Scenario Complexity for Unmanned Aircraft System Traffic

Presented by: **Min Xue**

NASA Ames Research Center
Moffett Field, CA

Minh Do

SGT, Inc.
Moffett Field, CA

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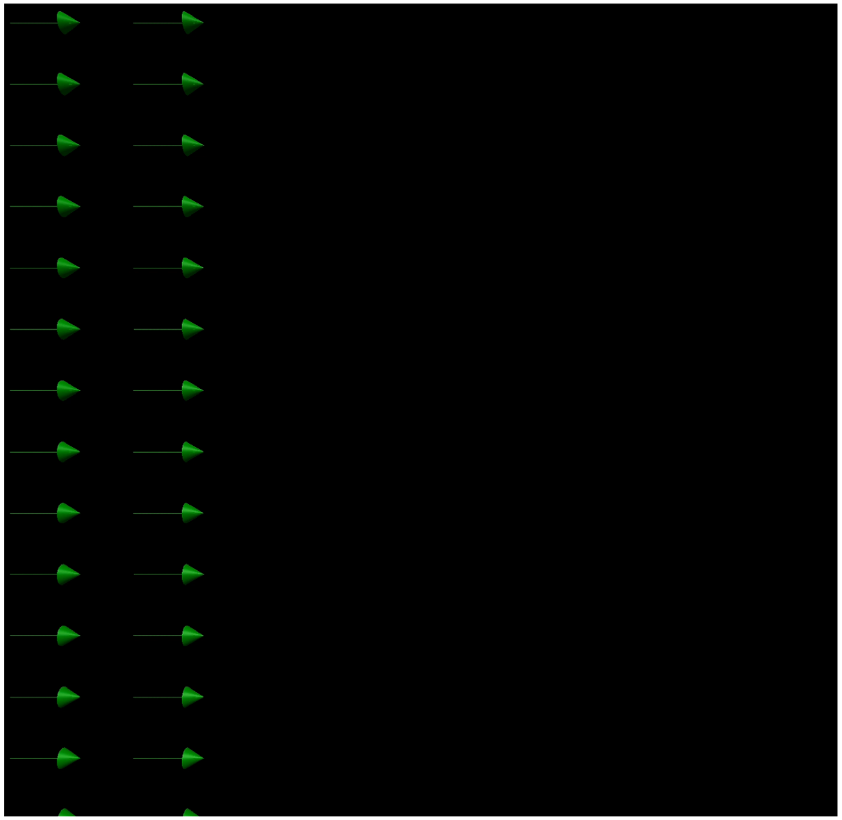
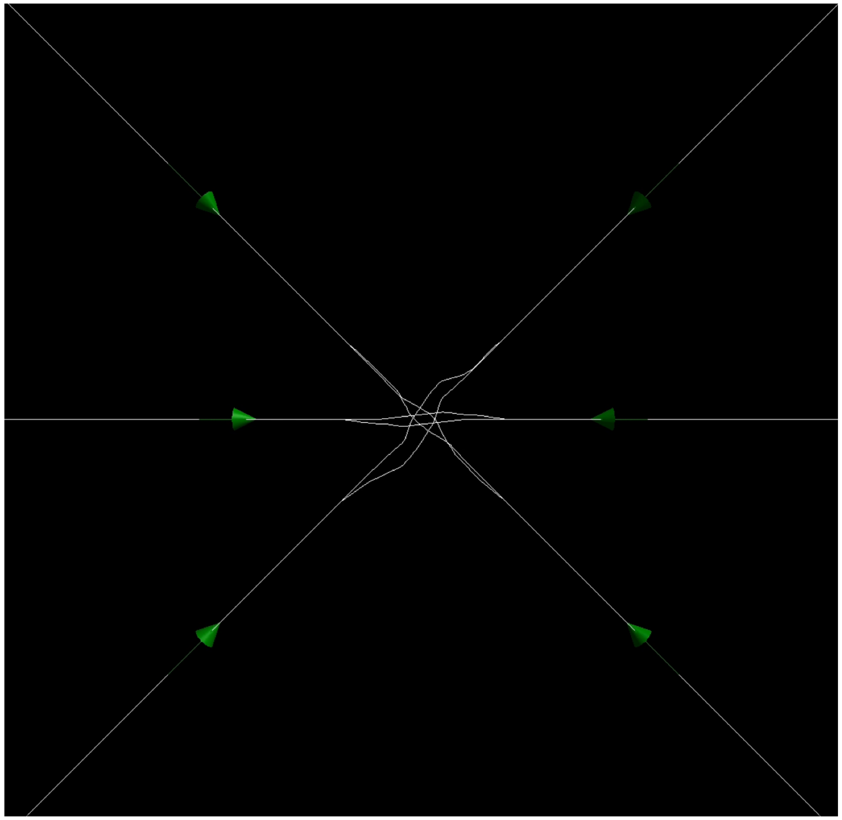
“High density” ≠ “High complexity”



High density & low complexity



Low density & high complexity

Motivation

1. Develop a **metric** that can **quickly approximate** the complexity of a given traffic scenario for:
    - Flight planning and scheduling

      Potential use: traffic management, vehicle operations
    - Quick risk assessment

      Potential use: insurance, traffic management
    - Traffic scenario categorization

      Potential use: traffic management, researchers
2. Develop **an evaluation approach** using high-fidelity simulations.

