Concepts and models for NEXTGEN air traffic flow management

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Systems Engineering
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Outline

1. Key issues in NextGen
    1. Seven key elements of NextGen specific to TFM
    2. Current trends and future opportunities with AFPs

2. Mathematical approaches to TFM modeling
    1. Automated graph topology model building
    2. Aggregate travel time estimation
    3. Standard LTI formulation
    4. Constrained optimization formulations

3. Applications
    1. Impact of convective weather on en route traffic
    2. NAS-wide TFM
    3. Dynamic airspace configuration

Next Generation (NextGen)

- Joint Planning and Development Office (JPDO) has laid out an operational vision for the Next Generation (NextGen) air transportation system

- NextGen better addresses needs and intentions of airspace system users
  - In particular, planning for possible 2x or 3x increase in demand

Essential Elements for NextGen TFM

1. **Explicit representation of uncertainty and mitigate impact via contingency plans**
   - Today, uncertainty is processed informally
   - Planning tends to be single-scenario or wait- and-see
2. **Flexible Plans and dynamic adjustments**
   - Robust w.r.t. uncertainties
3. **Collaborative TFM and distributed decision-making**

Essential Elements for NextGen TFM

4. Trajectory-based operations

- Take airport-to-airport user intentions into account

5. Coordination with capacity management (dynamic airspace configuration)

- Second half of the demand-capacity balancing equation

6. Performance-based operations and services

- Provision for non-uniform services

7. Economic controls

- Market-based mechanisms for demand control pre-day of operations

Key point 6: Performance-based Services (PBS)

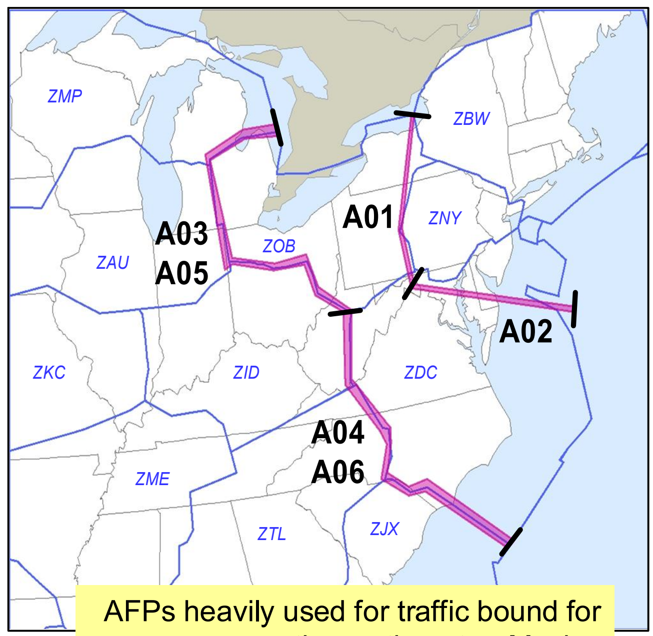
- Provide air traffic services commensurate with aircraft technology or aircraft/carrier performance capabilities
  - ADS-B, RNAV, self-separation
- Tiers are created in GDPs
  - Preference given to long-haul flights in awarding landing slots
- E.g. Alaska Air can make parallel landings even in the fog at SFO
  - Allocate GDP slots for two kinds of aircraft?
- New areas of research in resource allocation
  - E.g. Prioritization based on aircraft type or performance

Key point 7: Market-based Mechanisms

- Ground Delay Programs (GDPs) today have algorithms for swapping slots between carriers
  - Compression
  - Slot credit substitution
- Primitive 'bartering' economies, compared to non-aviation resources
  - Nonetheless, forerunner of future market mechanisms

Airspace Flow Programs (AFP)

- Reduce traffic flow rate over a designated flow constrained area (FCA)
  - Carriers can reroute
  - Estimated annual savings of $90M
- Leverages and generalizes GDP resource allocation models and principles
  - FSM assigns ground delay to flights



AFPs heavily used for traffic bound for the northeast or Mexico

AFP Near Future

- FCAs created on the fly
  - Largely static (canned) FCAs right now
- Automated algorithm for determining flight delays and reroutes
  - Some flights get to use the FCA; others take ground delay or are rerouted
  - Equity and Efficiency taken into account

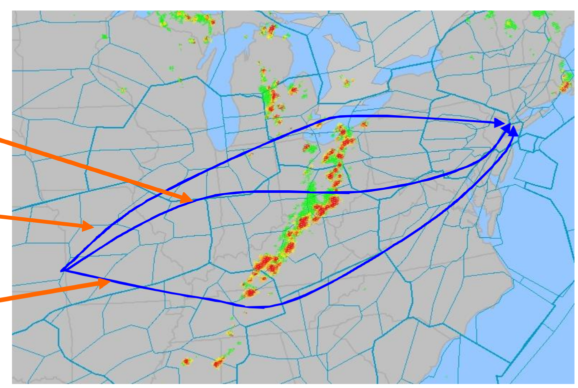
AFP Near Future

- User routing preferences taken into account
  - Multiple flight plans with prioritization (electronic negotiation)

Option 1: Route through FCA
(If ground delay is not too large)

Option 2: Northern route
(If delay for first choice is large)

Option 3: Southern route
(If can be done without delay)



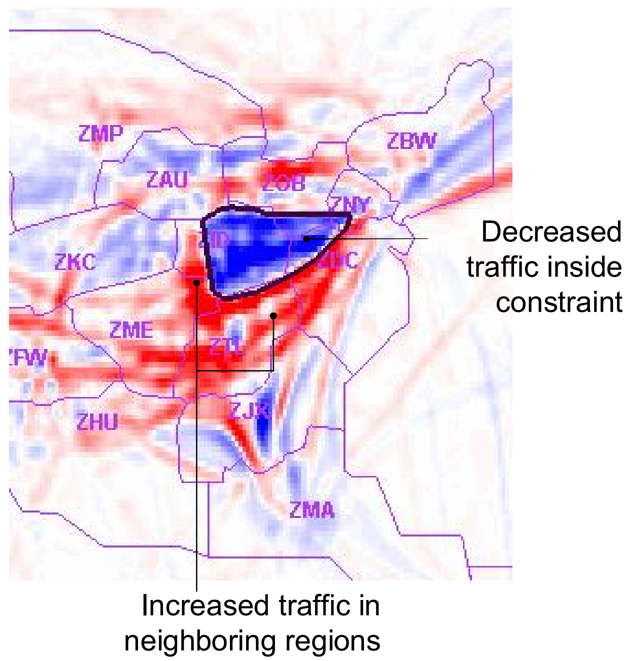
AFP Far Future

- Probabilistic weather forecasts (explicit representation)
- Market-based mechanisms
- Application to other resources
  - E.g. surface or terminal
- Coordination with parallel traffic management initiatives (other AFPs, GDPs, etc.)
- Real-time response to FCA capacity change
- Dynamic, automatic generation of FCAs

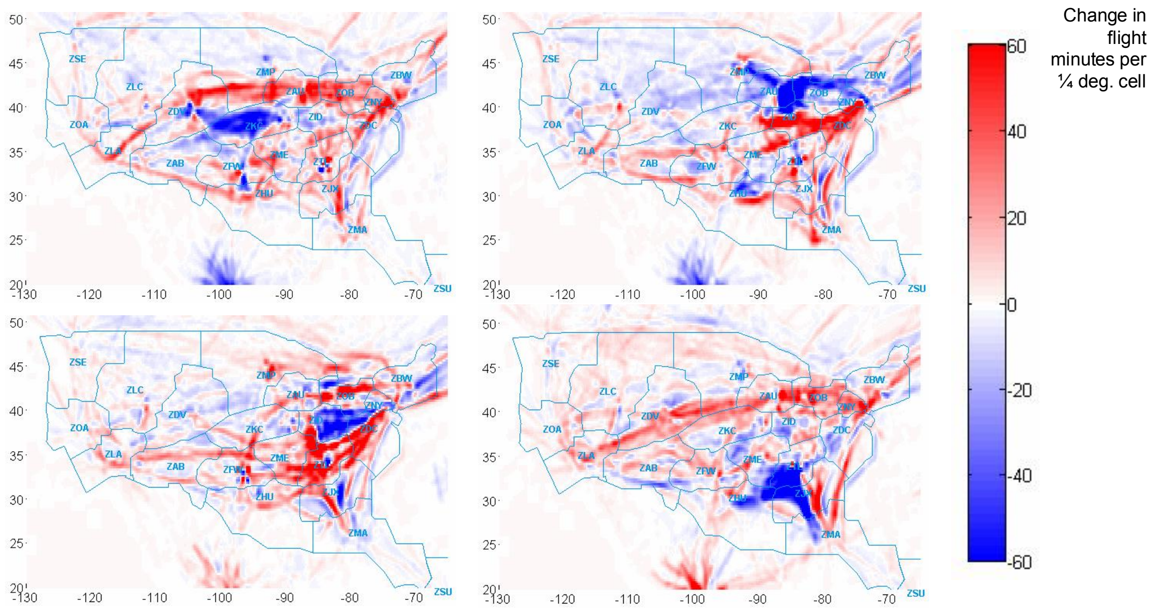
Sphere of Influence

- Influence of a capacity/demand imbalance (such as a WX disruption) extends far beyond ‘constrained’ region
- How far do these surges in demand propagate? What is the increase in demand within 60, 120, 180 miles of a constraint?

- Need for System thinking and modeling



Visualization of Demand Effects



Data Set: all flights, June & July 2005, AOA 14,000 ft, between 1800Z - 0200Z

Coordination of TMIs

- Traffic management initiatives are mostly done in isolation today
  - Sometimes working at cross-purposes
- Need to coordinate parallel TMIs
  - Tier 1 model or Evaluator capability
- Also, tie in airport surface control
  - E.g. Departure Flow Manager (DFM) coordinates departures into strategic TFM picture

System Thinking

- We tend to think in terms of flights, airports, and traffic centers, etc.
  - But NAS is largely composed of circulating aircraft and interconnected flows
  - Small perturbations make us acutely aware that all the subsystems are interrelated

- Need for aggregate flow modeling and system understanding
  - Might need a new battery of metrics
  - Changes to the system over time are especially challenging

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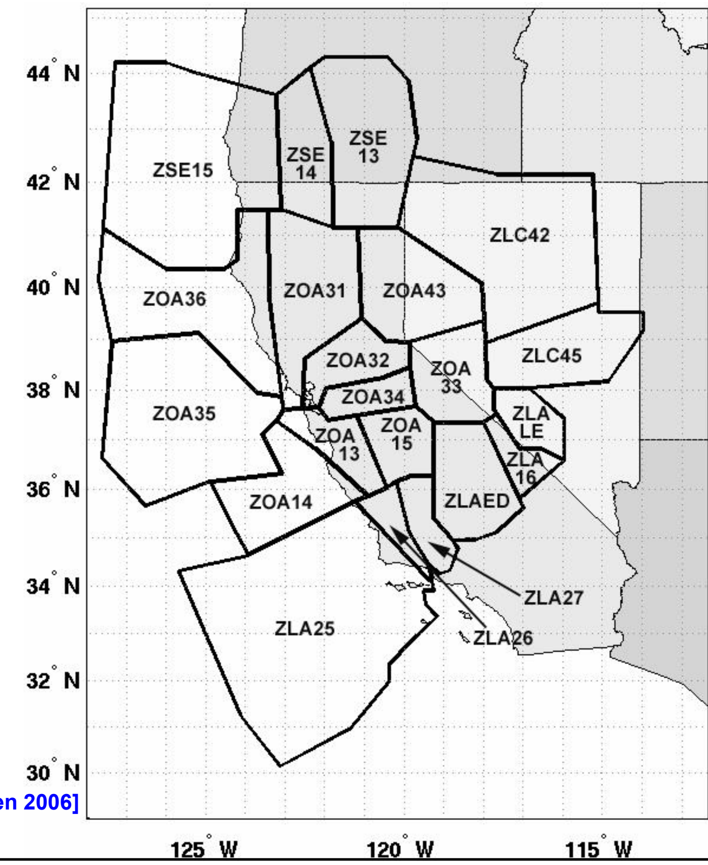
Mathematical modeling

1. Gain understanding of en-route challenges faced by NextGen
   1. Analysis of remote effects of disturbances on en route traffic flow, in particular holding patterns and reroutes.
   2. Traffic flow management based on airborne delays when demand exceeds capacity. Delay minimization.
   3. Contribute to the analysis of NAS infrastructure for new paradigms (NextGen, NGATS), in the present case: dynamic airspace, tubes, etc.
2. Method: creation of a NAS-wide high altitude traffic model
   1. Tool: aggregate description of traffic, which is validated against traffic data (for example ETMS / ASDI)
   2. Development of a model which allies
      1. Tractability
      2. Analyzability
      3. Accuracy
3. Practical implementations
   1. Optimization based software environment (C, C++, python)
   2. Integration into NASA FACET (Metron Aviation)

