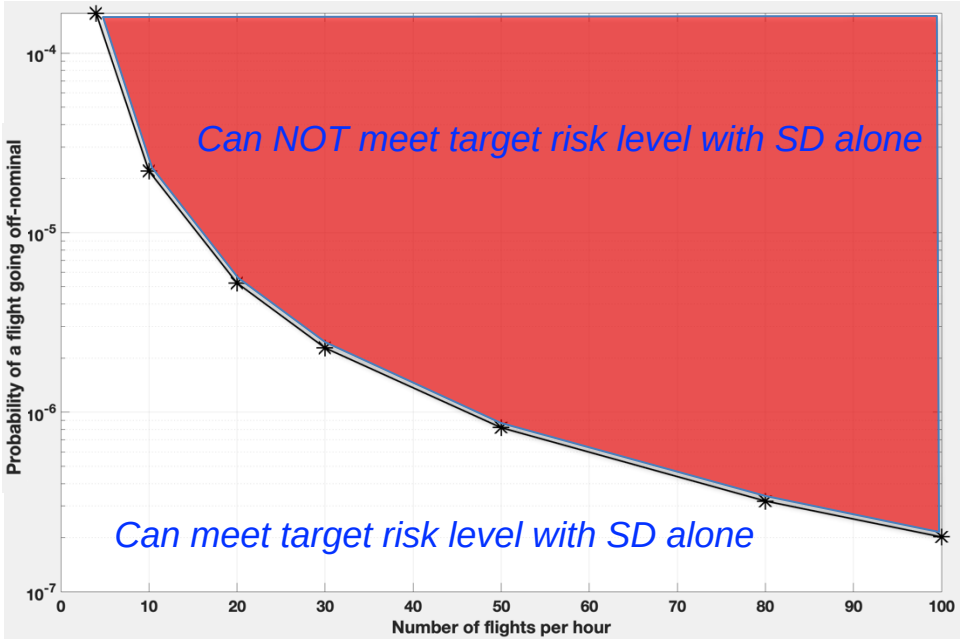
$$\frac{1}{x} \leq 2 \cdot \left(1 - \sqrt[m(m-1)]{1 - \frac{Target\ UAtoUA\ Collision\ Risk}{P(MAC|withoutSD)}}\right)$$

When SD alone can not meet the target UA-to-UA collision risk

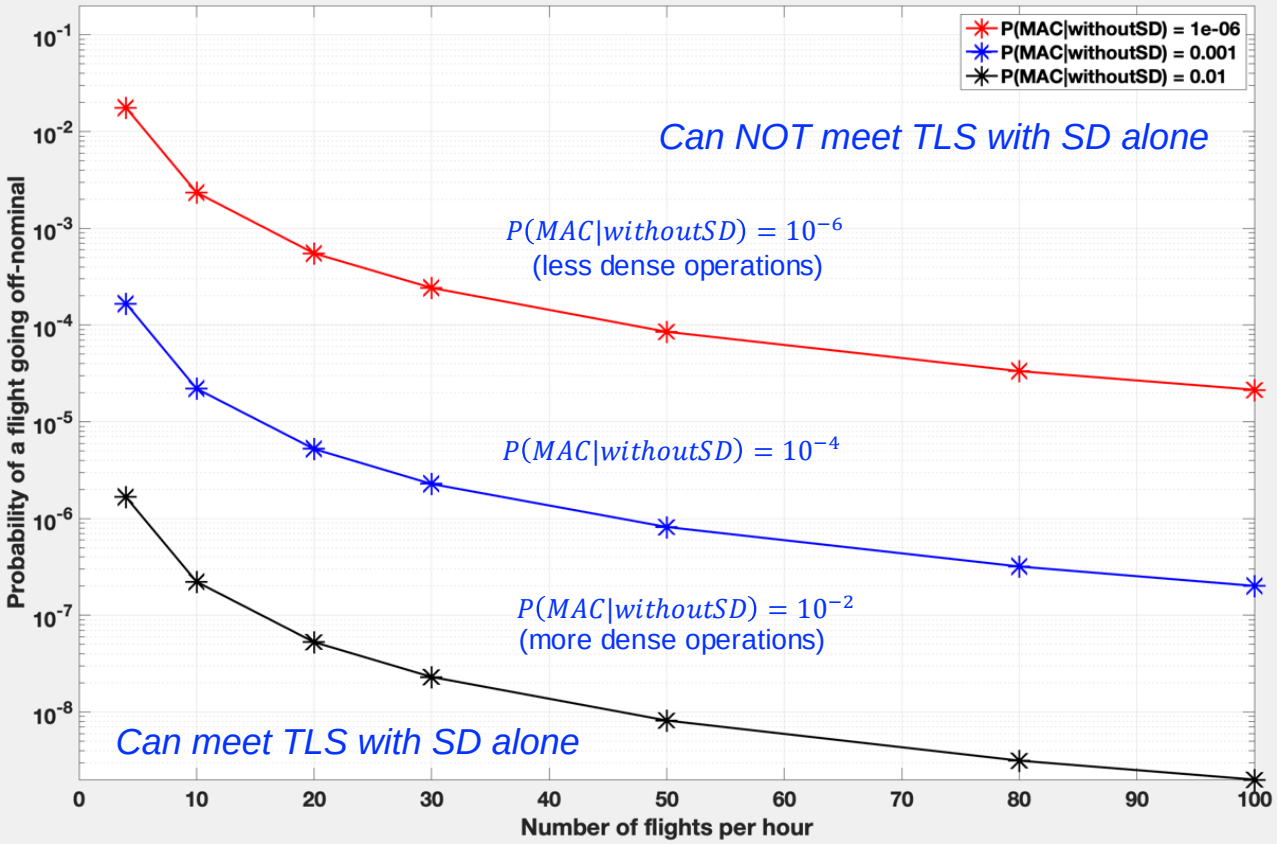
$$\frac{1}{x} \leq 2 \cdot \left(1 - \sqrt[m(m-1)]{1 - \frac{Target\ UA - UA\ Collision\ Risk}{P(MAC|withoutSD)}}\right)$$