Outline

- Background
- Method
  - Conflict resolution
  - Complexity metric
- Experiments
  - Test scenarios
  - Evaluation

Background

- Cognitive complexity (e.g. Dynamic Density)
  - Evaluated with controller's workload ratings
  - Aircraft count is the dominant factor
- Intrinsic traffic disorder
  - Geometrical approach for traffic divergence, convergence, and sensitivity
  - Entropy of the traffic dynamic system
- Complexity map
  - Velocity vector field
  - Instantaneous calculation via optimization

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Method

Develop a metric constructed based the **number of potential conflicts** weighted by the **conflict resolution cost**:

- Compute conflict resolution maneuvers using Mixed-Integer Linear Programming (MILP)
  - Vehicle trajectory model
  - Speed constraint
  - Turn rate constraint
  - Separation constraint
  - Finite Horizon
  - Objective
- Construct complexity metric

Vehicle Trajectory Model

$$\forall\, t \geq 0,$$

$$\begin{bmatrix} p_{x,t+1} \\ p_{y,t+1} \\ v_{x,t+1} \\ v_{y,t+1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p_{x,t} \\ p_{y,t} \\ v_{x,t} \\ v_{y,t} \end{bmatrix} + \begin{bmatrix} \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{2}\Delta t^2 \\ \Delta t & 0 \\ 0 & \Delta t \end{bmatrix} \begin{bmatrix} a_{x,t} \\ a_{y,t} \end{bmatrix}$$

Speed constraints

Maximum speed:

$$\forall\ i \in [1 \ldots N],\ \forall\ t \in [t_{si}, t_{ei}],\ \forall\ k \in [1 \ldots K] :$$

K= 10

$$v_{x,i,t} \cdot \sin(\frac{2\pi k}{K}) + v_{y,i,t} \cdot \cos(\frac{2\pi k}{K}) \leq v_{max}$$

Minimum speed:

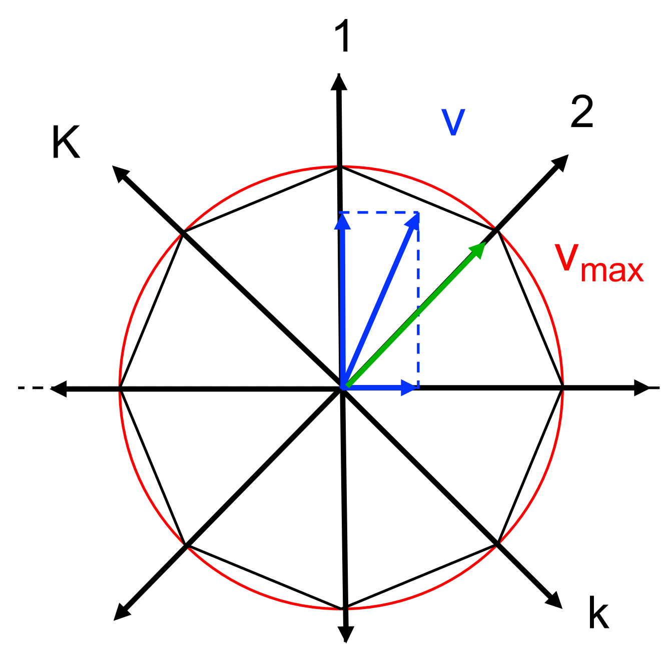
$$\forall\ i \in [1 \ldots N],\ \forall\ t \in [t_{si}, t_{ei}],\ \forall\ k \in [1 \ldots K] :$$

$$v_{x,i,t} \cdot \sin(\frac{2\pi k}{K}) + v_{y,i,t} \cdot \cos(\frac{2\pi k}{K}) \geq v_{min} - M \cdot c_{t,k}$$

$$\sum_{k=1}^{K} c_{t,k} \leq K - 1$$

$$c_{t,k} \in [0, 1]$$

K-side polygon method



Turn rate constraint

Turn rate

$$a_{max} = v_{max} \cdot \omega_{max}$$

$$\forall\, i \in [1 \ldots N],\ \forall\, t \in [t_{si}, t_{ei}],\ \forall\, k \in [1 \ldots K]:$$
$$a_{x,i,t} \cdot \sin\left(\frac{2\pi k}{K}\right) + a_{y,i,t} \cdot \cos\left(\frac{2\pi k}{K}\right) \leq a_{max}$$

Separation Constraint

Minimum separation

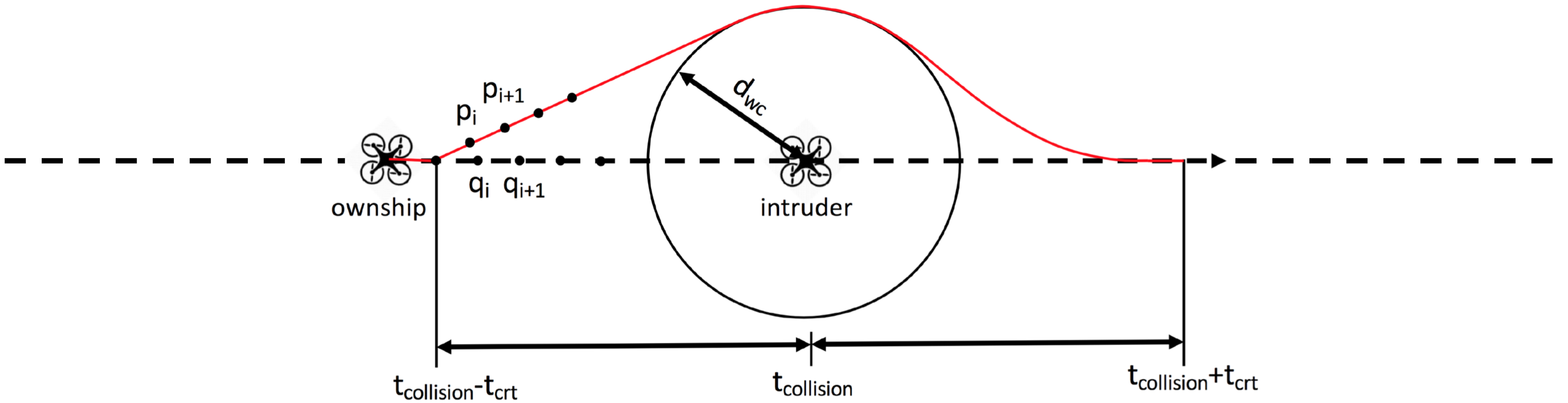
$$\forall\ i, j \in [1 \ldots N],\ \forall\ i \neq j, \forall\ t \in [t_{si}, t_{ei}],\ \forall\ k \in [1 \ldots K] :$$

