Modeling the Intrinsic Safety of Unstructured and Layered Airspace Designs

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Outline

Introduction

Conflict Rate Models

Fast-Time Simulation Experiments

Results

Conclusions
1. Introduction
Centralized vs. Decentralized Airspace

Centralized ATC

Decentralized ATC

Decentralized ATC is expected to increase capacity

[Adapted from J. M. Hoekstra 2001]
Previous Research: Metropolis Project

Four Airspace Concepts of Increasing Structure

- **Unstructured**
  - 0 Constraints

- **Layers**
  - 1 Constraint
    - Altitude

- **Zones**
  - 2 Constraints
    - X Position
    - Y Position

- **Tubes**
  - 4 Constraints
    - X Position
    - Y Position
    - Altitude
    - Speed

*Layers* showed the highest safety and capacity

[Sunil et al. 2016]
Layered Airspace

- Airspace segmented into **vertical bands**
- Direct horizontal routes
- **Cruising altitude dependent on heading**
- Layers **improved safety** relative to unstructured airspace
Intrusions vs. Conflicts

- Intrusions/loss-of-separations occur when the minimum separation requirements are violated.
- Conflicts are predicted intrusions within the look-ahead time.
Intrinsic Safety and Conflict Rate

• Intrinsic safety of an airspace design:
  – The safety without active conflict resolution

• Conflict rate, a metric of intrinsic safety:
  – The number of conflicts in a particular area/volume of airspace at a given moment in time

Conflict Rate, $C = 7$
Goal of this Research

• Model the intrinsic safety of unstructured and layered airspace designs as a function of physical airspace characteristics

• Extend conflict rate model from Hoekstra et al. 2016 for en route airspace
2. Conflict Rate Models
Conflict Rate Model

\[
\text{Conflict Rate} = X \\
\text{Number of combinations of 2 aircraft} \times \text{Conflict probability between any 2 aircraft}
\]
Modeling Approach

2D Unstructured Airspace

3D Unstructured Airspace

3D Layered Airspace
2D Unstructured Airspace

Conflict Rate = \frac{N_{cruising}(N_{cruising} - 1)}{2} \times p_{2\text{cruising}}

Where:
- $C_{UA2D}$ = Conflict rate for 2D unstructured airspace
- $N_{cruising}$ = Number of cruising aircraft
- $p_{2\text{cruising}}$ = Conflict probability between any 2 cruising aircraft
2D Unstructured Airspace

Conflict Probability Between Cruising Aircraft

\[ p_{2\text{cruising}} = \frac{A_c}{A} \]

\[ p_{2\text{cruising}} = \frac{2 D_{\text{sepH}} \bar{v}_{\text{relH}} t_l}{A} \]

Where:

- \( A \) = Total airspace area
- \( A_c \) = Area searched for conflicts
- \( D_{\text{sepH}} \) = Horizontal separation minima
- \( \bar{v}_{\text{relH}} \) = Horizontal relative velocity
- \( t_l \) = Conflict detection look-ahead time
2D Unstructured Airspace

Horizontal Relative Velocity

\[ v_{rel_H} = 2 \, v \, \sin \left( \frac{|\Delta h d g|}{2} \right) \]

\[ \bar{v}_{rel_H} = \int v_{rel_H} \, P(v_{rel_H} = x) \, dv_{rel_H} \]

Aircraft velocities assumed to be equal
2D Unstructured Airspace

Heading Difference PDF

\[ P(v_{relH} = x) = P(|\Delta Hdg| = x) \]

\[ P(|\Delta Hdg| = x) = \frac{2}{\alpha} \left( 1 - \frac{|\Delta Hdg|}{\alpha} \right) \]

\( \alpha \) is the permitted heading range for cruising aircraft

For unstructured airspace, \( \alpha = 360^\circ (2\pi) \)
2D Unstructured Airspace

Horizontal Relative Velocity

- $\bar{v}_{rel_H} = \int v_{rel_H} P(v_{rel_H} = x) \, dv_{rel_H}$

- $\bar{v}_{rel_H} = \int_0^\alpha 2 \, v \sin \left(\frac{x}{2}\right) \cdot \frac{2}{\alpha} \left(1 - \frac{x}{\alpha}\right) \, dx$

- $\bar{v}_{rel_H}(\alpha) = \frac{8 \, v}{\alpha} \left(1 - \frac{2}{\alpha} \sin \frac{\alpha}{2}\right)$

- $\bar{v}_{rel_H}(2\pi) = \frac{4v}{\pi}$ Expected relative velocity for UA
2D Unstructured Airspace

