Analyzing the Effect of Traffic Scenario Properties on Conflict Count Models

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Outline

Introduction

Baseline Analytical Model

Fast-Time Simulation Experiments

Results and Numerically Adjusted Models

Conclusions
1. Introduction
ATM in Fast-Time Simulations
Four Airspace Concepts of Increasing Structure Compared Using Fast-Time Simulations
# Pros and Cons of Simulations

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can be very realistic</td>
<td>Time consuming</td>
</tr>
<tr>
<td>Analyze different conditions</td>
<td>Results can be qualitative</td>
</tr>
<tr>
<td>High-level system dynamics</td>
<td>Difficult to generalize results</td>
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</tbody>
</table>
Conflict Count Models

Number of combinations of 2 aircraft

Inst. Conflict Count = \( X \)

Conflict probability between any 2 aircraft
Intrinsic Airspace Safety

Intrinsic safety is the safety that is provided **exclusively** by the *constraints* imposed on traffic motion by an *airspace design*.
Conflict Count Models

Inst. Conflict Count = \text{Number of combinations of 2 aircraft} \times \text{Conflict probability between any 2 aircraft}
What is a Traffic Scenario?

A traffic scenario describes the distributions of aircraft:

1. Speed
2. Heading
3. Altitude
4. Density/Spatial
Traffic Scenario Assumptions

1. **Speed** is equal for all aircraft
2. **Heading** distribution is uniform
3. **Altitude** distribution is uniform
4. **Density/spatial** distribution is uniform

How accurate are these models for more realistic traffic scenarios?
Research Goals

1. Study the effect of traffic scenario assumptions on the **accuracy** of analytical conflict count models for more realistic traffic scenarios
   - Unstructured airspace used as a case study

2. Derive and test ‘**model adjustments**’ to generalize the models for all traffic scenarios
2. **Baseline Analytical Model**
Intrusions vs. Conflicts

Intrusion

\[ 2S_h \]

Conflict
Conflict Count Model for Unstructured Airspace

\[
\text{Inst. Conflict Count} = \text{Number of combinations of 2 aircraft} \times \text{Conflict probability between any 2 aircraft}
\]
Number of Combinations of 2 A/C

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

\[ p \]
Average Conflict Probability

\[ p = \frac{B_c}{B_{total}} \]
Average Conflict Probability

\[ p = \frac{B_{c,h} + B_{c,v}}{B_{total}} = \frac{4 S_h S_v \mathbf{E} (V_{r,h}) t_l + \pi S_h^2 \mathbf{E} (V_{r,v}) t_l}{B_{total}} \]

\[ \mathbf{E} (V_{r,h}) = \frac{4V}{\pi} \]

\[ \mathbf{E} (V_{r,v}) = V \sin(\gamma) \left( 1 - \varepsilon^2 \right) \]
Traffic Scenario Assumptions

Assumes uniform **altitude** and **density/spatial** distributions of traffic

\[ p = \frac{B_c}{B_{\text{total}}} \]
Traffic Scenario Assumptions

Assumes equal ground speed and uniform heading distribution of traffic

\[ p = \frac{4 S_h S_v \mathbb{E}(V_{r,h}) t_l + \pi S_h^2 \mathbb{E}(V_{r,v}) t_l}{B_{total}} \]

\[ \mathbb{E}(V_{r,h}) = \frac{4V}{\pi} \]

\[ \mathbb{E}(V_{r,v}) = V \sin(\gamma) (1 - \varepsilon^2) \]
Traffic Scenario Assumptions

1. **Speed** is equal for all aircraft
2. **Heading** distribution is uniform
3. **Altitude** distribution is uniform
4. **Density/spatial** distribution is uniform

For **Unstructured Airspace**, all 4 assumptions affect the **average conflict probability** between any two aircraft.
3. Fast-Time Simulation Experiments
BlueSky Open ATM Simulator

https://github.com/ProfHoekstra/bluesky
4 Assumptions – 4 Experiments

1. Ground-Speed Experiment
2. Heading Experiment
3. Altitude Experiment
4. Spatial Experiment

Traffic Scenarios
- 5 Densities (5-100 a/c per 10,000 NM²)
- 5 Repetitions
Ground Speed Experiment