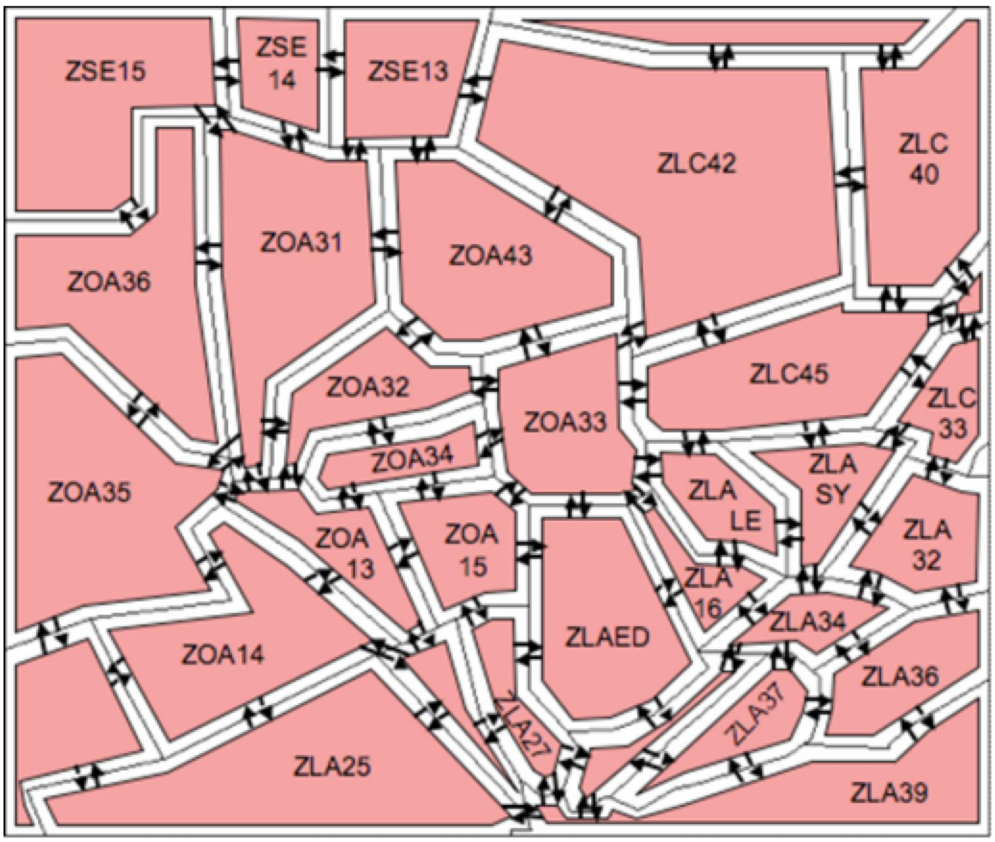
Inside an ARTCC: sectors



[Robelin, Sun, Wu, Bayen 2006]

[Sun, Bayen 2007]

Conceptual framework: network flow



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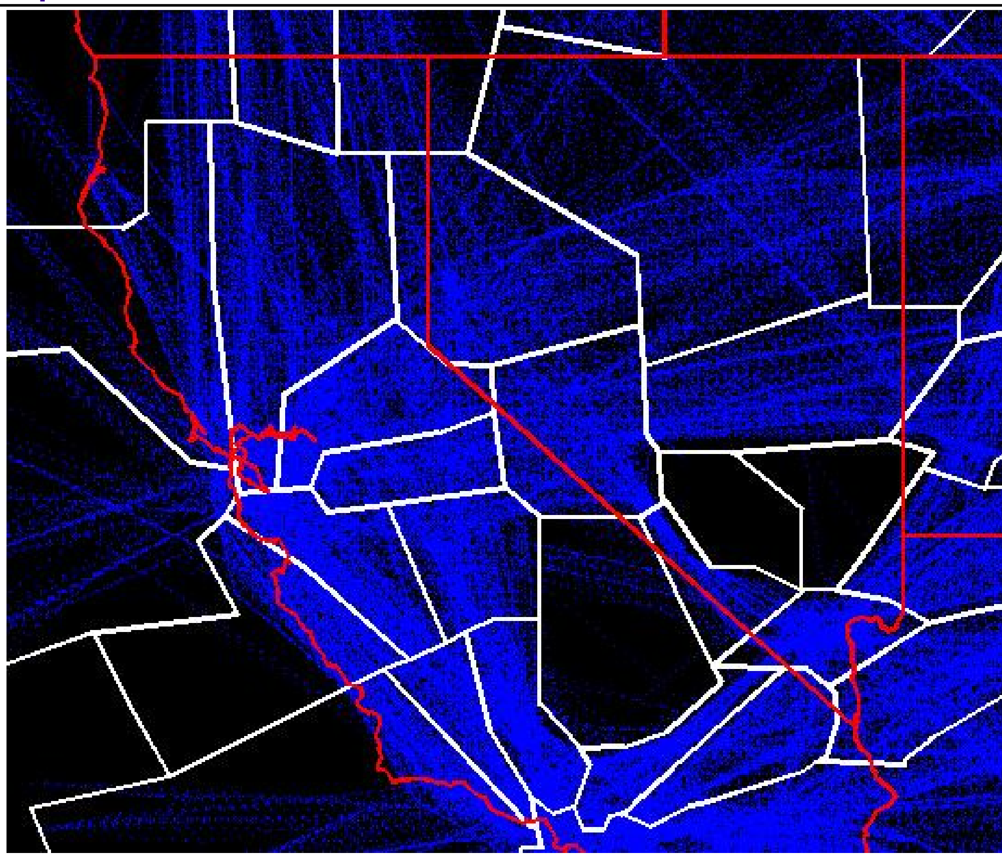

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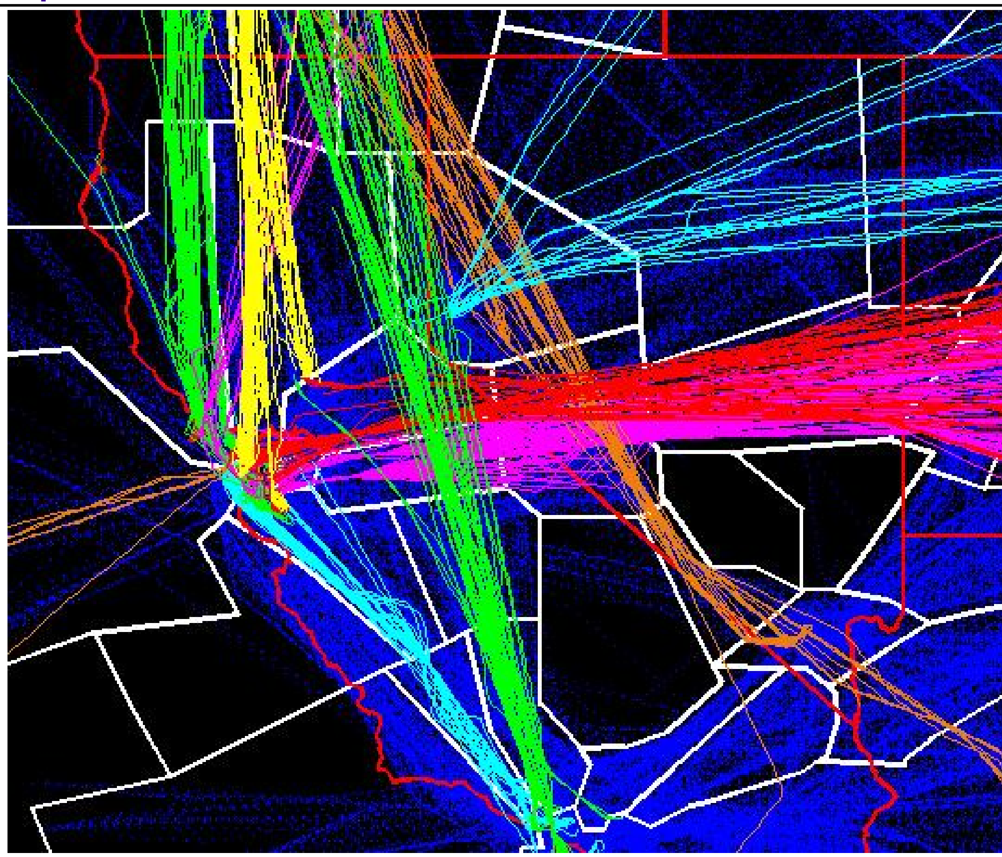

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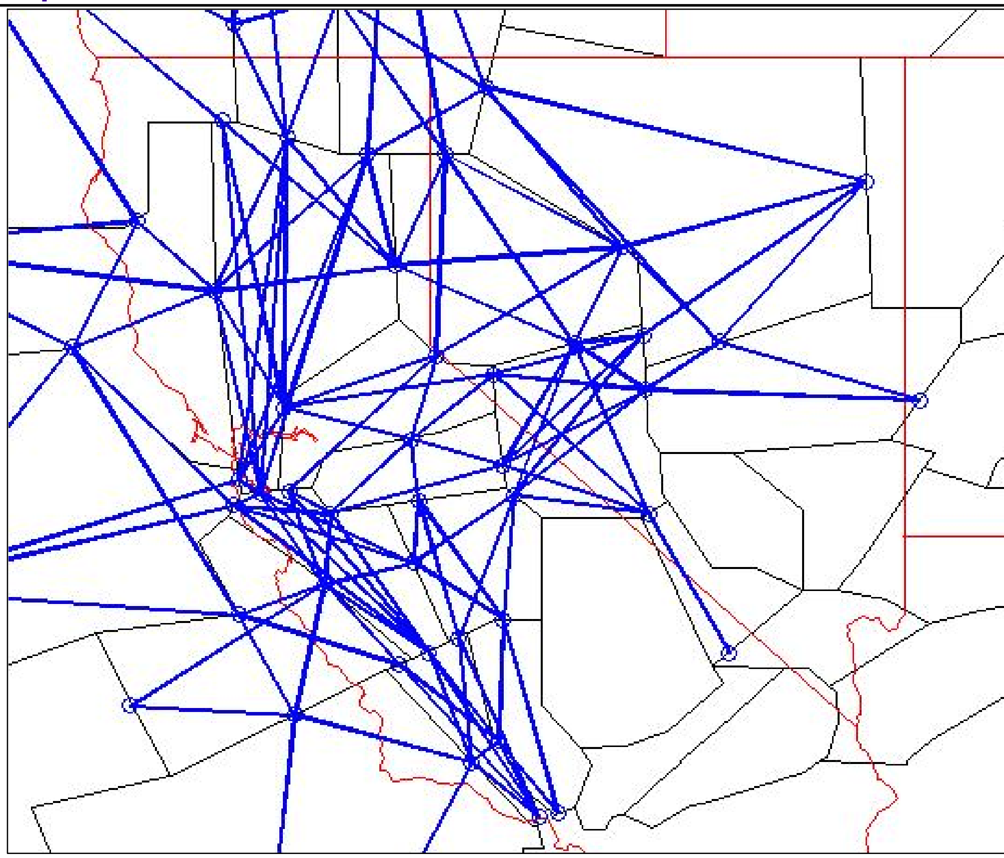
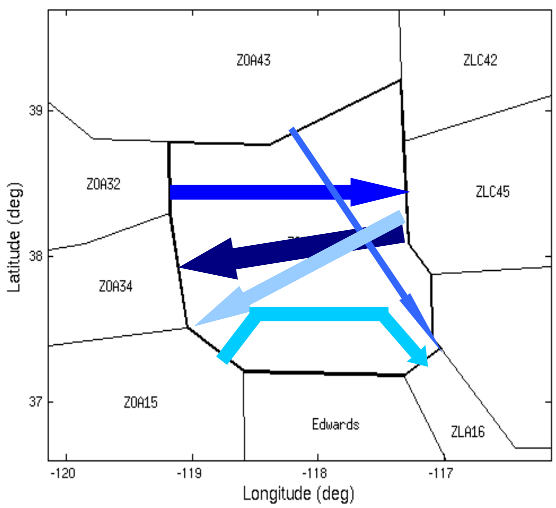
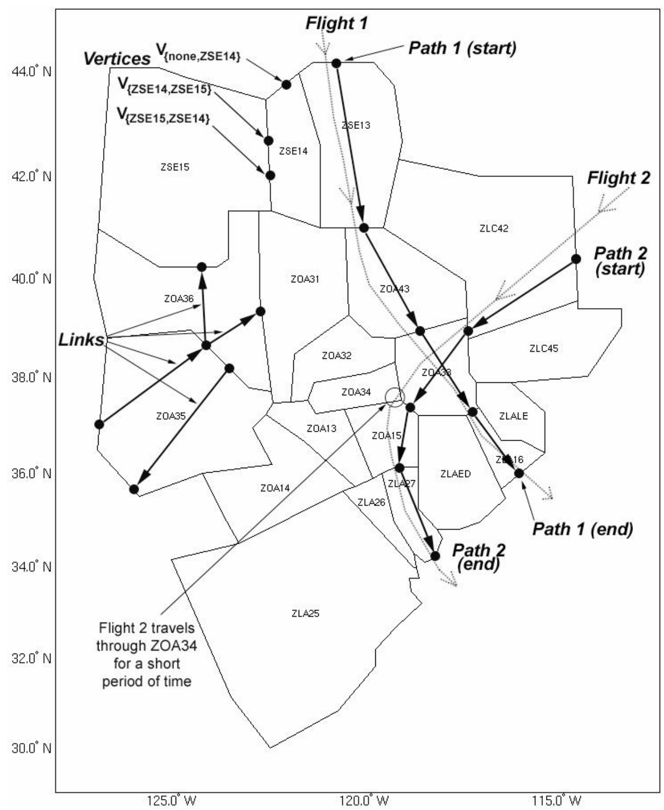


Conceptual goal: graph building (flows)

