Analytical Workload Model for Estimating En Route Sector Capacity in Convective Weather*

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16 June 2011

*This work was sponsored by the Federal Aviation Administration under Air Force Contract No. FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
Issues with Existing Airspace Capacity Models

• Weather-impact models yield flow reduction relative to historical fair-weather traffic (fractional availability)
  – Route blockage model
  – Sector min-cut max-flow approach
  – Directional ray scanning method

• Controller workload, which determines sector capacity, is not taken into account

• Workload-based sector models give absolute capacity values but weather effects not included
  – Detailed simulation models
  – “Macroscopic” analytical models

⇒ Incorporate convective weather effects into analytical sector workload model
Outline

• Motivation
• Sector capacity model without weather
• Sector capacity model with weather
• Results and issues
• Summary
Controller Workload Limits Traffic

- Sector reaches capacity when the controller team is fully occupied
- Queuing grows with three critical traffic-dependent event rates

**Conflict rate**

\[ \lambda_c = (2 \frac{N^2}{Q}) M_h M_v V_{21} \]

- Sector aircraft count \( N \)
- Sector airspace volume \( Q \)
- Miss distances \( M_h, M_v \)
- Mean closing speed \( V_{21} \)

**Monitor Alert Parameter (MAP) basis**

**Transit (boundary crossing) rate**

\[ \lambda_t = \frac{N}{T} \]

- Sector aircraft count \( N \)
- Mean sector transit time \( T \)

**Recurring event (scanning/monitoring) rate**

\[ \lambda_r = \frac{N}{P} \]

- Sector aircraft count \( N \)
- Recurrence period \( P \)
Task-Based Analytical Sector Workload Model

\[ G = G_b + G_c + G_r + G_t \]

- **Background**
  - Service times (empirical)
  - \( G_b = \tau_c [(2 N^2/Q) M_h M_v V_{21}] \)

- **Conflict**
  - Occurrence rates (calculated from airspace parameters)
  - \( G_c = \tau_c [N/P] \)

- **Recurring**
  - \( G_r = \tau_r [N/P] \)

- **Transition**
  - \( G_t = \tau_t [N/T] \)

**Determining the unknown service times**

- **Live approach**
  - Measure controller performance

- **Regression approach**
  - Observe peak daily counts \( N_p \) for many sectors
  - Calculate corresponding model capacities \( N_m \)
  - Find service times that best fit \( N_m \) to \( N_p \) bound

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Welch et al., 2007: Macroscopic model for estimating en route sector capacity, 7th USA/Europe ATM R&D Seminar, Barcelona, Spain
Effect of Altitude Changes

- Aircraft with vertical rates cause increased uncertainty
- Adapt by increasing vertical miss distance $M_v$
  - Determine fraction $F_{ca}$ of aircraft with $\geq 2000$ ft altitude change
  - As $F_{ca}$ grows, increase $M_v$ linearly from 1000 ft to $M_{vmax}$

$$M_{vmax} \approx 1600 \text{ ft}$$
(for NAS)
Simple analytical model can bound data well and is suitable for real-time application.
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Convective Weather Avoidance Model (CWAM)

Creating the model

ENSEMBLE OF CIWS WEATHER & ETMS TRAJECTORIES

IDENTIFY WEATHER ENCOUNTERS

Planned Path

Actual Path

VIL

Planned Path

Actual Path

VIL

Planned Path

Actual Path

VIL

Planned Path

Actual Path

CLASSIFY TRAJECTORY

Non-deviation

Mean Deviation Threshold

Deviation

Begin Deviation

Actual Path

End Deviation

Planned Path

Data Editing

Decision Point

Actual Path

Planned Path

EDITED TRAJECTORIES

DEVIA TION DATABASE

Classified Weather Encounters

Non-Deviation

Deviation

Edited Trajectories

2006-2008 Database

Total Weather Encounters: ~10000
Weather Encounters w/ Deviation: ~1500
Weather Encounters w/o Deviation: ~3500
Weather Encounters Edited: ~5000
Weather Avoidance Field (WAF)

Applying the model

CIWS WEATHER DATA
- VIL
- EchoTop

DEVIATION DATABASE
- Non-Deviation
- Deviation

Spatial Filters

Deviation Probability
- Flight Altitude – 16km EchoTop 90th Percentile
- 60km VIL Area Coverage

WEATHER AVOIDANCE FIELD
- Deviation Probability Lookup Table
- Flight Altitude – 16km EchoTop 90th Percentile
- 60km VIL Area Coverage
Weather Blockage Modification to Sector Workload Model

No Weather

\[ G_{\text{max}} = G_b + \frac{\tau_r}{P} N + \frac{\tau_t}{T} N + \frac{\tau_c B N}{Q} (N + 1) \]