$P(MAC|withoutSD) = 10^{-4}$

Target: 10^{-7} UA-to-UA collision



Analysis with different *P(MAC|withoutSD)*



In order to maintain the target level of safety (UA-to-UA collision risk) by **SD alone**, the **higher operational tempo/density** is, the **lower likelihood of off-nominal flights** will be required.

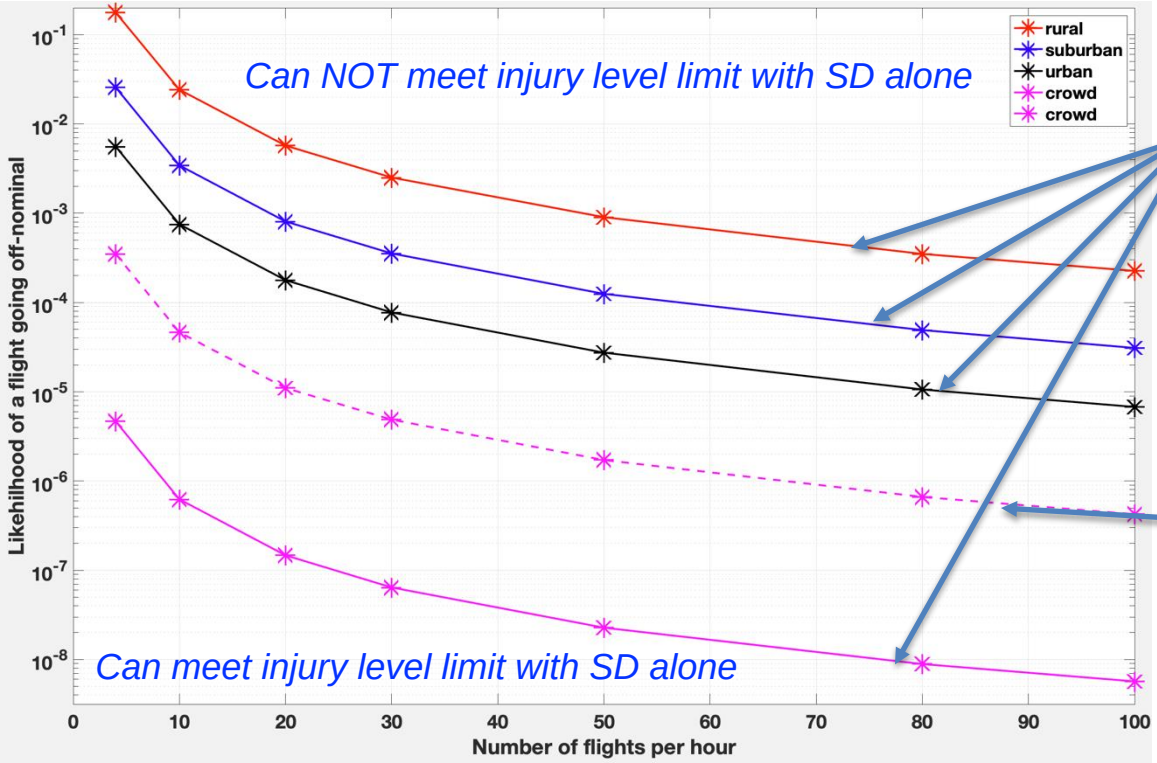
Outline

- Analysis Method
  - Assumptions in service modeling
  - Analysis model
  - Relation between off-nominal flights and UA-to-UA collision risk
- Results
  - Results driven by UA-to-UA collision risk
  - Results driven by ground injury risk
- Conclusions

When SD alone can not meet the target injury risk on the ground

$P(MAC|withoutSD) = 10^{-4}$

If switch from target UA-UA collision per flight hour 1.0×10^{-7} to target injuries per flight hour.



Target: 2.0×10^{-7} injuries per flight hour
(equivalent to **10** injuries each year if 10K operations/hour and 14 hours/day)

Target: 1.5×10^{-5} injuries per flight hour
(equivalent to 766 injuries each year if 10K operations/hour and 14 hours/day)
Note: SD alone is sufficient for operations in “rural”, ”suburban”, and “urban” areas

Conclusions

- This work defines the operational thresholds when SD alone is insufficient, requiring CMSA services.
- The thresholds were derived using two risk metrics: UA-to-UA collision risk and ground injury risk.
- The probability of a flight going off-nominal is the key factor in determining when CMSA services are required
- As operational tempo, density, and complexity increase, the baseline UA-to-UA collision risk without SD rises, thereby driving an increased demand for CMSA services.