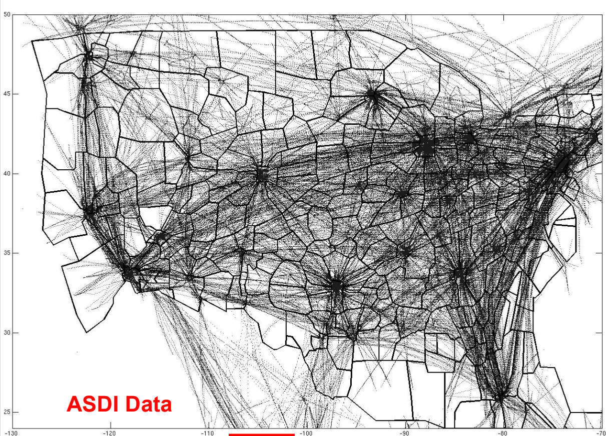


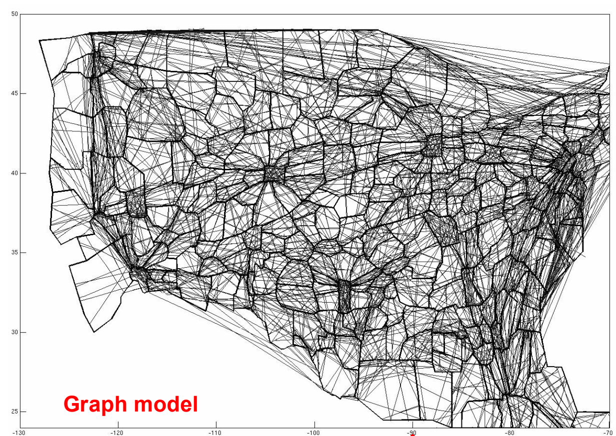


[Histon, Hansman, 2000]

Models: graph model of air traffic flow

- Flight tracks – graph theoretical model



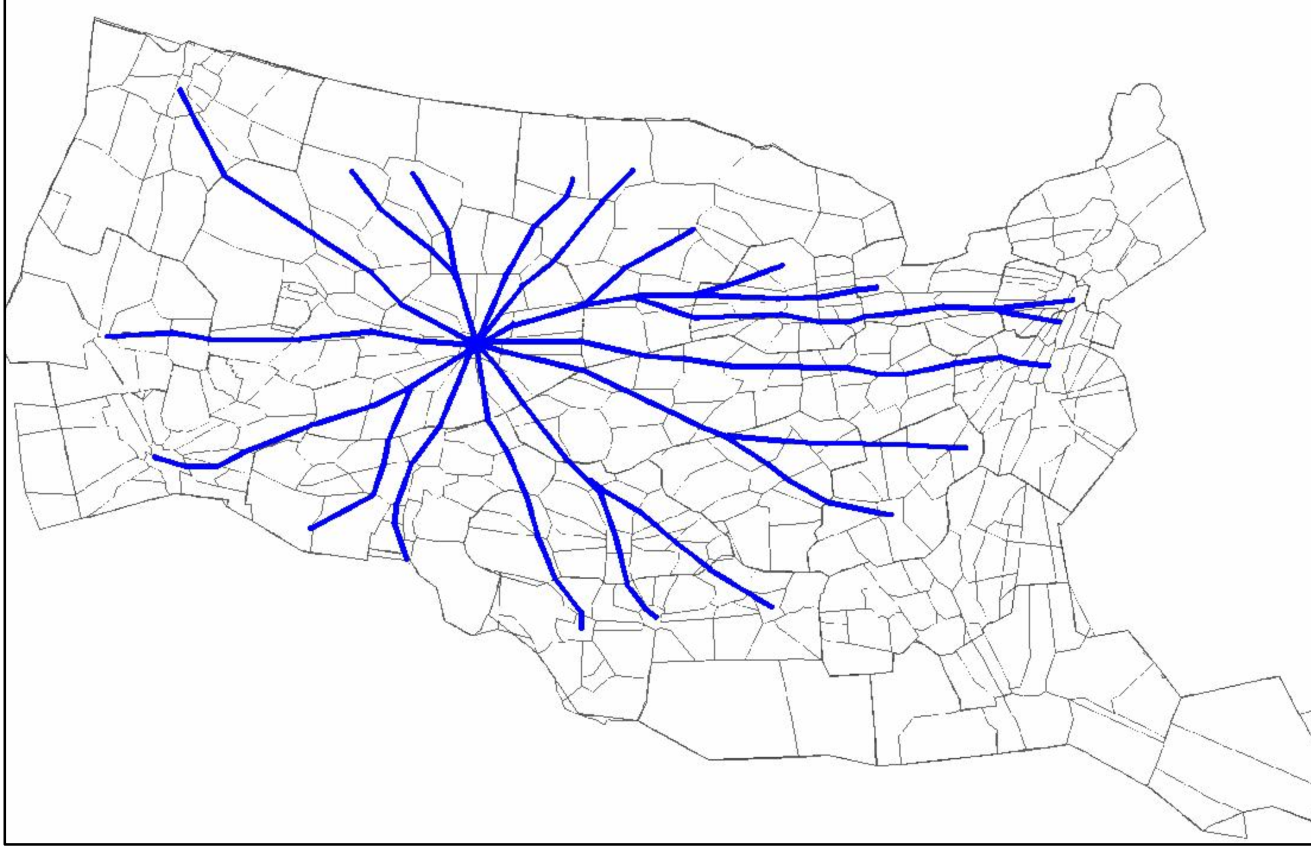


automated identification procedure: clustering; pattern recognition

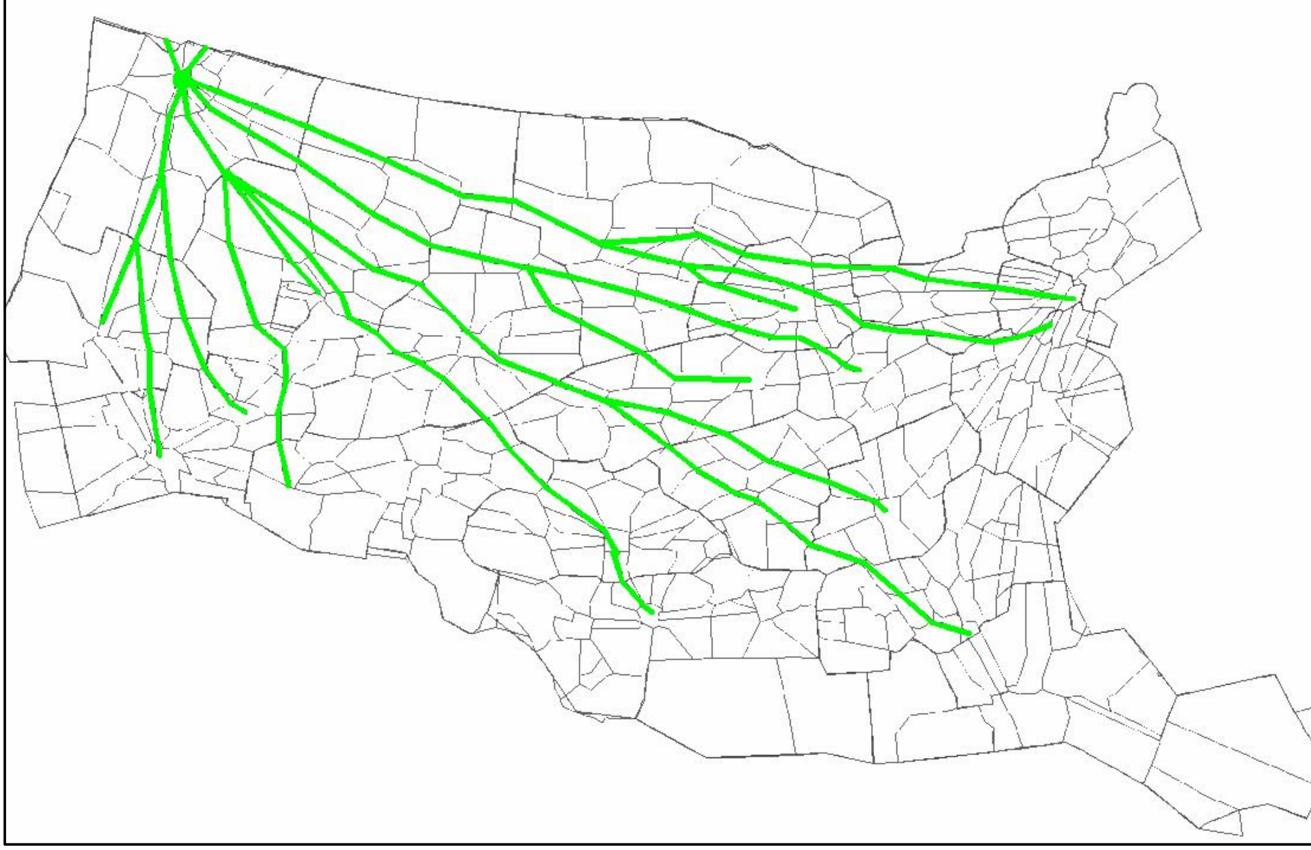
Source of the data: FAA/CNA

[Sun, Strub and Bayen 2007]

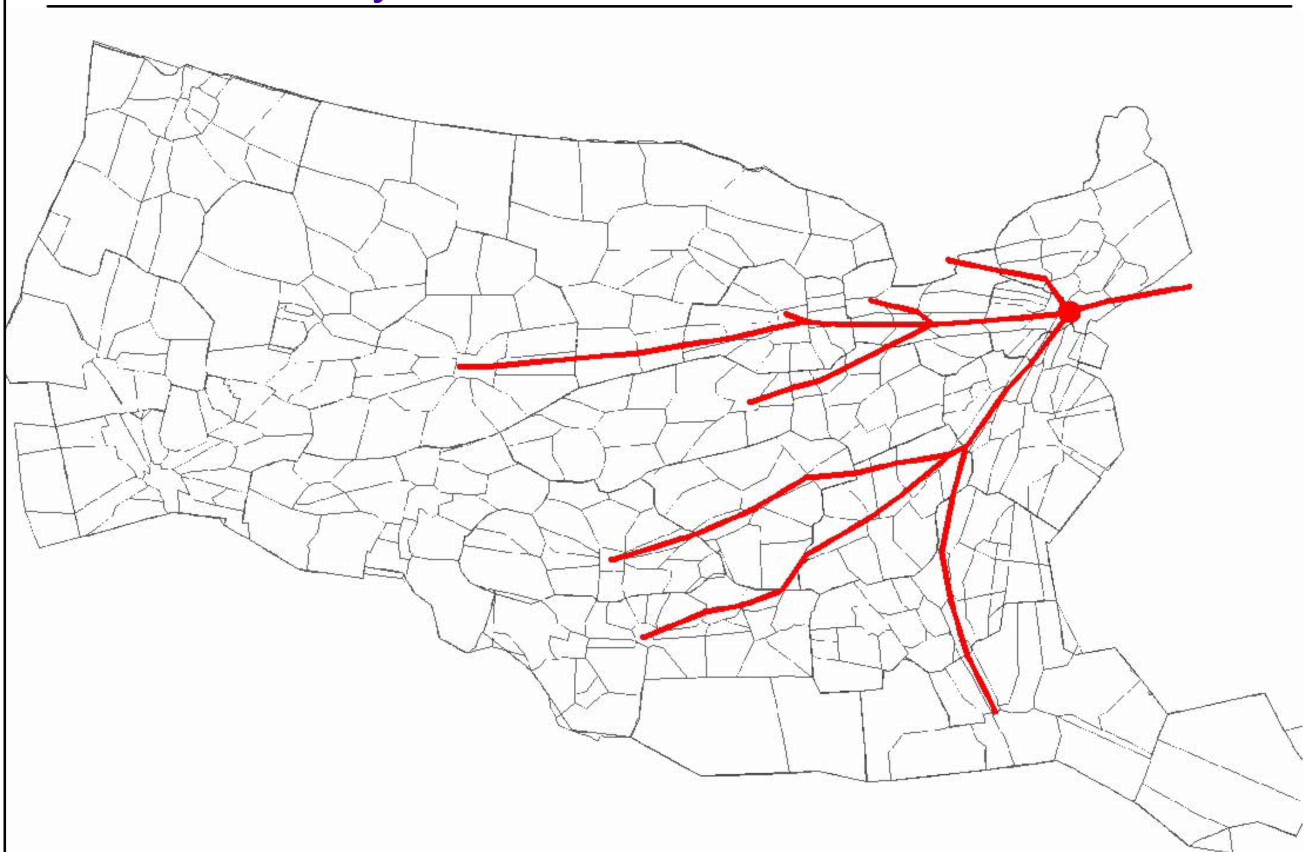
Multicommodity flow - DEN



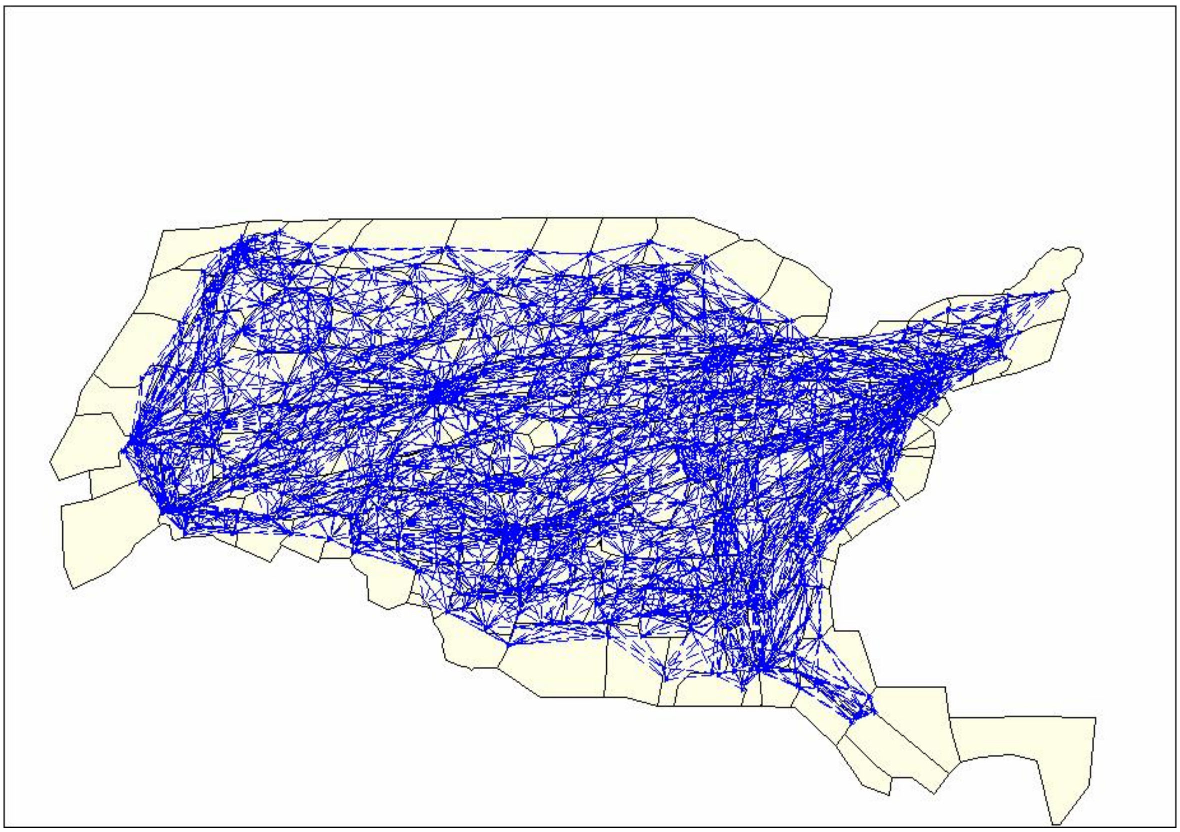
Multicommodity flow - SEA



Multicommodity flow - LGA



Network flow model (dynamic)



