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**

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

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

**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

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

- **Service times (empirical)**
  - \( G_c = \tau_c \left( \frac{2 N^2}{Q} M_h M_v V_{21} \right) \)
  - \( G_r = \tau_r \left[ \frac{N}{P} \right] \)
  - \( G_t = \tau_t \left[ \frac{N}{T} \right] \)

- **Occurrence rates (calculated from airspace parameters)**

- **Fraction of controller time**

- **Sector workload intensity**

- **Background** as conflicts arise
- **Conflict** periodic
- **Recurring** at sector crossings
- **Transition** Traffic limit for sector

**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

**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 \( M_{v_{max}} \)

\[ M_{v_{max}} \approx 1600 \text{ ft (for NAS)} \]
Fitted Capacities vs. Peak Counts
(790 NAS Sectors July–August 2007)

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

IDENTIFY WEATHER ENCOUNTERS

CLASSIFY TRAJECTORY

Non-deviation

Mean Deviation Threshold

Deviation

Begin Deviation

Actual Path

End Deviation

Planned Path

Data Editing

Actual Path

Planned Path

Decision Point

DEVIAION 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

Spatial Filters

Deviation Probability

Flight Altitude – 16km
Echo Top 90th Percentile

60km VIL Area Coverage

WEATHER AVOIDANCE FIELD

Deviation Probability
Lookup Table

Flight Altitude – 16km
Echo Top 90th Percentile

60km VIL Area Coverage

CIWS WEATHER DATA

VIL

EchoTop

DEVIATION DATABASE

Non-Deviation

Deviation

Statistical Pattern Classifier

60km VIL Area Coverage
Weather Blockage Modification to Sector Workload Model

No Weather

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

With Weather

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

- \( F_w \) = fraction of airspace blocked by weather
- \( \tau_w \) = 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 \( \tau_w = 45–60 \) s estimated by experienced air traffic controller
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Some Results Using Observed Weather

- Fair-weather model capacity
  - \( \tau_w = 30 \text{ s} \)
  - \( \tau_w = 90 \text{ s} \)

Actual sector peak count

- Model capacity with \( \tau_w = 30 \text{ s} \)
- Model capacity with \( \tau_w = 90 \text{ s} \)
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 $F_{ca}$ 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 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, $N_{MAP} = T/36$ (18 aircraft limit)

$[T$ is mean transit time, in seconds]

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