$$(p_{x,i,t} - p_{x,j,t}) \cdot \sin(\frac{2\pi k}{K}) + (p_{y,i,t} - p_{y,j,t}) \cdot \cos(\frac{2\pi k}{K}) \geq d_{wc} - M \cdot c_{t,k}$$

$$\sum_{k=1}^{K} c_{t,k} \leq K - 1$$

$$c_{t,k} \in [0, 1]$$

Finite Horizon



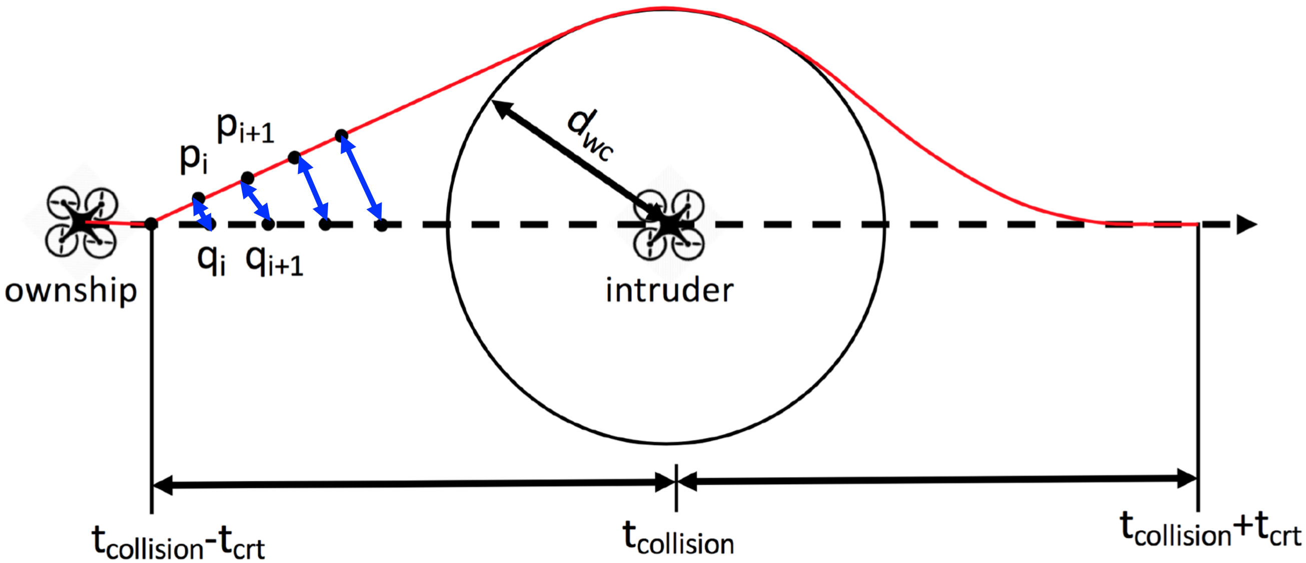
$$[t_{collision} - t_{crt}, t_{collision} + t_{crt}]$$

or $[t_{si}, t_{ei}]$.

t_{crt}: time threshold to start a conflict resolution maneuver

Objective

Objective: Minimize the deviation from original trajectory.