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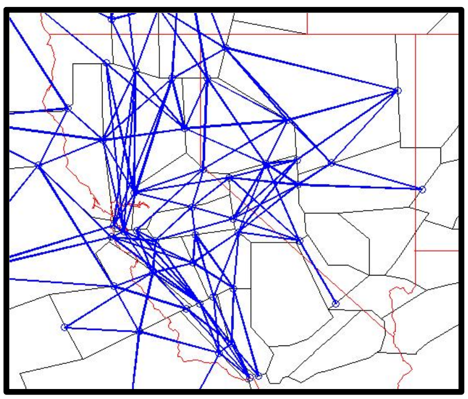
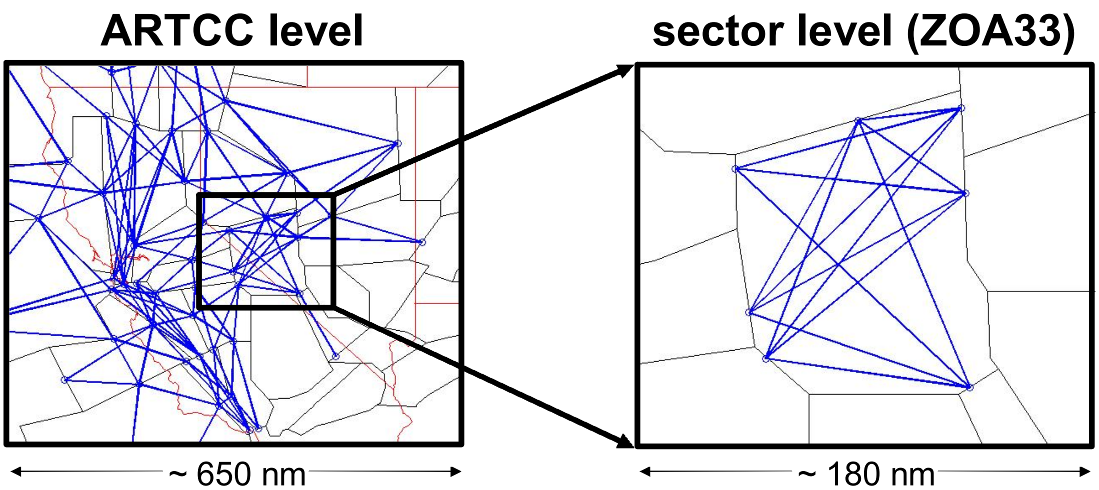
Traffic flow model on a single link

ARTCC level



~ 650 nm

Traffic flow model on a single link



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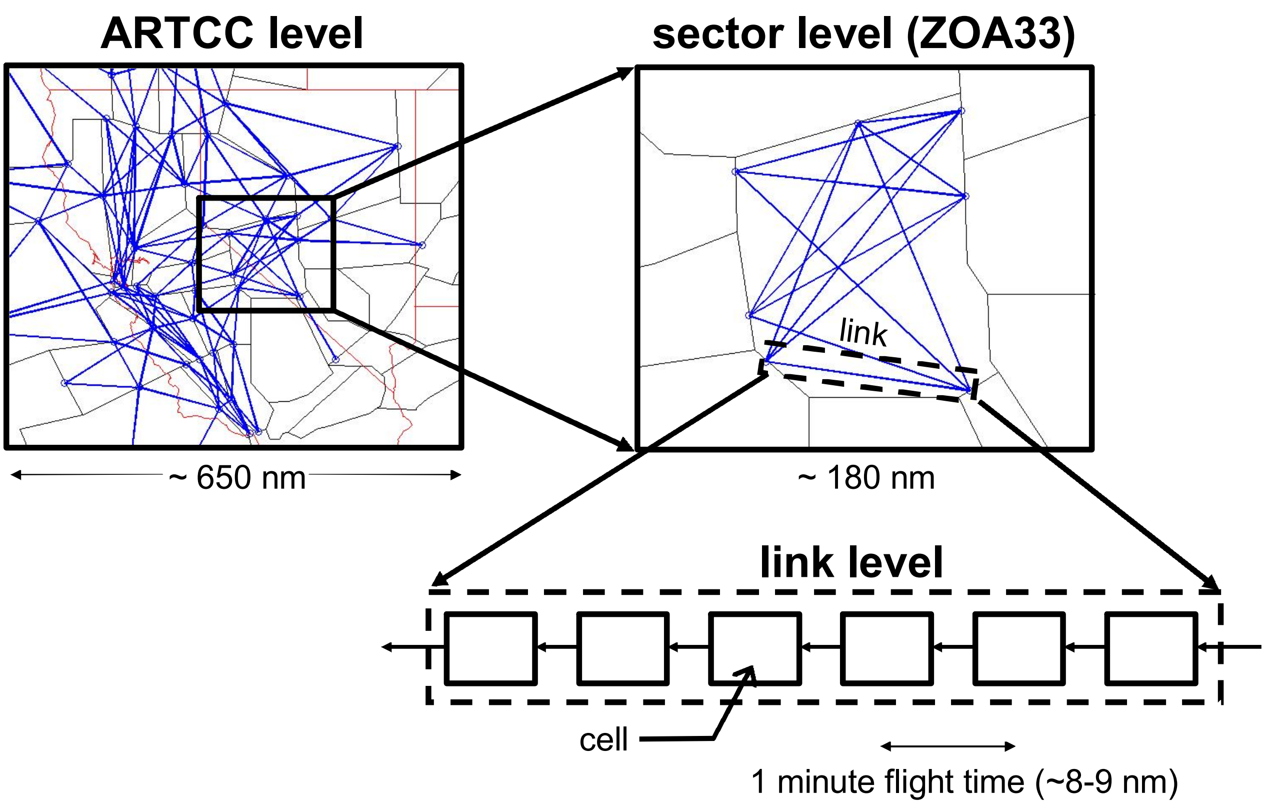
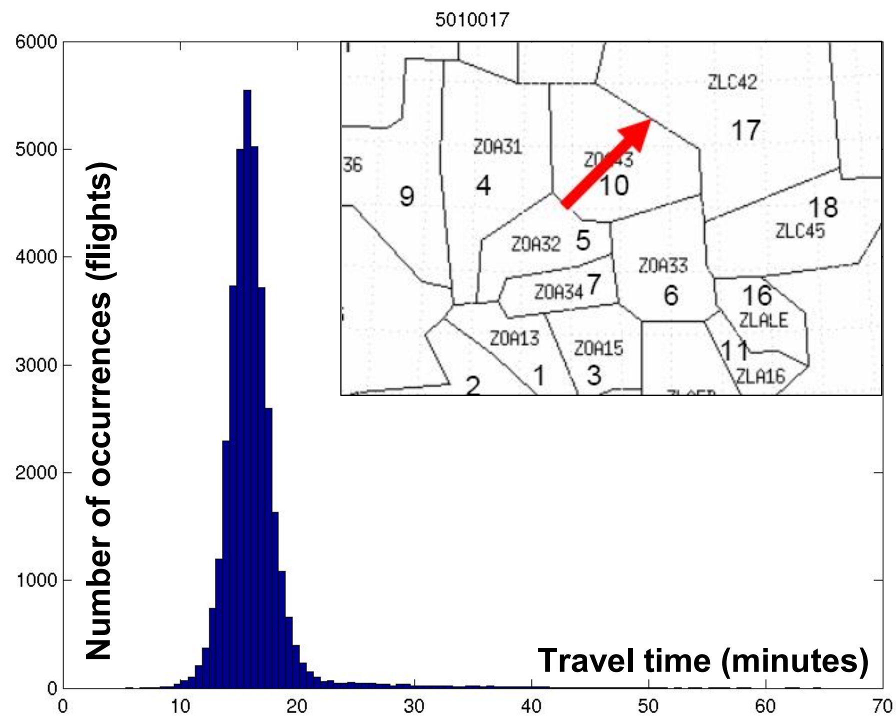


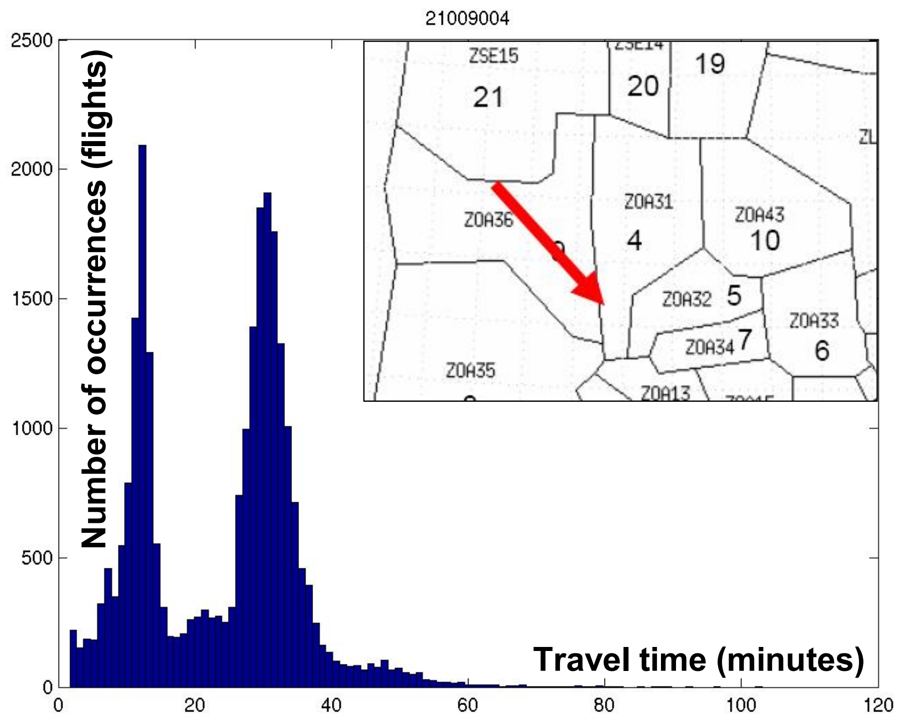
Distribution of travel time



Travel times through the link ZOA32-ZOA43-ZLC42

Departure flights from the bay area.