With Weather

\[ G_{\text{max}} = G_b + \left( \frac{\tau_r + \tau_w F_w}{P} \right) N + \frac{\tau_t N}{T} + \frac{\tau_c B N (N + 1)}{Q (1 - F_w)} \]

- \( F_w = \text{fraction of airspace blocked by weather} \)
- \( \tau_w = \text{time needed per reroute due to weather blockage} \)

- **Compute** \( F_w \) **from WAF data**
  - 80% WAF contours
  - Integrate over WAF contours at 2000-ft altitude increments
  - Fractional blockage of 3D sector volume
- **Fit to observed sector peak counts during weather to obtain** \( \tau_w \)
  - Compare to \( \tau_w = 45–60 \text{ s estimated by experienced air traffic controller} \)
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Some Results Using Observed Weather

- **ZDC32 060623**
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- **ZDC32 070821**
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- Actual sector peak count
- Fair-weather model capacity
- Model capacity with \( \tau_w = 30 \) s
- Model capacity with \( \tau_w = 90 \) s
Weather Effects on Sector Transit Time

- “Cutting corners” to avoid weather decrease mean sector transit time
- Use fitted wx blockage-transit time relationship to adjust mean transit time in capacity forecast
- $F_{ca}$ does not show dependence on weather blockage
Model vs. Observed Peak Sector Count

- Capacity model should bound sector peak count data
- Still do not have a lot of heavy weather impact cases
- For now set $\tau_w = 45$ s (consistent with subject matter expert estimate)

31 ARTCC-days worth of data used
Some Results with Forecast Weather

- Historical mean sector transit time and $F_{ca\ per}$ are used in forecast
  - Transit time adjusted for weather blockage
  - Better to use time-dependent forecast values of transit time and $F_{ca\ per}$ if available
Model Dependencies

- Three workload components affected by weather
  - Conflict resolution task (via available airspace reduction)
  - Weather rerouting task
  - Sector hand-off task (via mean transit time reduction)
- The rerouting and hand-off tasks dominate the dependence of workload on weather except at very high weather blockages
Capacity vs Weather Blockage Fraction

Capacity dependence on weather blockage is nonlinear

- Sector Volume = 5,000 \text{ nm}^3
- Sector Volume = 10,000 \text{ nm}^3
- Sector Volume = 30,000 \text{ nm}^3
Sector weather blockage forecast errors

- Sector weather blockage is scalar: Straightforward error analysis
- Need to accumulate more data for heavy weather cases

22 ARTCC-days worth of data used
Sector Capacity Forecast Errors

- No sector capacity truth available
- Comparison of model capacity using forecast data vs. observed data
- Accurate forecast of sector transit time as important as weather forecast
Directional Capacity Issue

- Sector capacity (peak traffic count) is scalar—no differentiation based on flow direction
- But flow capacity is directional
  - Sector transit time depends greatly on sector shape and travel direction
  - Weather blockage can be highly directional
- Formulate workload model for directional capacity
  - Replace scalar $F_w$ with directional weather blockage in reroute term
  - Utilize existing directional blockage model
- Scalar capacity depends on directional capacity and 4D flight trajectories—a difficult forecast problem
Summary

- Sector capacity model based on analytical workload model was modified to include weather effects
- Difficult to validate because “truth” is not available
  - Model as upper bound—use statistics
  - Initial results are promising—need to analyze more data
- Sector capacity forecast uncertainties arise from
  - Sector transit times
  - Weather
- Weather forecast uncertainties are large at several hours in advance
  - Huge effort in developing complicated and ultradetailed capacity model may not be justified
- Need to tackle directional capacity issue
- Collaboration with MIT ORC and Metron to provide sector capacity input to air traffic flow optimization models
Back-up Slides
Monitor Alert Parameter (MAP) Model

MAP capacity is based on handoff workload, assuming 36-second handoff time per flight.

Peak aircraft count, \( N_{\text{MAP}} = T/36 \) (18 aircraft limit)

\( T \) is mean transit time, in seconds.

Peak throughput, \( F_{\text{MAP}} = N_{\text{MAP}}/T \)

\( F_{\text{MAP}} = 100 \) aircraft/hour

Operational MAP settings:
- over-estimate capacity of small sectors by ignoring conflict workload
- show that workload, not MAP rule, limits small-sector capacity

Lincoln Laboratory model
- accounts for additional workload effects
- extrapolates small sector workload capacity to large sectors
- shows that 18-aircraft limit under-estimates capacity in large sectors

Advantages of fitting models to peak count and transit time data:
- simple and inexpensive
- can determine system workload parameters for
  - entire NAS
  - individual centers
- could support automated performance and parameter updates
Convective Weather Forecast Issues

Actual

1-hr fcst

2-hr fcst

3-hr fcst

19:30  20:00  20:30  21:00  21:30  22:00  UT

ZME26 2010-6-17 25-kft WAF