Summary

- \( C_{UA_{2D}} = \frac{N_{cruising}(N_{cruising} - 1)}{2} p_{2_{cruising}} \)

- \( p_{2_{cruising}} = \frac{2 D_{sepH} \vec{v}_{relH} t_l}{A} \)

- \( \vec{v}_{relH} = \frac{4v}{\pi} \)

Where:

- \( C_{UA_{2D}} \) = Conflict rate for 2D unstructured airspace
- \( N_{cruising} \) = Number of cruising aircraft
- \( p_{2_{cruising}} \) = Conflict probability between any 2 cruising aircraft
- \( A \) = Total airspace area
- \( A_c \) = Area searched for conflicts
- \( D_{sepH} \) = Horizontal separation minima
- \( v_{relH} \) = Horizontal relative velocity
- \( t_l \) = Conflict detection look-ahead time
Modeling Approach

2D Unstructured Airspace

3D Unstructured Airspace

3D Layered Airspace
3D Unstructured Airspace

- Cruising + **Climbing/Descending aircraft**

Number of combinations of 2 aircraft

- Conflict Rate \( X \) = Conflict probability between any 2 aircraft

\[
C_{UA} = \frac{N(N-1)}{2} p_{2UA}
\]

Where:

- \( C_{UA_{3D}} \) = Conflict rate for 3D Unstructured Airspace (UA)
- \( N \) = Number of aircraft (all flight phases)
- \( p_{2UA} \) = Conflict probability between any 2 aircraft for UA
3D Unstructured Airspace

Conflict Probability Between Any 2 Aircraft

\[ V_{cv} = \pi D_{sepH}^2 v_{relV} t_l \]

\[ V_{ch} = 4 D_{sepH} D_{sepV} v_{relH} t_l \]
3D Unstructured Airspace

Conflict Probability Between Any 2 Aircraft

- \[ p_{2UA} = \frac{V_{cH}}{V_{total}} + \frac{V_{cV}}{V_{total}} \]

- \[ p_{2UA} = \frac{4 D_{sepH} D_{sepV} v_{relH} t_l}{V_{total}} + \frac{\pi D_{sepH}^2 v_{relV} t_l}{V_{total}} \]

- \[ v_{relH}(2\pi) = \frac{4v}{\pi} \]

- \[ v_{relV} = ? \]
3D Unstructured Airspace

Vertical Relative Velocity

- \( v_V = v \sin \gamma \)
- \( v_{relV} = f(\Delta \gamma) \)
- \( \ddot{v}_{relV} = \int v_{relV} P(|\Delta \gamma| = x) \, d|\Delta \gamma| \)

En route Airspace:

|\gamma| = 0 \text{ for cruising aircraft}

|\gamma| = \gamma_{C/D} \text{ for climbing/descending aircraft}
# 3D Unstructured Airspace

Discretized Vertical Relative Velocity

<table>
<thead>
<tr>
<th>AC1</th>
<th>AC2</th>
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</thead>
<tbody>
<tr>
<td>![Plane Icon]</td>
<td>![Plane Icon]</td>
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<tr>
<td>0</td>
<td>(v \sin \gamma_{C/D})</td>
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<td>(v \sin \gamma_{C/D})</td>
<td>(2v \sin \gamma_{C/D})</td>
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</tbody>
</table>

Table 1: \(v_{relv}\) based on flight phase
3D Unstructured Airspace

Discretized Vertical Relative Velocity

Table 2: \( P(\lvert \Delta \gamma \rvert = x) \) based on flight phase

<table>
<thead>
<tr>
<th>AC1</th>
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<tbody>
<tr>
<td>( \varepsilon^2 )</td>
<td>( \frac{\varepsilon - \varepsilon^2}{2} )</td>
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<td>( \frac{\varepsilon - \varepsilon^2}{2} )</td>
<td>( \frac{(1 - \varepsilon)^2}{4} )</td>
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</tbody>
</table>

\[ \varepsilon = \frac{N_{cruising}}{N_{total}} \]
3D Unstructured Airspace
Discretized Vertical Relative Velocity

- \( \bar{v}_{relv} = \int v_{relv} P(|\Delta \gamma| = x) \, d|\Delta \gamma| \)

- \( \bar{v}_{relv} = \sum v_{relv} P(|\Delta \gamma| = x) \)
### 3D Unstructured Airspace

#### Discretized Vertical Relative Velocity

<table>
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<th>AC1</th>
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</tbody>
</table>