Occurrence of a second peak

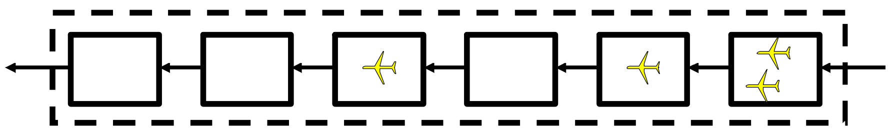


Travel times through the link ZSE15-ZOA26-ZOA31

Possibility: one descending bay area, one passing by

Eulerian dynamics on a link

delay system at the link level



state: cell counts

$$x(1) = \begin{bmatrix} x_6(1) \\ x_5(1) \\ x_4(1) \\ x_3(1) \\ x_2(1) \\ x_1(1) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 1 \\ 2 \end{bmatrix}$$

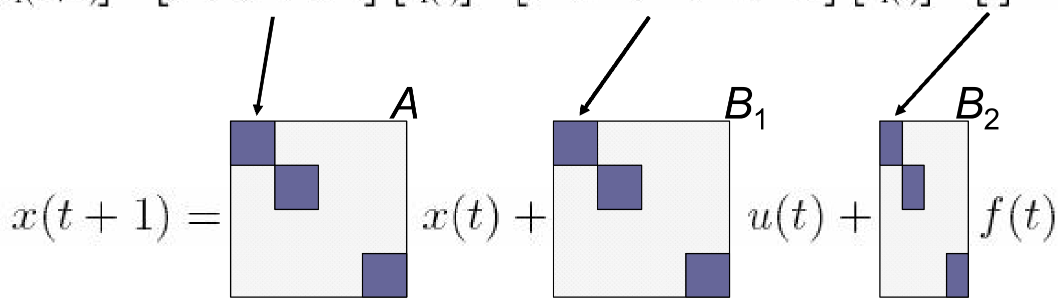
[Robelin, Sun, Wu, Bayen 2006]

[Sun, Bayen 2007]

ARTCC level Eulerian model

link level

$$\begin{bmatrix} x_6(t+1) \\ x_5(t+1) \\ x_4(t+1) \\ x_3(t+1) \\ x_2(t+1) \\ x_1(t+1) \end{bmatrix} = \overbrace{\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}}^{A_i} \begin{bmatrix} x_6(t) \\ x_5(t) \\ x_4(t) \\ x_3(t) \\ x_2(t) \\ x_1(t) \end{bmatrix} + \overbrace{\begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}}^{B_{1,i}} \begin{bmatrix} u_6(t) \\ u_5(t) \\ u_4(t) \\ u_3(t) \\ u_2(t) \\ u_1(t) \end{bmatrix} + \overbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}}^{B_{2,i}} f(t)$$



Air Route Traffic Control Center (ARTCC) level

Sparse LTI dynamical system:
blocks are nilpotent or upper diagonal matrices

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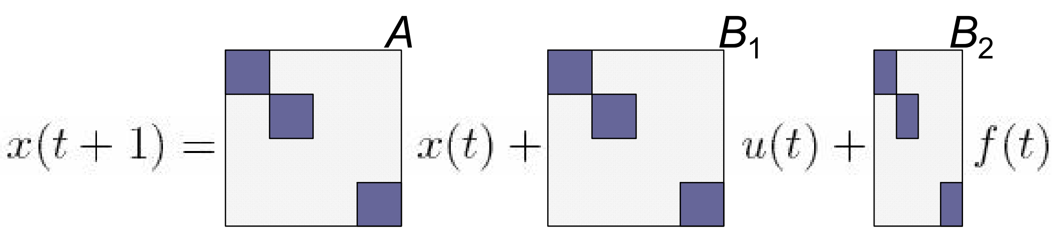
Analysis of control theoretic properties

System controllable (unconstrained)

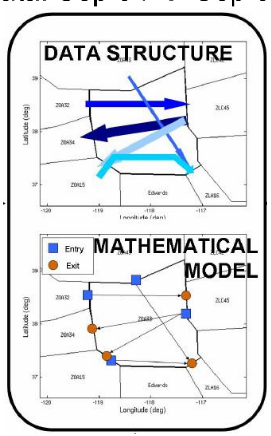
Case with constraints of nonnegativity and integrality of *x*, *u* and *f*: problem becomes NP-hard

$$x(t+1) = A\,x(t) + B_1\,u(t) + B_2\,f(t)$$



Validation of predictive capabilities

Model: based on a full year of ETMS/ASDI data: Sep 04 → Sep 05



Validation of predictive capabilities

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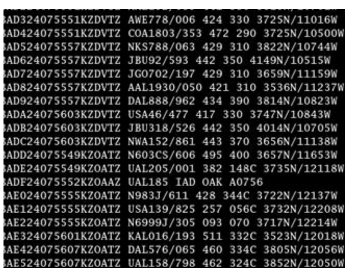

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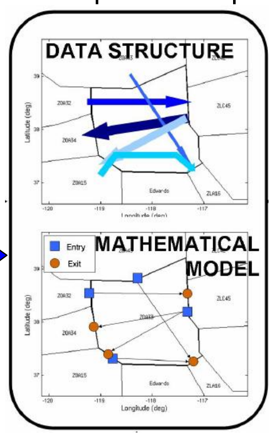

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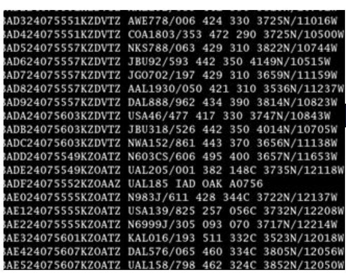

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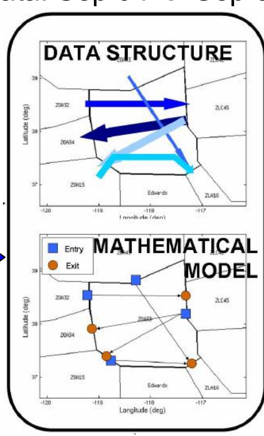
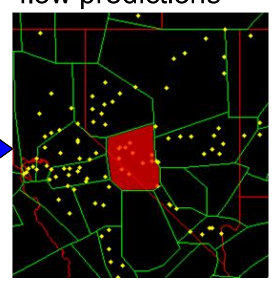


Output: aggregate flow predictions



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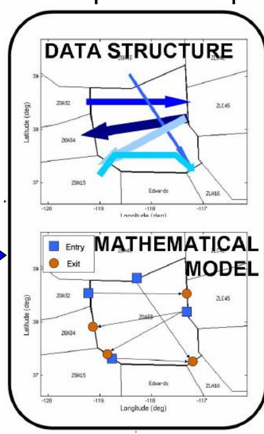

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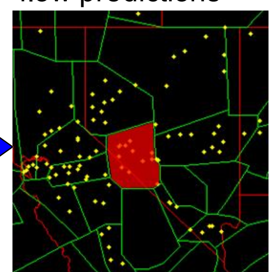

Comparison data:
For the same day:
true sector counts,
(not used by the model)

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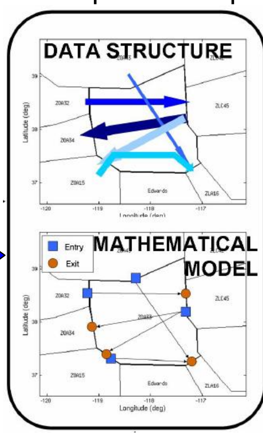
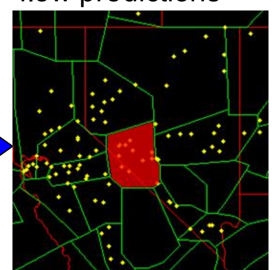
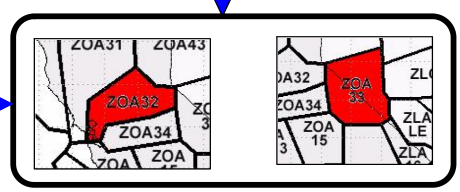


Output: aggregate flow predictions

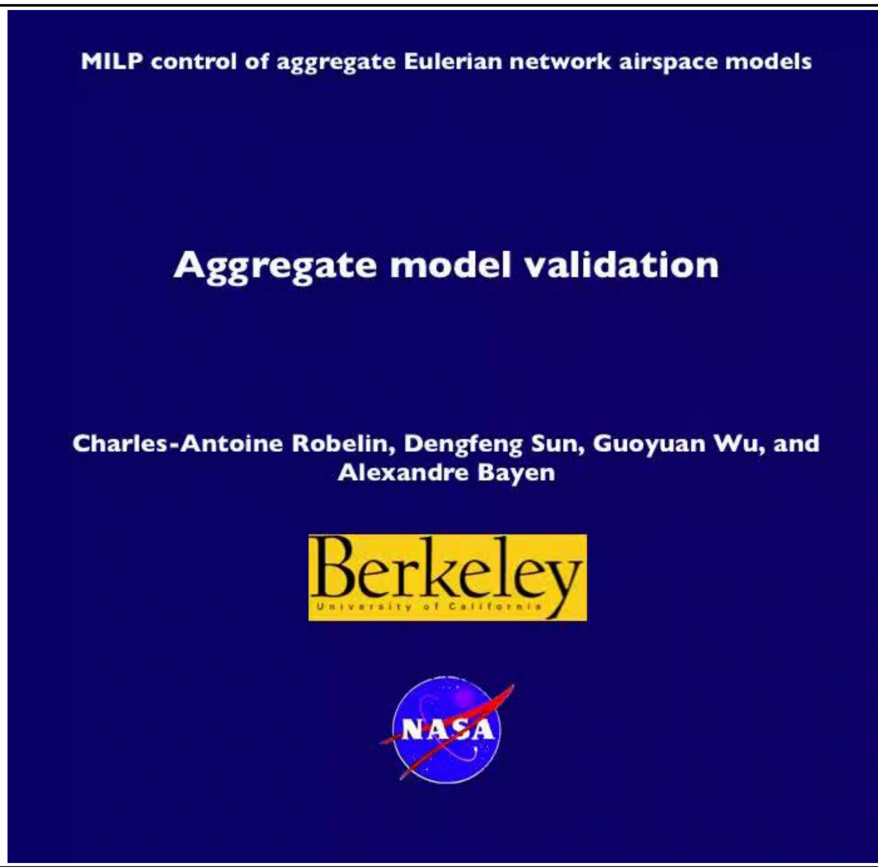


Comparison data:
For the same day: true sector counts, (not used by the model)

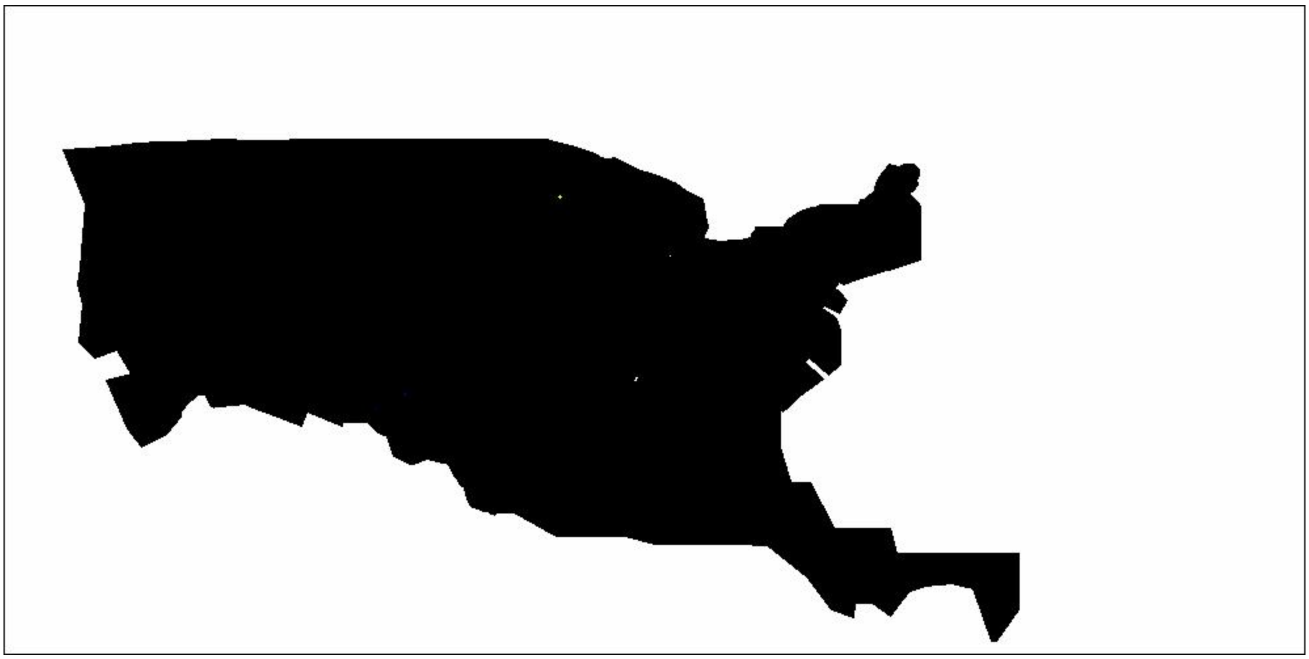


Comparison metrics:
for example sector counts

Aggregate model validation



Example of validated forward simulation



Simulation capabilities

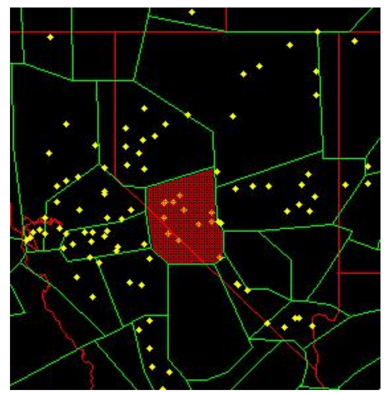
1. Software environment written in C/C++ with a Matlab interface, in which we can
    1. Implement traffic simulations (with four traffic flow models so far)
    2. Implement Traffic Flow Management optimization algorithms
    3. Input/output results from/to FACET
2. Once completed will be an open source software, online for download
    1. Provided with a Matlab interface
    2. In which the user can input their own model or run preprogrammed models
    3. With which the user can run optimization software such as CPLEX for TFM algorithms
3. Currently includes 4 flow models
    1. The Stanford continous PDE flow model (Bayen, Raffard, Waslander, Tomlin)
    2. The Multicommodity cell transmission model (Sun, Robelin, Bayen)
    3. The 1D Menon Model (Menon, Sweriduk, Bilimoria)
    4. The 2D Menon Model (Menon, Sweriduk, Lam, Diaz, Bilimoria)
4. Its current functionalities include
    1. Validation of the predictive capabilities of the different models
    2. Optimal flow routing algorithms using: LP, MILP, adjoint-based optimization