Equal Speed

Baseline analytical model

Uniform Distribution

Different mix of aircraft types

Normal Distribution

Bimodal Distribution
Heading Experiment

Uniform

Normal

Bimodal

Ranged-Uniform
Altitude Experiment

Baseline analytical model

One preferred destination

Two preferred destinations

Traffic in upper airspace for fuel efficiency
Spatial Experiment

Uniform

Hot Spot 1

Hot Spot 2
4. Results and Numerically Adjusted Models
Model Accuracy Measurement

Analytical Model for Ideal Traffic Scenario

No. Inst Conflicts = Model \cdot k

\( k = 1 \quad 100\% \text{ accuracy} \)

\( k < 1 \quad \text{Overestimation} \)

\( k > 1 \quad \text{Underestimation} \)

\( k = 1.024 \ (97.6\%) \)
Ground Speed Experiment

No substantial effect of ground speed distribution on safety for Unstructured Airspace
Ground Speed Adjustment

\[ V_{r,h \, \text{baseline}} = 2 \, V \, \sin\left(\frac{|\Delta\psi|}{2}\right) \]

\[ \mathbb{E}(V_{r,h})_{\text{baseline}} = \int_{0}^{\alpha} V_{r,h} \, P(|\Delta\psi|) \, d\Delta\psi \]

\[ \rightarrow \frac{4V}{\pi} \]
Ground Speed Adjustment

\[ V_{r,h \, \text{adjusted}} = \left( V_1^2 + V_2^2 - 2V_1V_2 \cos(\Delta \psi) \right)^{1/2} \]

\[ \mathbf{E} (V_{r,h})_{\text{adjusted}} = \int \int \int_{V_1, V_2, \Delta \psi} V_{r,h} (V_1, V_2, \Delta \psi) P(|\Delta \psi|) P(V_1) P(V_2) \, d\Delta \psi \, dV_1 \, dV_2 \]

<table>
<thead>
<tr>
<th></th>
<th>Baseline (Equal)</th>
<th>Uniform</th>
<th>Normal</th>
<th>Bimodal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>509</td>
<td>512</td>
<td>507</td>
<td>509</td>
</tr>
</tbody>
</table>
Ground Speed Experiment

![Graph showing the number of instantaneous conflicts for different ground speeds](image)

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<th>Baseline Equal</th>
<th>Uniform</th>
<th>Normal</th>
<th>Bimodal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analytical</strong></td>
<td>1.024 (97.6%)</td>
<td>1.026</td>
<td>1.026</td>
<td>1.020</td>
</tr>
<tr>
<td><strong>Adjusted</strong></td>
<td>1.024 (97.6%)</td>
<td>1.022</td>
<td>1.029</td>
<td>1.019</td>
</tr>
</tbody>
</table>
Heading distribution can cause the analytical model to over-estimate conflict counts.
Heading Adjustment

\[ V_{r,h \ baseline} = 2 \ V \ \sin \left( \frac{|\Delta \psi|}{2} \right) \]

\[ \mathbf{E} (V_{r,h})_{baseline} = \int_{0}^{\alpha} V_{r,h} \ P (|\Delta \psi|) \ d\Delta \psi \]

\[ P (|\Delta \psi|)_{uniform} = \frac{1}{\pi} \left( 1 - \frac{\Delta \psi}{2\pi} \right) \]

\[ \frac{4V}{\pi} \]
Heading Adjustment

V_{r,h \text{ adjusted}} = \left( V_1^2 + V_2^2 - 2V_1V_2 \cos(\Delta \psi) \right)^{1/2}

E(V_{r,h \text{ adjusted}}) = \int \int \int_{V_1, V_2, \Delta \psi} V_{r,h} (V_1, V_2, \Delta \psi) P(|\Delta \psi|) P(V_1) P(V_2) \, d\Delta \psi \, dV_1 \, dV_2

<table>
<thead>
<tr>
<th>Baseline (Uniform)</th>
<th>Bimodal</th>
<th>Normal</th>
<th>Ranged-Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>509</td>
<td>485</td>
<td>395</td>
<td>370</td>
</tr>
</tbody>
</table>
Heading Experiment