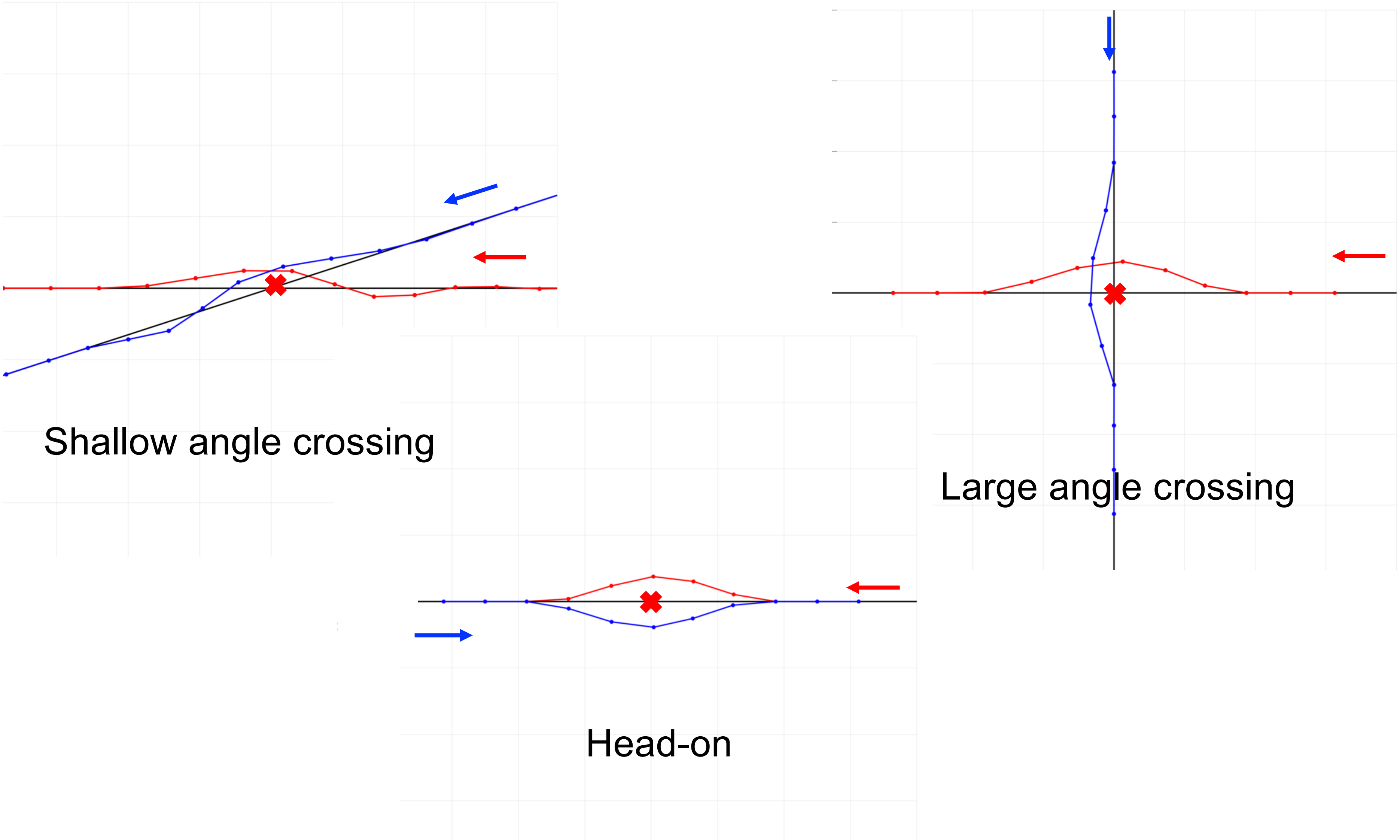


$$\min_{\mathbf{p},\mathbf{a}} J = \sum_{i=1}^{N} \sum_{t=t_{si}}^{t_{ei}} d_{i,t}$$

$$\forall\, i \in [1, N], \forall\, t \in [t_{si}, t_{ei}],\ \forall\, k \in [1 \ldots K] :$$

$$(p_{x,i,t} - q_{x,i,t}) \cdot \sin(\frac{2\pi k}{K}) + (p_{y,i,t} - q_{y,i,t}) \cdot \cos(\frac{2\pi k}{K}) \le d_{i,t}$$

Sample conflict resolution from MILP



Method

Develop a metric constructed based the number of potential pairwise conflicts weighted by the conflict resolution cost:

- Compute conflict resolution maneuvers using Mixed-Integer Linear Programming (MILP) formulation:
  - Vehicle trajectory model
  - Speed constraint
  - Turn rate constraint
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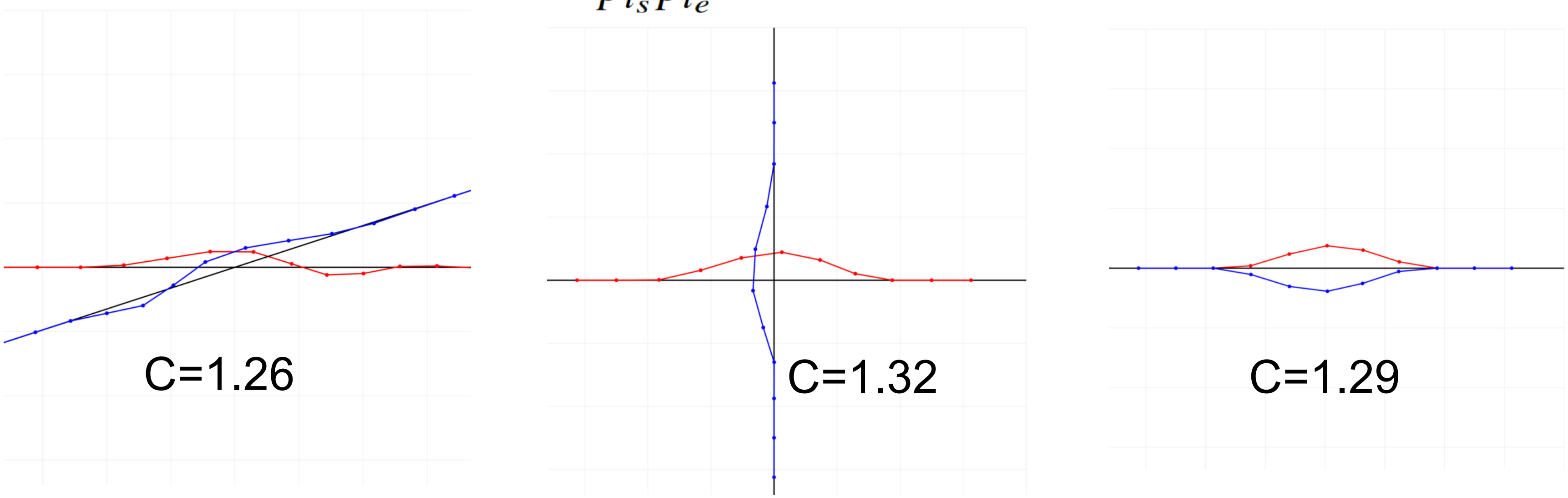
Scenario Complexity Metric (SC)