Example 1: control application

Operational problem

Hard sector count enforcement

Objective function: minimization of overall delay



Formulation

MILP formulation of delay mitigation

Practical CPLEX implementation, LP relaxation

min: $$\sum_{k=0}^{N} c^T x_k$$

subject to:

$$x_0 = B_2 f_0$$

$$x_{k+1} = Ax_k + B_1 u_k + B_2 f_k,\ k \in \{0, \cdots, N-1\}$$

$$Ex_k + Lu_k \leq M,\ k \in \{0, \cdots, N-1\}$$

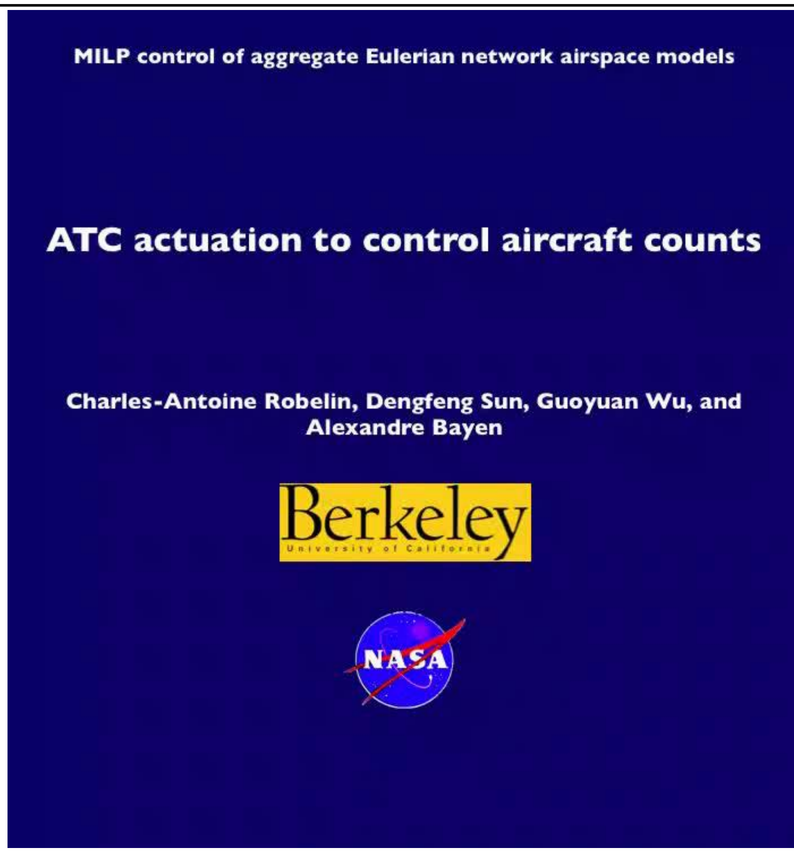
$$x_N \in \chi_f$$

N: number of time steps, *c*: vector of 1's

E, L, M: implement user-specified constraints (capacity, nonnegativity, etc)

χ_f: set of feasible final states, *x*, *f*, *u*, *A*, B_1, B_2: as defined earlier

Overload control



Outline

1. Key issues in NextGen
    1. Seven key elements of NextGen specific to TFM
    2. Current trends and future opportunities with AFPs

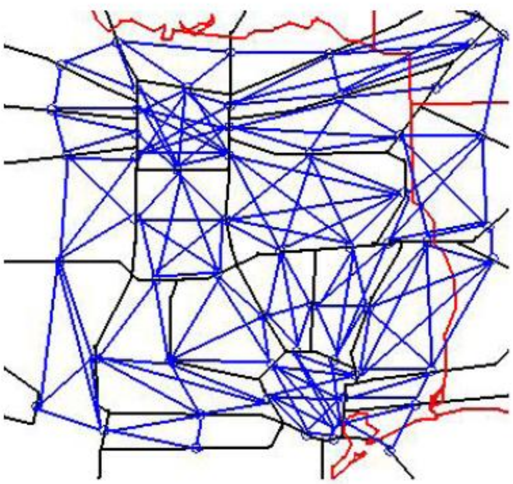
2. Mathematical approaches to TFM modeling
    1. Automated graph topology model building
    2. Aggregate travel time estimation
    3. Standard LTI formulation
    4. Constrained optimization formulations

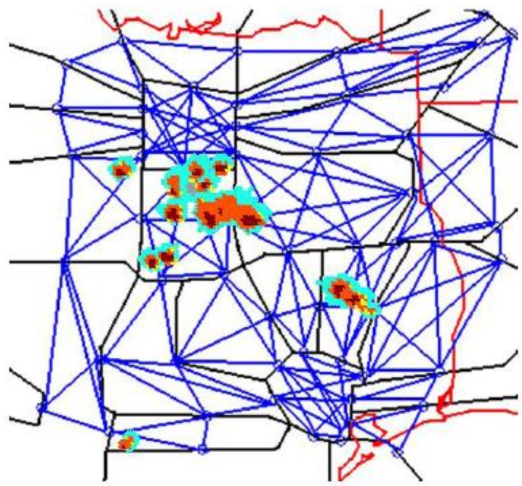
3. Applications
    1. Impact of convective weather on en route traffic
    2. NAS-wide TFM
    3. Dynamic airspace configuration

Application 1: impact of convective weather

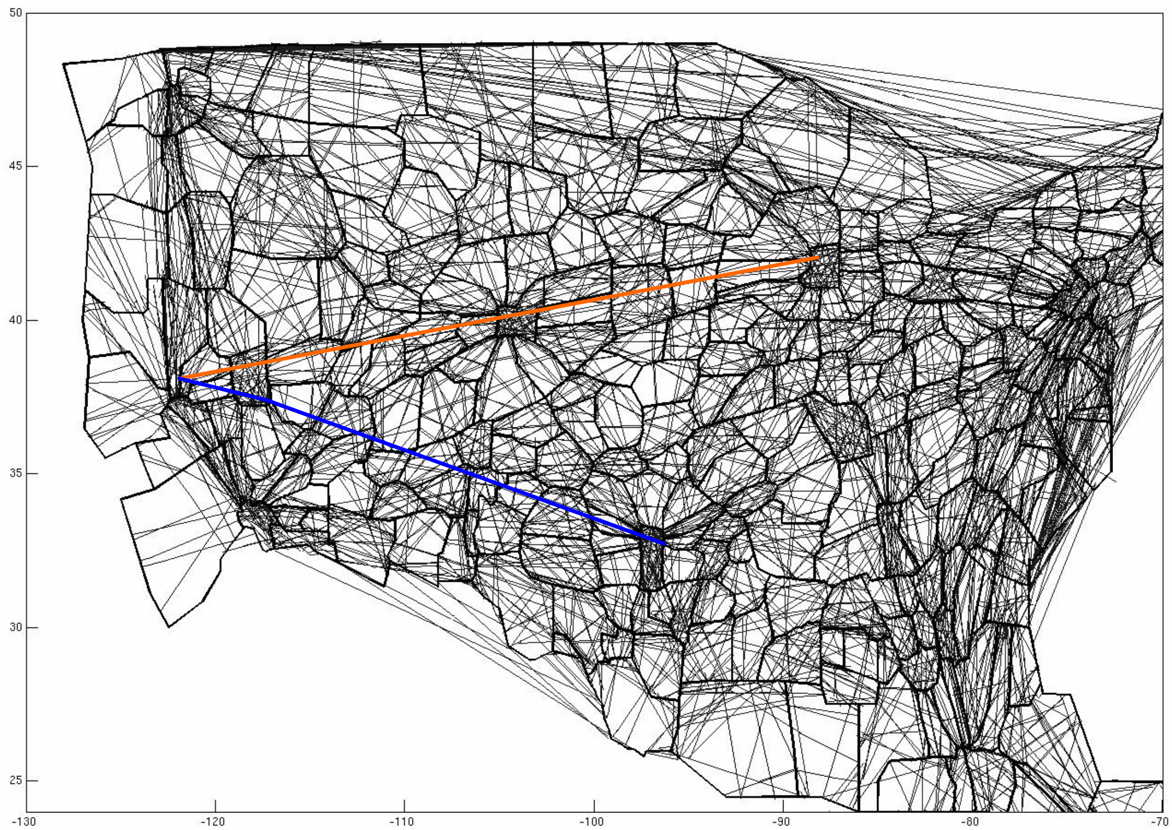
Impact of weather on capacity and en route traffic

- → **Delays**
- → **Optimal reroutes / playbooks**

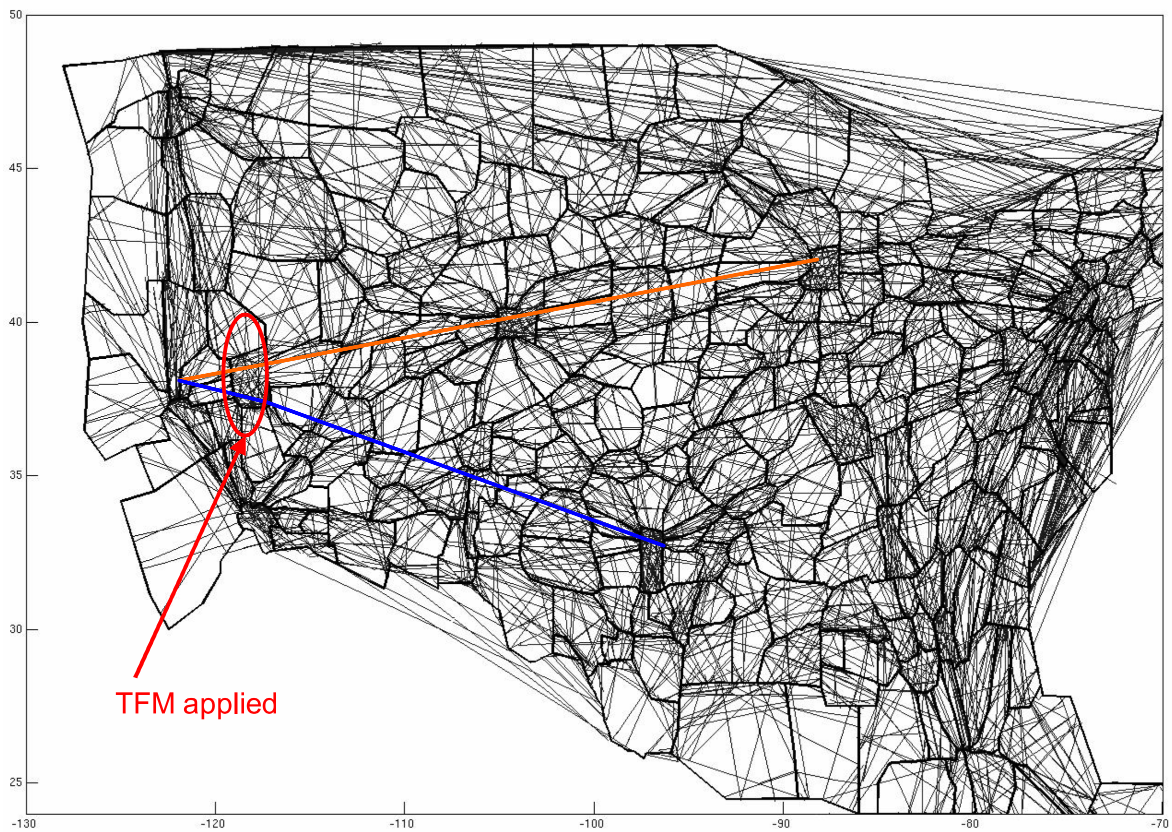




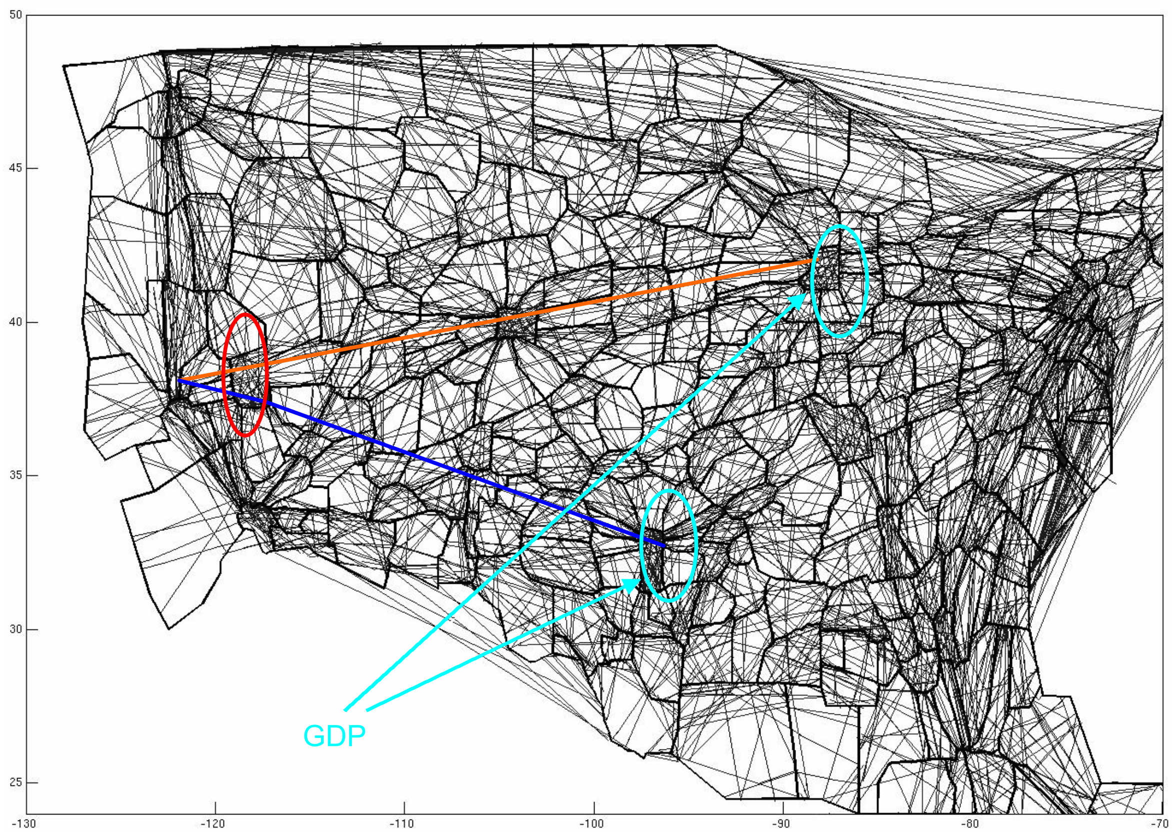
Application 2: sector count control (2-hour TFM)