**Formulas:**

\[ \frac{v \sin \gamma_{C/D}}{D} \]

\[ \frac{2v \sin \gamma_{C/D}}{D} \]

\[ \frac{(1 - \varepsilon)^2}{4} \]

\[ \frac{(1 - \varepsilon)^2}{4} \]
3D Unstructured Airspace
Discretized Vertical Relative Velocity

- $\bar{v}_{relV} = \bar{v}_{relV} = \int v_{relV} P(|\Delta \gamma| = x) \, d|\Delta \gamma|$

- $\bar{v}_{relV} = \sum v_{relV} P(|\Delta \gamma = x|)$

- $\bar{v}_{relV} = v \sin \gamma_{C/D} (1 - \varepsilon^2)$
3D Unstructured Airspace

Summary

- \( C_{UA} = \frac{N(N-1)}{2} p_{2UA} \)

- \( p_{2UA} = \frac{4 D_{sepH} D_{sepV} v_{relH} t_l}{V_{total}} + \frac{\pi D_{sepH}^2 v_{relV} t_l}{V_{total}} \)

- \( v_{relH}(2\pi) = \frac{4v}{\pi} \)

- \( v_{relV} = v \sin \gamma_{C/D} (1 - \varepsilon^2) \)

Where:

- \( N \) = Number of aircraft
- \( D_{sepH} \) = Horizontal Sep. Minima
- \( D_{sepV} \) = Vertical Sep. Minima
- \( v_{relH} \) = Horizontal realtive velocity
- \( v_{relV} \) = Vertical realtive velocity
- \( t_l \) = Look-ahead time
- \( V_{total} \) = Total airspace volume
- \( \varepsilon \) = Proportion of cruising a/c
Modeling Approach

2D Unstructured Airspace

3D Unstructured Airspace

3D Layered Airspace
3D Layered Airspace

1. Conflict Pair Reduction

Both reduction effects act only on conflicts between **cruising aircraft**
3D Layered Airspace

\[ C_{LAY} = C_{LAY_{cruising}} + C_{LAY_{cruising-C/D}} + C_{LAY_{C/D}} \]

Number of combinations of 2 aircraft in 1 Layer

Conflict Rate 1 Layer = \( X \)

Conflict probability between any 2 aircraft
3D Layered Airspace

Cruising Conflicts: Conflict Pair Reduction

- \( C_{cruising_i} = \frac{N_{cruising_i} (N_{cruising_i} - 1)}{2} p_{2cruising} \)

- \( L = \) Number of cruising layers

- \( C_{LAY\ cruising} = \sum_{0}^{L} C_{cruising_i} \)

- \( N_{cruising} = L \cdot N_{cruising_i} \)

- \( C_{LAY\ cruising} = \frac{N_{cruising} \left( \frac{N_{cruising}}{L} - 1 \right)}{2} p_{2cruising} \)
3D Layered Airspace

Cruising Conflicts: Relative Velocity Reduction

- \( p_{2cruising} = \frac{2 D_{sepH} \bar{v}_{relH} t_l}{A} \)

- \( \bar{v}_{relHcruising}(\alpha) = \frac{8 v}{\alpha} \left( 1 - \frac{2}{\alpha} \sin \frac{\alpha}{2} \right) \)

[Adapted from J.Hoekstra et al 2016]
3D Layered Airspace

Cruising-Climbing/Descending Conflicts

- $C_{LAY\text{cruising}-C/D} = N_{cruising} N_{C/D} p_{2\text{cruising}_{CD}}$

- $p_{2\text{cruising}_{CD}} = \frac{4 D_{sep_H} D_{sep_V} v_{rel_H} t_l}{V_{total}} + \frac{\pi D_{sep_H}^2 v_{rel_v} t_l}{V_{total}}$

- $v_{rel_H}(2\pi) = \frac{4v}{\pi}$

- $\bar{v}_{rel_V} = ?$
3D Unstructured Airspace

Discretized Vertical Relative Velocity

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$X$

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</table>
3D Layered Airspace

Cruising-Climbing/Descending Conflicts

- \( C_{LAY_{cruising-C/D}} = N_{cruising} N_{C/D} p_{2_{cruising-C/D}} \)

- \( p_{2_{cruising-C/D}} = \frac{4 D_{sep_H} D_{sep_V} v_{rel_H} t_l}{V_{total}} + \frac{\pi D_{sep_H}^2 v_{rel_V} t_l}{V_{total}} \)

- \( v_{rel_H}(2\pi) = \frac{4v}{\pi} \)

- \( \bar{v}_{rel_V} = 2v \sin \gamma_{C/D} (\varepsilon - \varepsilon^2) \)
3D Layered Airspace