Complexity of a pairwise conflict:

$$C = 1.0 + C_{fi} + C_{fj}$$

$$C_{f_m} = \left| \frac{\sum_{t=t_s}^{t_e} \overline{p_t p_{t+1}} - \overline{p_{t_s} p_{t_e}}}{\overline{p_{t_s} p_{t_e}}} \right| \cdot (t_e - t_s),\ where\ m = i\ or\ j$$



Complexity of a traffic scenario:

$$SC = \sum_{k=1}^{nc} C_k$$

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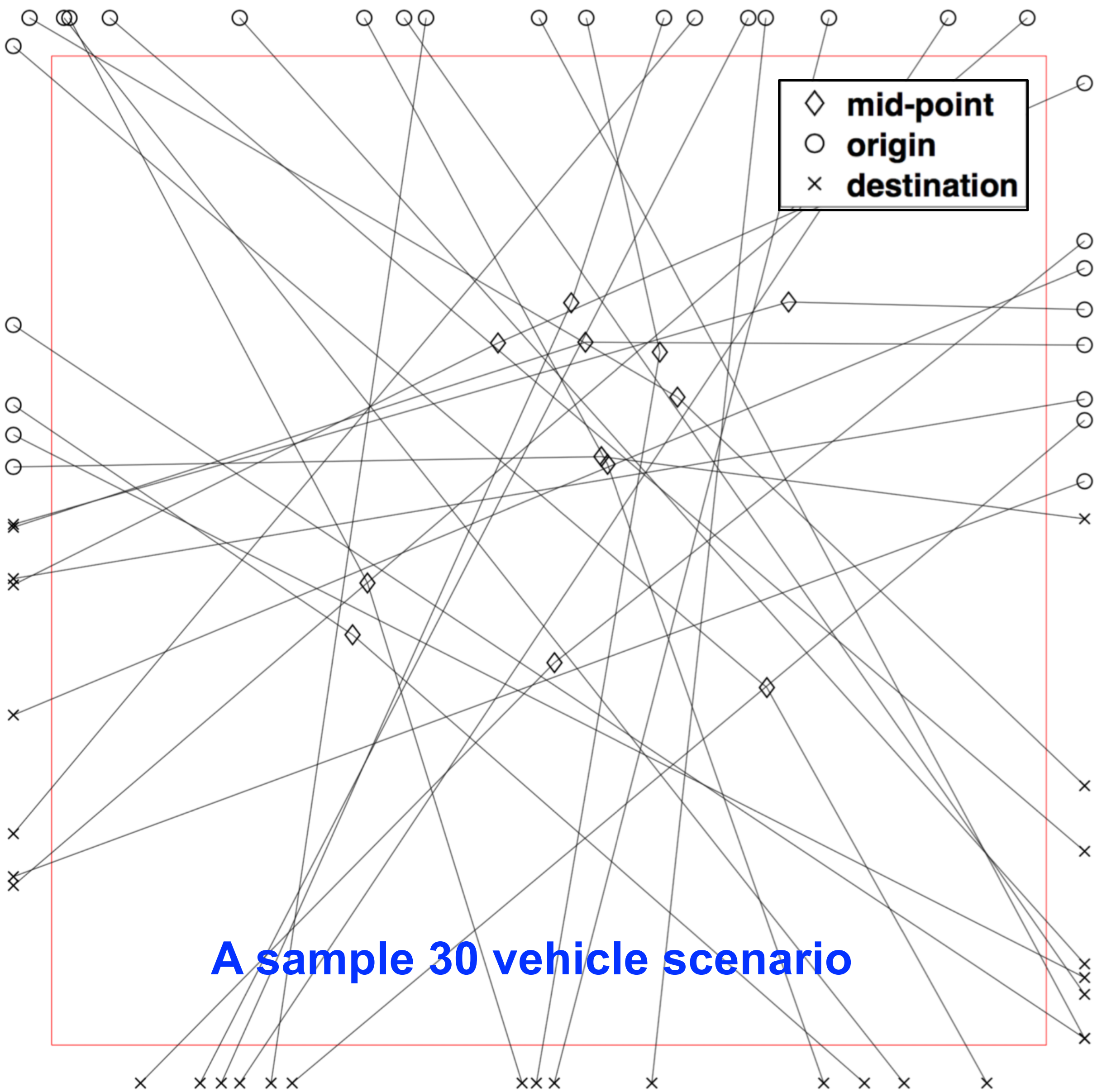
Test Scenario Generation