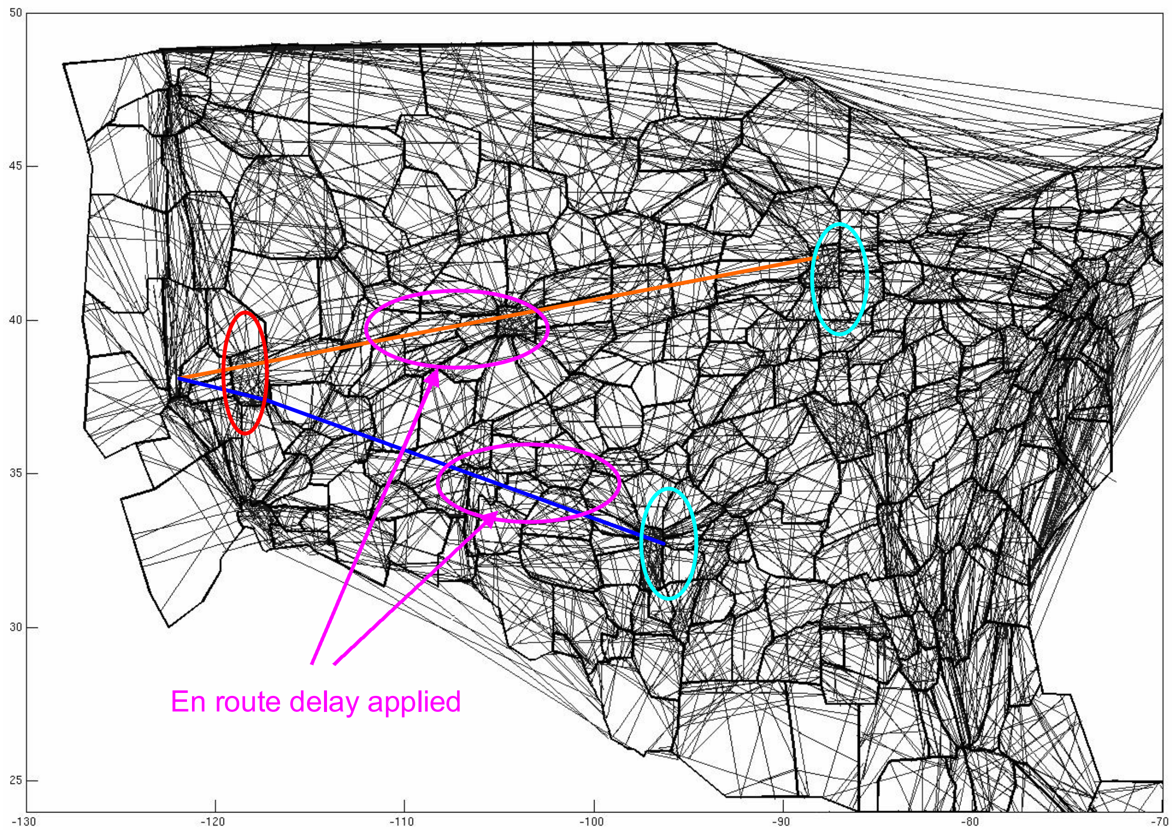
Application 2: sector count control (2-hour TFM)



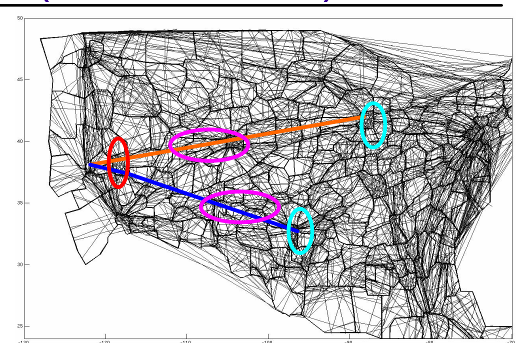
Application 2: sector count control (2-hour TFM)



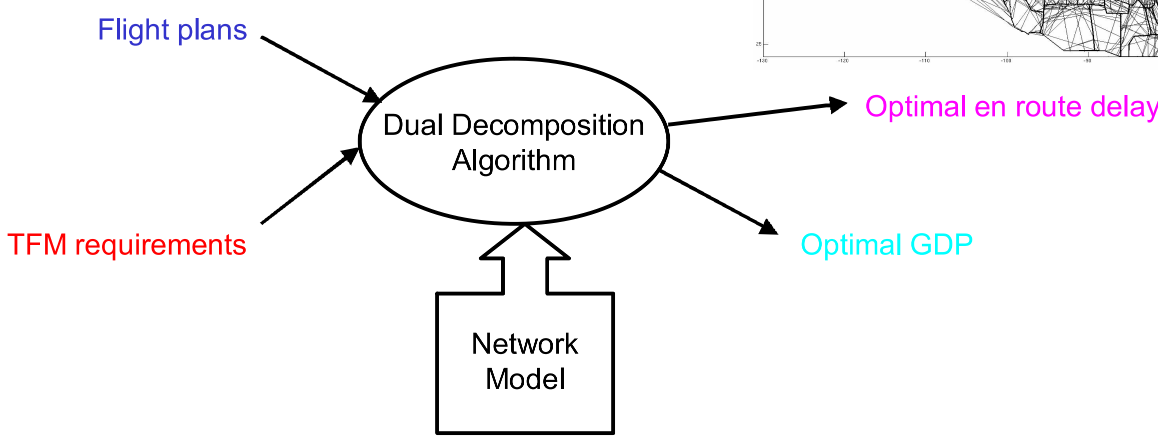
Application 2: sector count control (2-hour TFM)



Application 2: sector count control (2-hour TFM)

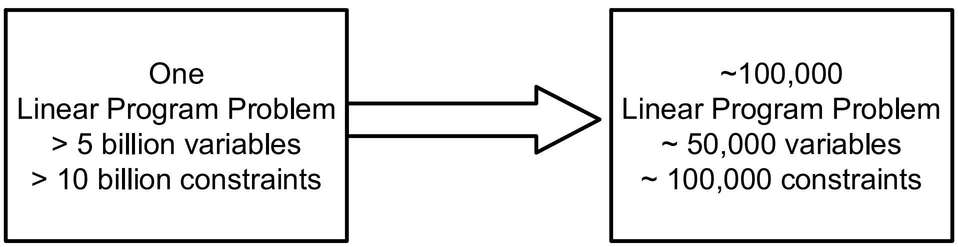


- More than 5 Billion variables
- More than 10 Billion constraints



Application 2: sector count control (2-hour TFM)

Why is dual decomposition useful?



Not solvable!!!

Solvable in real time!!!

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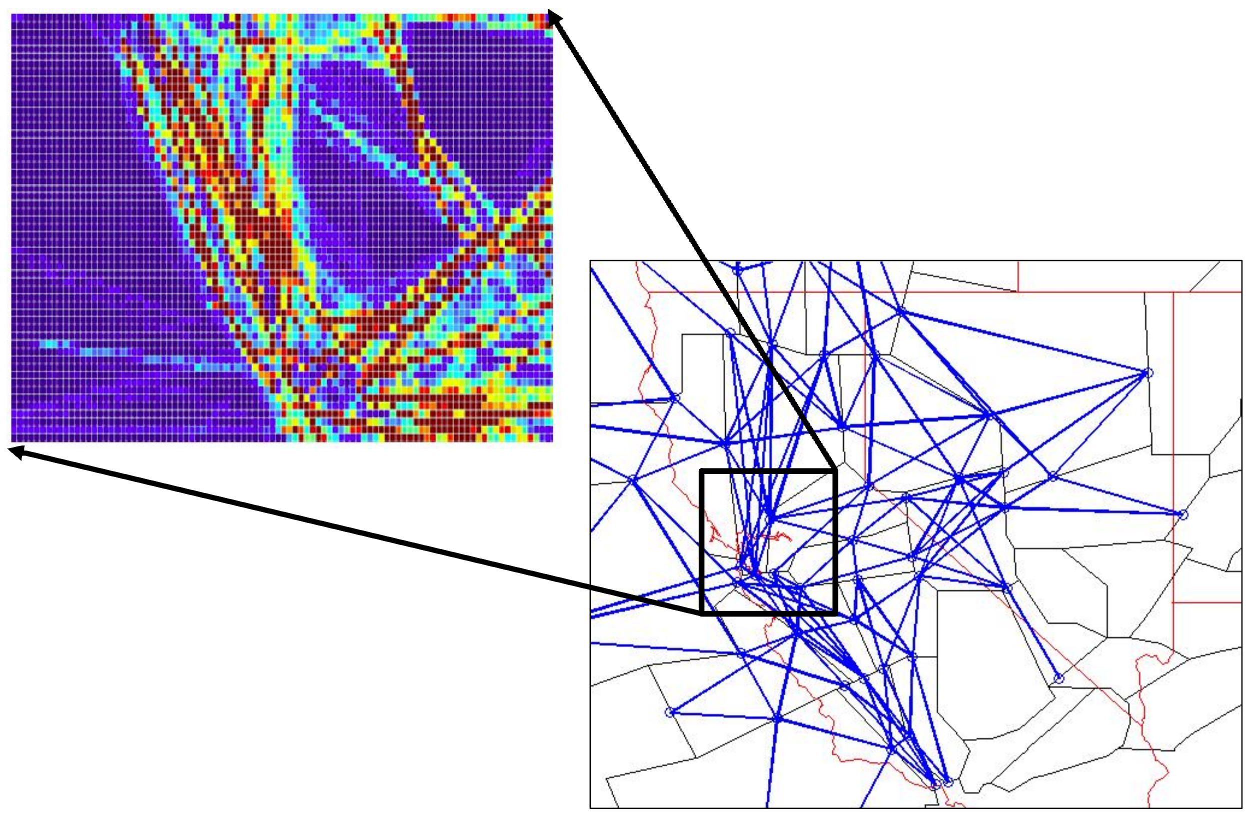
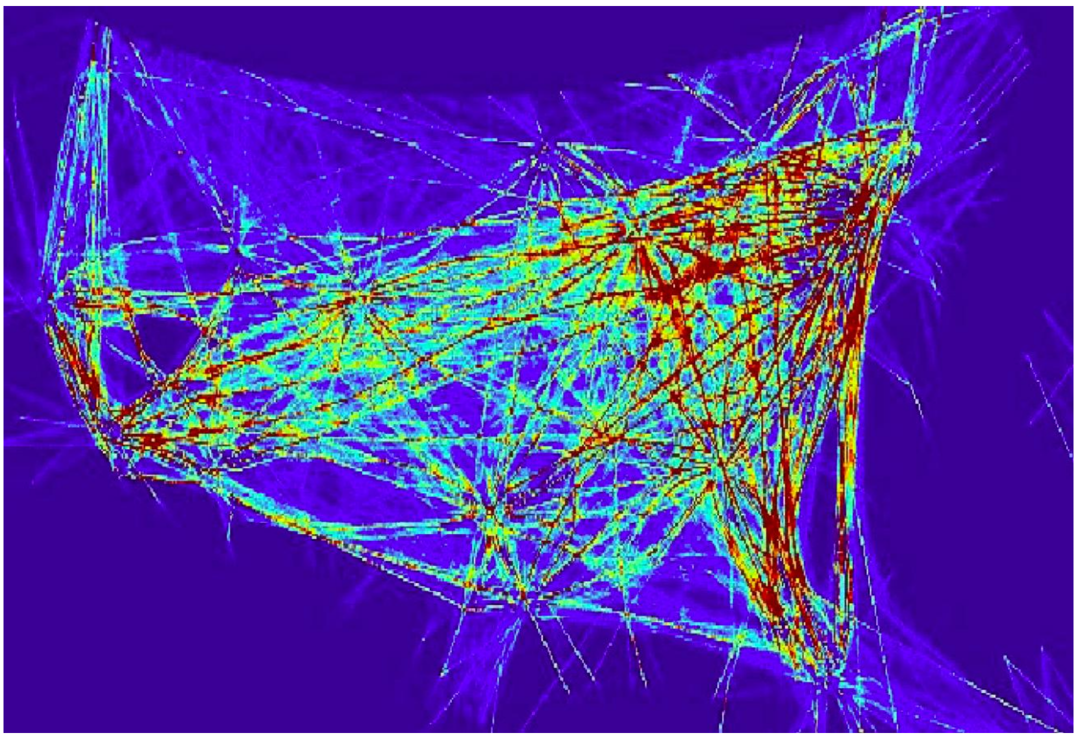
UC Berkeley