Climbing/Descending Conflicts

- \( C_{LAY\text{C/D}} = \frac{N_{C/D}(N_{C/D}-1)}{2} p_{2\text{C/D}} \)

- \( p_{2\text{C/D}} = \frac{4 D_{sep\text{H}} D_{sep\text{V}} v_{rel\text{H}} t_l}{V_{total}} + \frac{\pi D_{sep\text{H}} v_{rel\text{V}} t_l}{V_{total}} \)

- \( v_{rel\text{H}}(2\pi) = \frac{4v}{\pi} \)

- \( \bar{v}_{rel\text{V}} = ? \)
### 3D Unstructured Airspace

#### Discretized Vertical Relative Velocity

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</tbody>
</table>

- **0**
- **2v \sin \gamma_{C/D}**
- **2v \sin \gamma_{C/D}**
- **0**

\[\varepsilon - \varepsilon^2\]

\[\frac{(1 - \varepsilon)^2}{4}\]

\[\frac{(1 - \varepsilon)^2}{4}\]
3D Layered Airspace

Climbing/Descending Conflicts

- \( C_{LAY_{C/D}} = \frac{N_C/D(N_C/D-1)}{2} \ p_{2C/D} \)

- \( p_{2C/D} = \frac{4 \ D_{sep_H} D_{sep_V} v_{rel_H} t_l}{V_{total}} + \frac{\pi D_{sep_H}^2 v_{rel_v} t_l}{V_{total}} \)

- \( v_{rel_H}(2\pi) = \frac{4v}{\pi} \)

- \( \bar{v}_{rel_V} = v \ \sin \gamma_{C/D} \ (1 - \varepsilon^2) \)
3.

*Fast-Time Simulation Experiments*
BlueSky Open ATM Simulator

https://github.com/ProfHoekstra/bluesky
Experiment Physical Area

Top View

Side View

$D_{sepH} = 5 \text{ NM}$

$D_{sepV} = 1000 \text{ ft}$

$t_l = 5 \text{ mins}$
Primary Experiment
Validate Conflict Rate Models Under Ideal Conditions

1. Traffic Demand

<table>
<thead>
<tr>
<th>#</th>
<th>Density [ac/10,000 NM²]</th>
<th>Number of Instantaneous AC [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>112</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>156</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>217</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>303</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>423</td>
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<tr>
<td>7</td>
<td>37</td>
<td>589</td>
</tr>
<tr>
<td>8</td>
<td>51</td>
<td>822</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>1147</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>1600</td>
</tr>
</tbody>
</table>

2. Airspace Concept

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Heading Range Per Layer, α</th>
<th>Number of Layer Sets</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA</td>
<td>Unstructured Airspace</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L360</td>
<td>Layers 360</td>
<td>360°</td>
<td>8</td>
</tr>
<tr>
<td>L180</td>
<td>Layers 180</td>
<td>180°</td>
<td>4</td>
</tr>
<tr>
<td>L90</td>
<td>Layers 90</td>
<td>90°</td>
<td>2</td>
</tr>
<tr>
<td>L45</td>
<td>Layers 45</td>
<td>45°</td>
<td>1</td>
</tr>
</tbody>
</table>

- Europe: ≈ 7.5 per 10,000 NM² in Class A (FR24 14:00 6/14/2017)
- 10 Densities x 5 concepts x 10 repetitions = **500 Runs**

>1.2 million flights simulated
Flight Path Angle Variation

Effect of Proportion of Cruising Aircraft

1. Three Flight Path Angles for Climbing/Descending Aircraft
   a. 1.4°
   b. 2.8°
   c. 5.6°

2. Two Concepts
   a. Unstructured Airspace
   b. Layers 45

3. Traffic Demand

- 3 Flight Path Angles
- 2 Concepts
- 10 Densities
- 10 repetitions

= 600 runs

>1.4 million flights simulated
4. Results
Primary Experiment

Total Conflicts

Lower $\alpha$ improves safety
Increase in safety with lower $\alpha$ only for cruising conflicts
Primary Experiment

Conflict Types

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Cruising</th>
<th>Cruising-C/D</th>
<th>C/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA</td>
<td>96.8%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L360</td>
<td>-</td>
<td>96.4%</td>
<td>69.5%</td>
<td>67.5%</td>
</tr>
<tr>
<td>L180</td>
<td>-</td>
<td>97.0%</td>
<td>69.8%</td>
<td>67.7%</td>
</tr>
<tr>
<td>L90</td>
<td>-</td>
<td>96.9%</td>
<td>70.0%</td>
<td>68.3%</td>
</tr>
<tr>
<td>L45</td>
<td>-</td>
<td>91.8%</td>
<td>71.9%</td>
<td>71.0%</td>
</tr>
</tbody>
</table>
Flight Path Angle Experiment

\[ C_{LAY\text{cruising}-C/D} = N_{cruising} \frac{N_{C/D}}{p_{2\text{cruising}CD}} \]