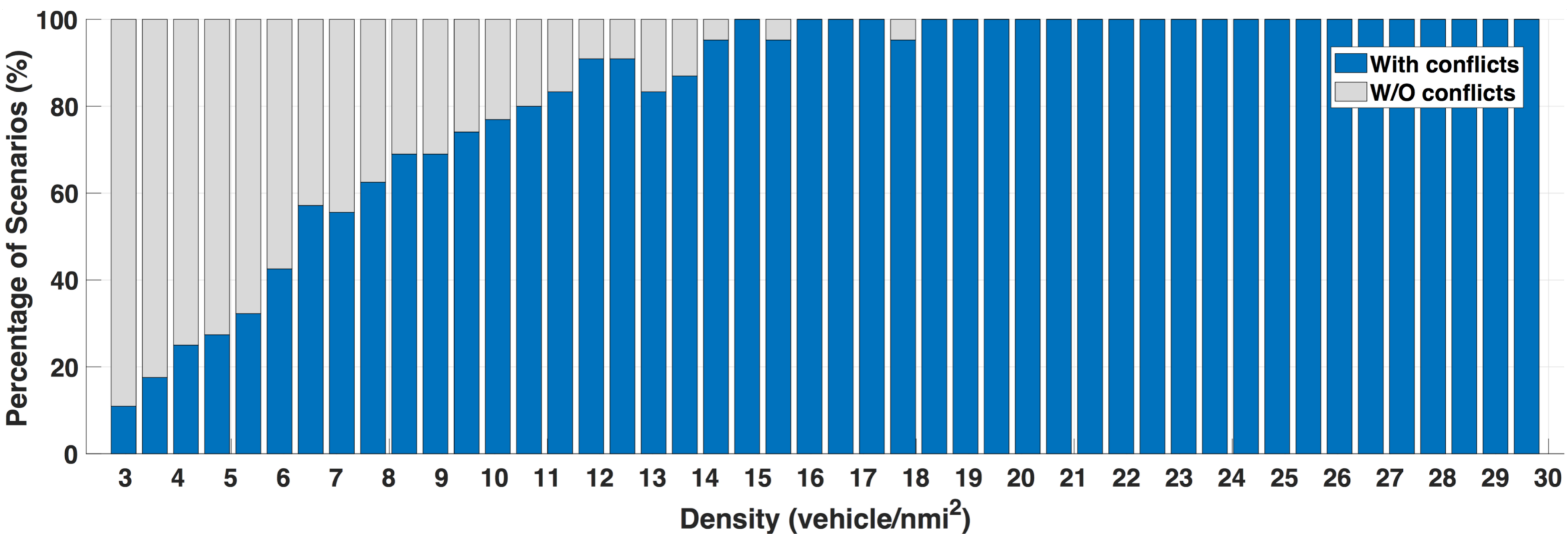


Criteria used in generation:

- $1.3x1.3\ nmi^2$ area
- Origin and destination outside of the area
- At most one turning point
- All flights depart within 5 minutes
- Target ground speeds [5, 20] meter/second

Test Scenarios

- Likelihood of conflict increases when density increases
- Only scenarios with conflicts were used
- 5-50 vehicles (3-30 vehicle/nmi^2, 46 density levels)
- A total of 920 scenarios with 20 scenarios per density level



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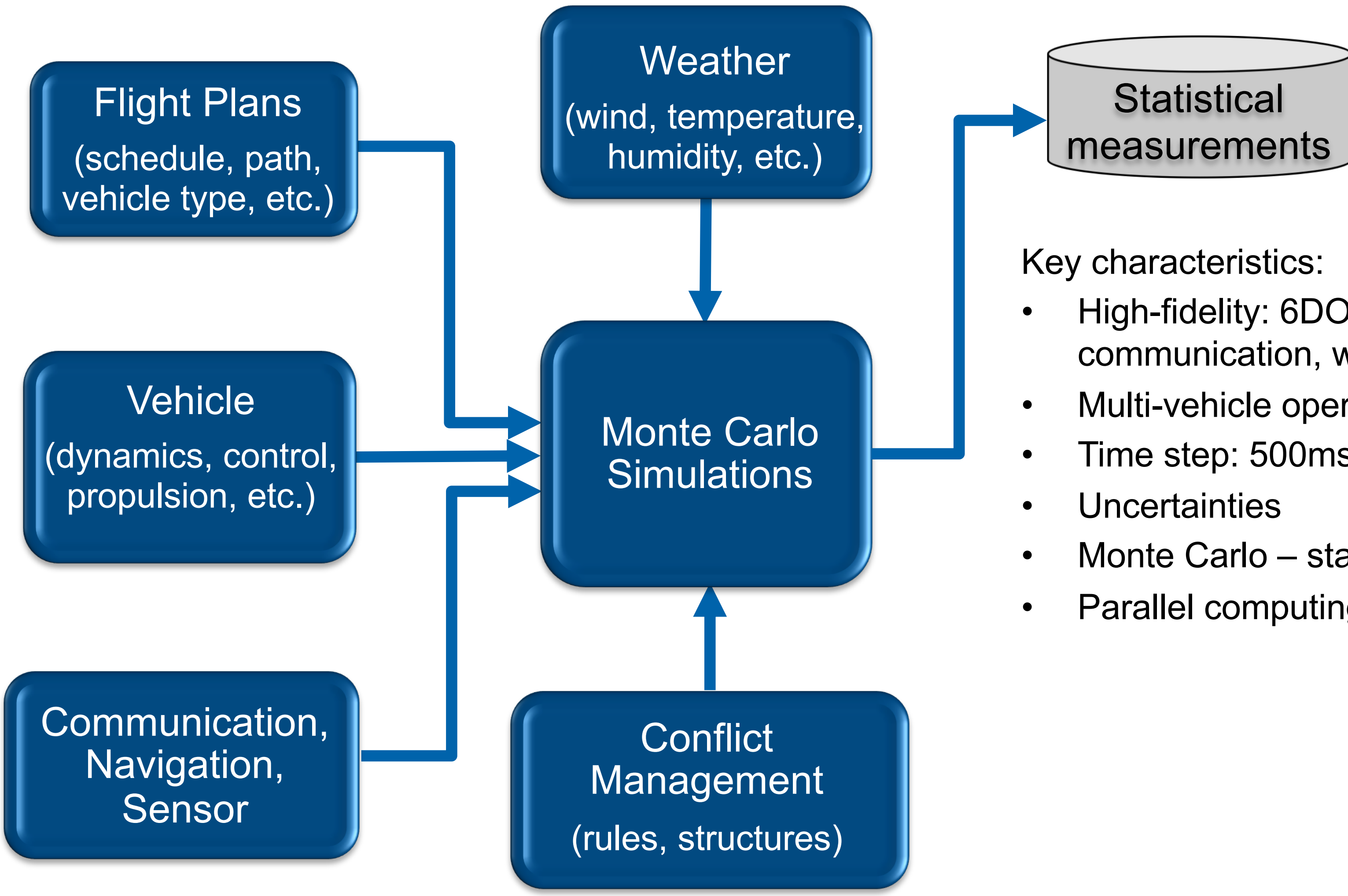
    - Comparison