Application 3: Dynamic Airspace Configuration

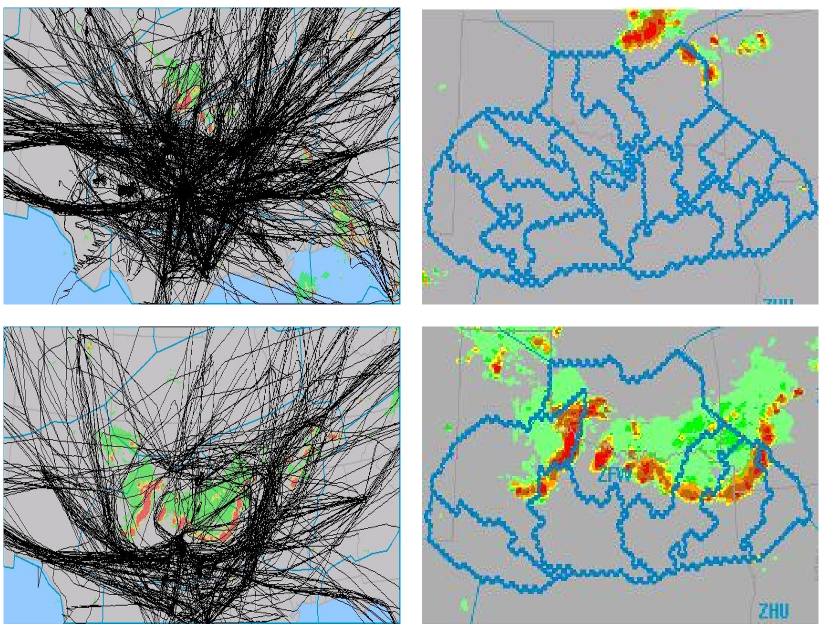


Application 3: Dynamic Airspace Configuration

Forecast model gives forecast of demand



Application 3: Dynamic Airspace Configuration



Low Wx Impact

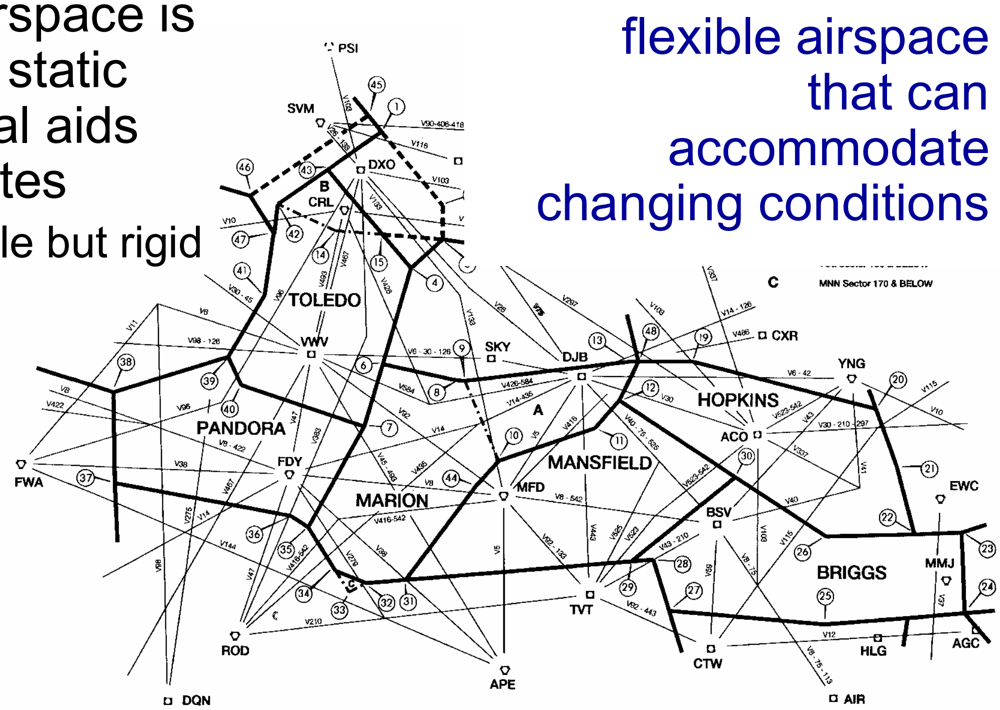
High Wx Impact
(resectorization)

- Similarly, resectorization could support AFP or other rerouting strategies (playbook plays)

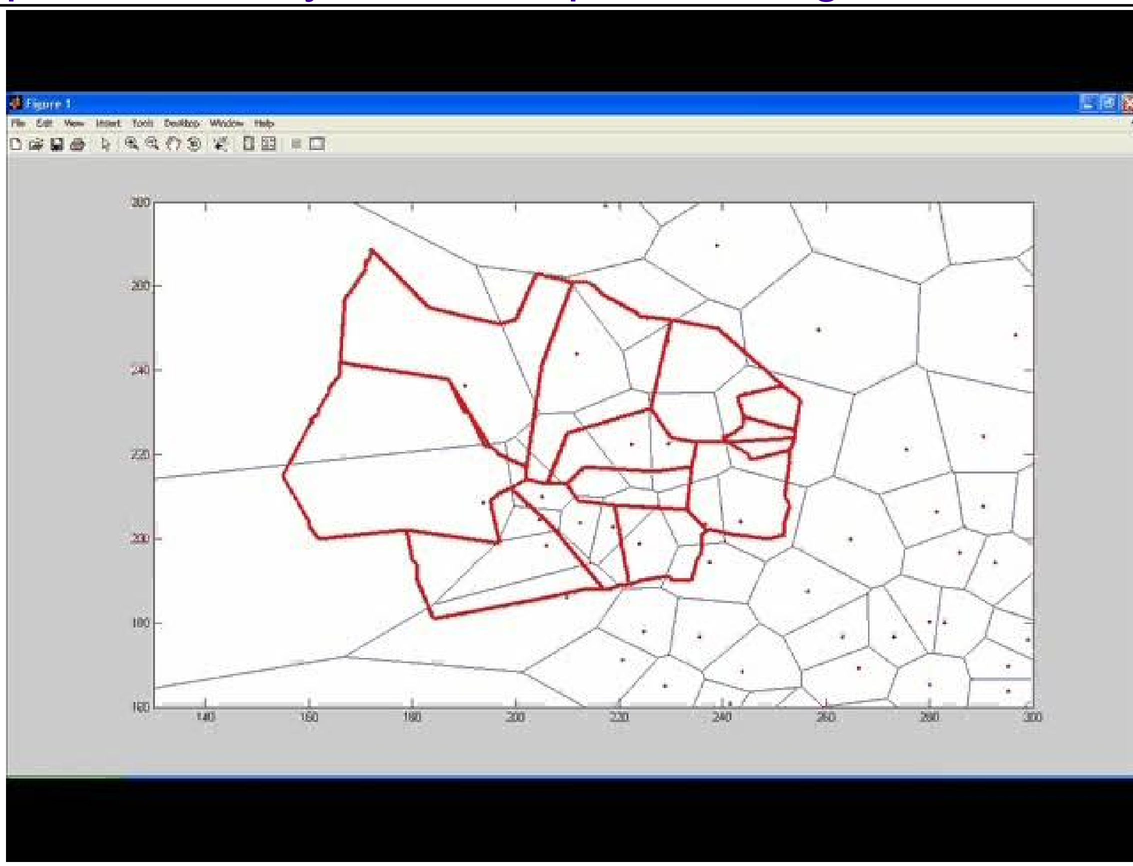
Application 3: Dynamic Airspace Configuration

- Today's airspace is defined by static navigational aids and jet routes
  – Predictable but rigid

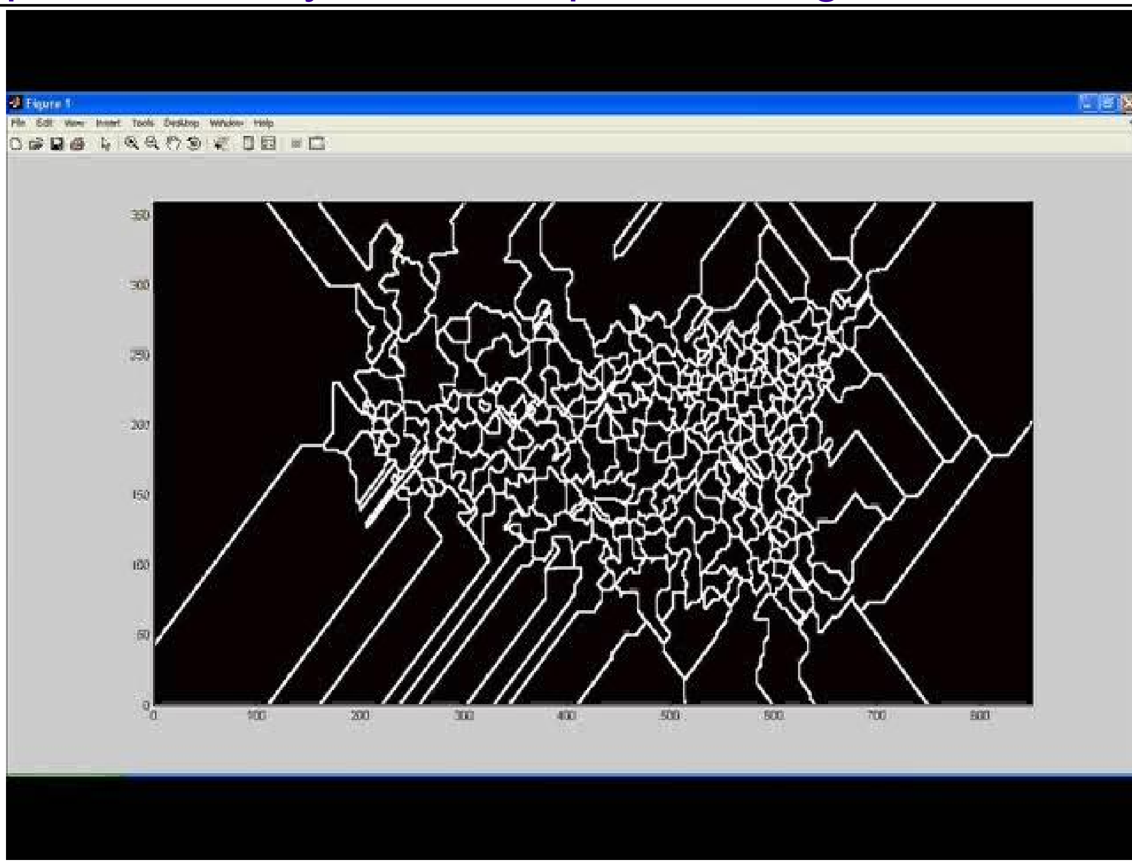
- Move toward more flexible airspace that can accommodate changing conditions



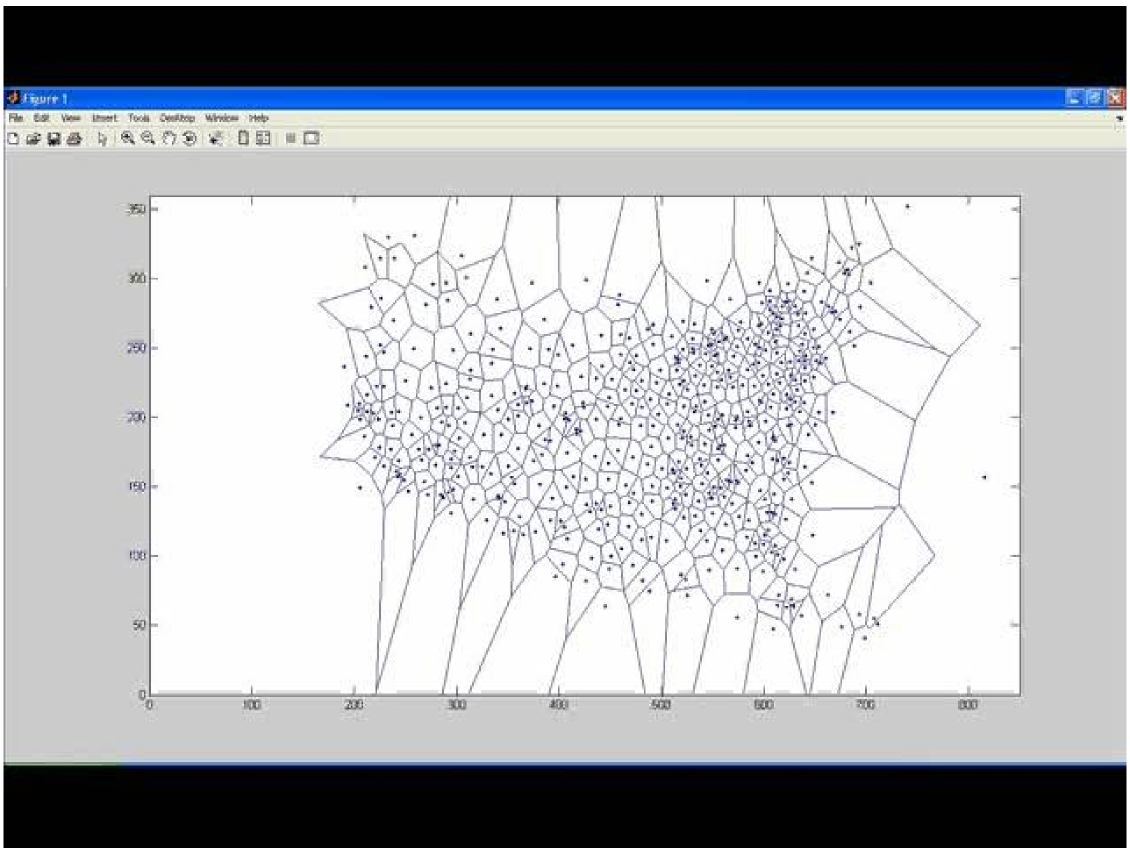
Application 3: Dynamic Airspace Configuration



Application 3: Dynamic Airspace Configuration



Application 3: Dynamic Airspace Configuration



Acknowledgments / Questions

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