The graph shows the number of instantaneous conflicts for different scenarios:
- Baseline / Uniform
- Bimodal
- Normal
- Ranged Uniform

The table below provides the number of instantaneous conflicts for analytical and adjusted methods:

<table>
<thead>
<tr>
<th></th>
<th>Baseline Uniform</th>
<th>Bimodal</th>
<th>Normal</th>
<th>Ranged Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>1.024 (97.6%)</td>
<td>1.004 (99.5%)</td>
<td>0.812 (76.8%)</td>
<td>0.768 (69.9%)</td>
</tr>
<tr>
<td>Adjusted</td>
<td>1.024 (97.6%)</td>
<td>1.041 (96.0%)</td>
<td>0.982 (98.1%)</td>
<td>0.974 (97.3%)</td>
</tr>
</tbody>
</table>
Altitude distribution can cause the analytical model to significantly **under-estimate** conflict counts.
Altitude Adjustment

\[ p = \frac{4 S_h S_v \mathbf{E} (V_{r,h}) t_l + \pi S_h^2 \mathbf{E} (V_{r,v}) t_l}{B_{total}} \]

\[ p = \frac{4 S_h S_v \mathbf{E} (V_{r,h}) t_l + \pi S_h^2 \mathbf{E} (V_{r,v}) t_l}{A_{total}} \cdot p_v \]

Altitude spread of all A/C

\[ p_v = \int_{Z_{min}}^{Z_{max}} \int_{h-S_v}^{h} P_z(h) \ P_z(u) \ du \ dh \quad \longrightarrow \quad p_v, \ uniform = \frac{1}{H} \]

A/C \( j \) in vertical range of A/C \( i \)
Altitude Experiment

![Graph showing the number of instantaneous conflicts for different altitude distributions.]

<table>
<thead>
<tr>
<th></th>
<th>Baseline Uniform</th>
<th>Normal</th>
<th>Bimodal</th>
<th>Ranged Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>1.024 (97.6%)</td>
<td>1.569  (63.7%)</td>
<td>1.416  (70.6%)</td>
<td>1.576 (63.4%)</td>
</tr>
<tr>
<td>Adjusted</td>
<td>1.024 (97.6%)</td>
<td>1.102  (90.6%)</td>
<td>0.994  (99.4%)</td>
<td>0.957 (95.5%)</td>
</tr>
</tbody>
</table>
Spatial Experiment

Spatial distribution can cause the analytical model to significantly **under-estimate** conflict counts.

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>Baseline / Uniform</th>
<th>Hot-Spot 1</th>
<th>Hot-Spot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>1.024 (97.6%)</td>
<td>1.724 (59.7%)</td>
<td>2.077 (48.1%)</td>
</tr>
</tbody>
</table>
Spatial Adjustment

\[ C_{total} = C_{area_1} + C_{area_2} + C_{area_{1,2}} \]
Spatial Experiment

![Graph showing the number of instantaneous conflicts for Baseline/Uniform, Hotspot 1, and Hotspot 2. The graph includes error bars for each data point.]

<table>
<thead>
<tr>
<th></th>
<th>Baseline Uniform</th>
<th>Hot-Spot 1</th>
<th>Hot-Spot 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>1.024 (97.6%)</td>
<td>1.724 (57.9%)</td>
<td>2.077 (48.1%)</td>
</tr>
<tr>
<td>Adjusted</td>
<td>1.024 (97.6%)</td>
<td>0.906 (89.6%)</td>
<td>1.017 (98.2%)</td>
</tr>
</tbody>
</table>
5.

Conclusions
Conclusions

• Analytical model very accurate for ideal traffic scenario
• Conflict probability was incorrectly predicted by analytical model for non-uniform heading, altitude and spatial distributions.
• Spatial distribution of traffic led to the largest negative impact on the accuracy of the analytical model
• Ground-speed distribution did not affect analytical model accuracy
• Numerical model adjustments increased model accuracy for non-ideal conditions
Conclusions

• Adjusted conflict count models:
  – Understand the relationships between the factors affecting airspace safety
  – Tool for practical airspace design applications

• Future work will extend model adjustments for layered and other airspace designs
Thank You For Your Attention!

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