Analysis Altitudes

Outside Analysis Altitudes

Underestimated
Flight Path Angle Experiment
Unstructured Airspace (Total Conflicts)

No significant effect of $\gamma_{C/D}$ on UA
Flight Path Angle Experiment

Layered Airspace (Total Conflicts)

Higher $\gamma_{C/D}$ improves safety for Layers
5. Conclusions
Conclusions

• 3D conflict rate models for unstructured and layered airspace concepts were derived

• Model accuracy was high when tested using fast-time simulations
  – Experiment design affected accuracy of climbing/descending conflicts

• Layered airspace safer than unstructured airspace
  – Conflict pair reduction
  – Relative velocity reduction

• Safety of Layered airspace increases when the heading range per altitude layer is decreased

• Conflict rate is inversely proportional to flight path angle
  – Layers concept more sensitive to changes in flight path angle
Thankyou For Your Attention!

[e.sunil@tudelft.nl]
[https://www.researchgate.net/profile/Emmanuel_Sunil]
6. Backup Slides
Dependent Variables

\[ C = \frac{N(N - 1)}{2} p_2 k \]

- \( k = 1 \rightarrow 100\% \) accurate
- \( k < 1 \rightarrow \) Overestimate
- \( k > 1 \rightarrow \) Underestimate

\[ \text{Accuracy} = 100\% - \frac{|1 - k|}{k}\% \]
## Flight Path Angle Experiment

### Model Accuracy

<table>
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<tr>
<th></th>
<th>Total</th>
<th>Cruising</th>
<th>Cruising-C/D</th>
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<tbody>
<tr>
<td>UA-1.4</td>
<td>85.6%</td>
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<tr>
<td>UA-2.8</td>
<td>96.8%</td>
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<tr>
<td>UA-5.6</td>
<td>96.2%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>L45-1.4</td>
<td>-</td>
<td>85.0%</td>
<td>65.9%</td>
<td>57.6%</td>
</tr>
<tr>
<td>L45-2.8</td>
<td>-</td>
<td>91.8%</td>
<td>71.9%</td>
<td>71.0%</td>
</tr>
<tr>
<td>L45-5.6</td>
<td>-</td>
<td>93.4%</td>
<td>97.3%</td>
<td>84.8%</td>
</tr>
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Accuracy *increases* with flight path angle
Flight Path Angle Experiment

\[ C_{LAY_{cruising-C/D}} = N_{cruising} \frac{N_{C/D}}{D} p_{2_{cruising}} \]

- An increase in flight path angle increases the proportion of cruising aircraft.
- This reduces the chance of interactions with aircraft outside analysis altitudes, thus increasing model accuracy.
Ground Speed Variation Experiment

Effect of Equal Speed Assumption

1. Three Ground Speed Distributions
   a. Equal
   b. Gaussian
   c. Uniform

2. Two Concepts
   a. Unstructured Airspace
   b. Layers 45

3. Traffic Demand

400kts 350kts 450kts 400kts

- 3 Speed Distributions
- 2 Concepts
- 10 Densities
- 10 repetitions

= 600 runs

>1.4 million flights simulated
## Ground Speed Variation Experiment

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<tr>
<th></th>
<th>Total</th>
<th>Cruising</th>
<th>Cruising-C/D</th>
<th>C/D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UA-Equal</strong></td>
<td>96.81%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>UA-Gaussian</strong></td>
<td>96.59%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>UA-Uniform</strong></td>
<td>96.58%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>L45-Equal</strong></td>
<td>-</td>
<td>91.80%</td>
<td>71.86%</td>
<td>71.02%</td>
</tr>
<tr>
<td><strong>L45-Gaussian</strong></td>
<td>-</td>
<td>87.75%</td>
<td>71.51%</td>
<td>69.16%</td>
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<tr>
<td><strong>L45-Uniform</strong></td>
<td>-</td>
<td>83.49%</td>
<td>72.05%</td>
<td>67.57%</td>
</tr>
</tbody>
</table>

- Accuracy for Unstructured Airspace unaffected by ground speed variation
- Accuracy for Layers decreases slightly with increasing ground speed variation