Complexity ground truth generation using Fe^3

Flexible engine for Fast-time evaluation of Flight environments (Fe^3)
(Using cloud GPU instances)



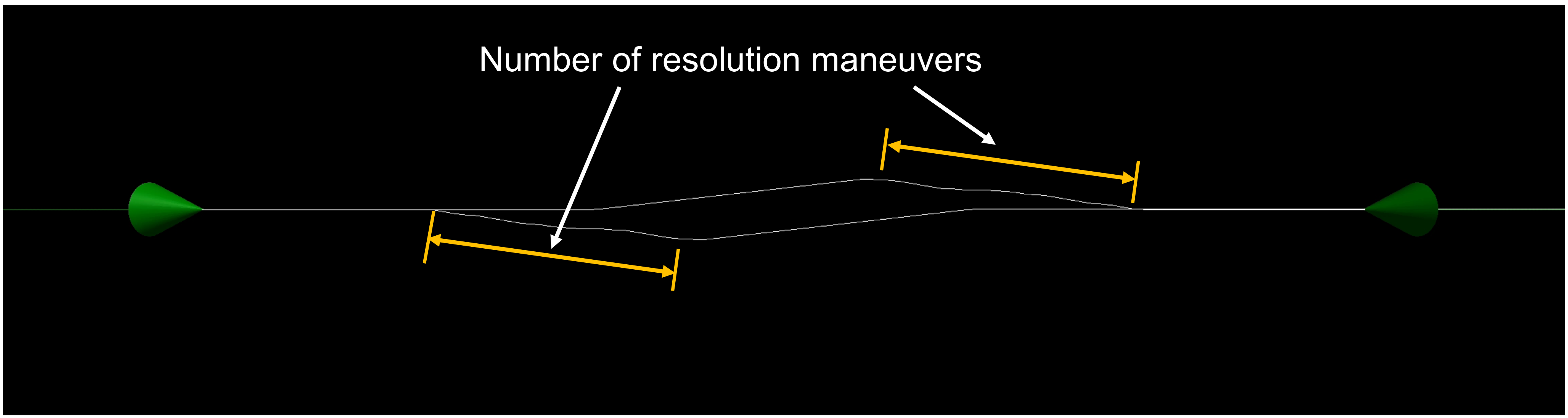
Key characteristics:

- High-fidelity: 6DOF, navigation, communication, wind, etc.
- Multi-vehicle operations
- Time step: 500ms
- Uncertainties
- Monte Carlo – statistics
- Parallel computing capability

Complexity measurement (ground truth)

Number of resolution maneuvers (or resolution duration)

- The total number of time steps when resolution maneuver commands were issued



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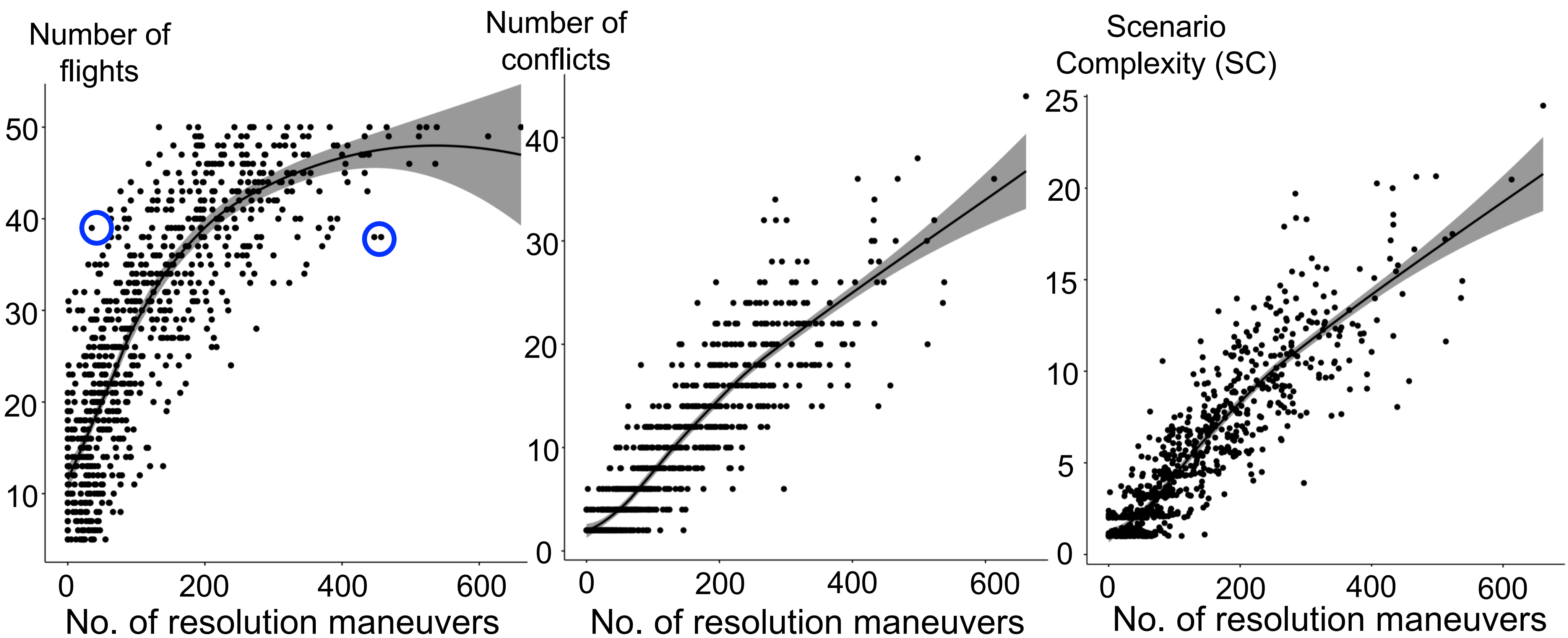
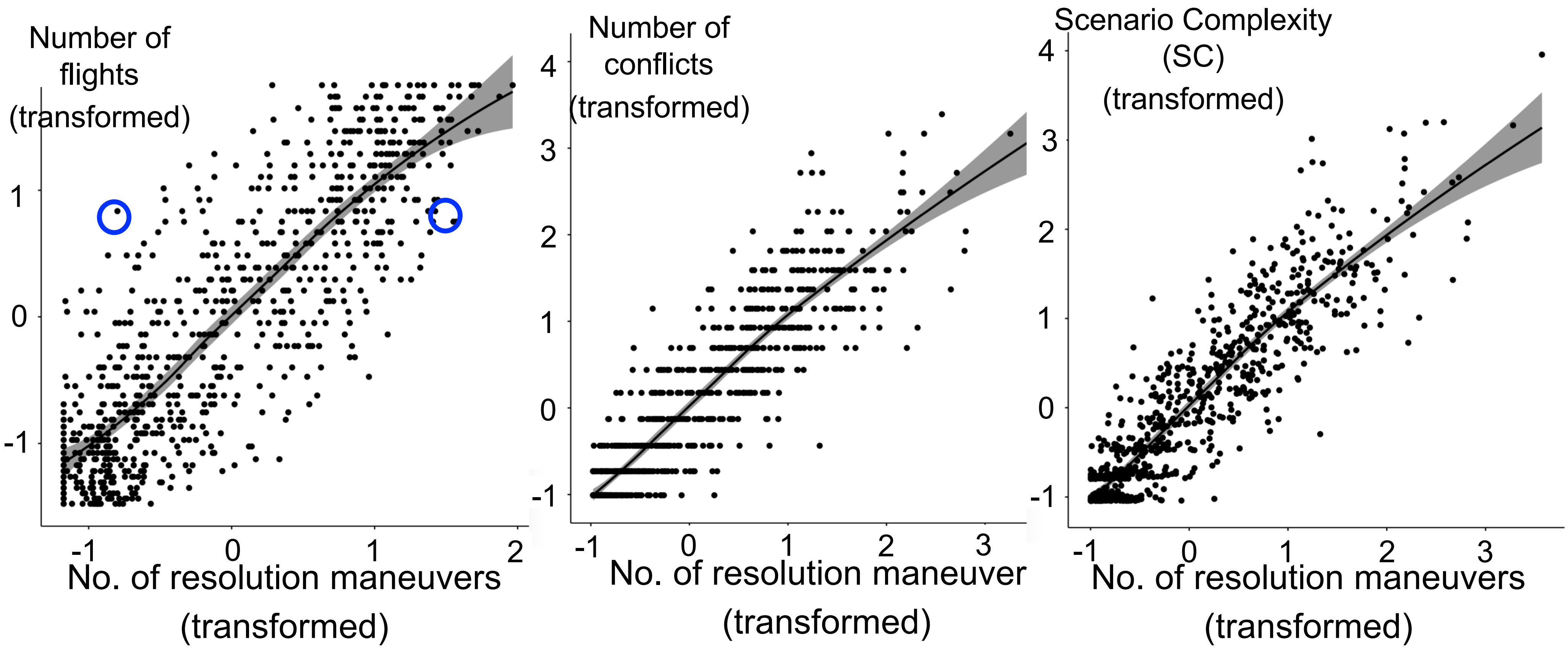
Comparison with Pearson Correlations



R=0.78 R=0.90 R=0.90

- The **number of flights** (or **density**) is **less correlated with the complexity** compared to the other two metrics
- The **SC metric** showed **similar correlation** with the complexity to the number of potential conflicts with **the Pearson method**

Comparison with ACE (Alternative Conditional Expectations) Correlations



R=0.85 R=0.908 R=0.913

- The **number of flights** (or **density**) is **less correlated with the complexity** compared to the other two metrics
- The **SC metric** showed **closer correlation** with the complexity than the number of potential conflicts

Summary

- A quick calculated metric is needed for UAS traffic management.
- A new complexity metric is proposed using results from the MILP formulation
- The approach of using high-fidelity simulation results as the ground truth to evaluate complexity metrics is valuable.
- Evaluation results showed that:
  - The traffic density has the lowest correlation with complexity.
  - Both the new metric and the number of potential conflicts have high correlations.
  - The new metric has slightly higher correlation than the number of potential conflicts

Future work

- Explore if there are other simple features that can better represent traffic complexity through regressions based on simulation results.
- Identify the best simple metric for traffic complexity.