ACT GLOBAL

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ICAO Colloquium on Aviation and Climate Change

Creating En Route (Cruise) Trajectories That Have Minimal Impact on the Environment

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Current Operations Sub-Optimal

- Except in a sub-set of instances…
  - certain regions of the Pacific
- Flight plans are sub-optimal from both the economic and the environmental perspective
  - Aircraft are constrained to fly fixed (or partially fixed) routes
  - Fuel cost and over-flight fees considered but emissions not explicitly considered
  - Combinatorial problem (from ANSP perspective) that is intractable given existing resources

Proposed Operations Not Tenable

- Trajectory-Based Operations (TBO) proposed as the way forward
  - Operators would negotiate 4D-trajectory with ANSPs and then "stick to the agreed trajectory" except in extenuating circumstances when they would have to "renegotiate" their trajectories
- However, this "Big giant head" approach to trajectory-based operations is not tenable…

Proposed Operations– Why not?

- Uncertain operating environment
  - Imperfect weather and trajectory prediction (poor understanding of dynamics of operating environment) means that the local optimal solution might often not be the same as the global optimal solution
  - changing airspeed to maintain planned groundspeed can put aircraft in a position where it is unable to meet its ultimate RTA

Proposed Operations– Why not?

- If we ignore uncertainties…
  - Really large MILP problem due to large number of aircraft combinations and long duration of aircraft trajectories (each aircraft is considered multiple times)
- If we consider uncertainties….
  - Huge stochastic programming problem due to large number of aircraft combinations, long duration of aircraft trajectories, and very large number of possible events and recourse actions (similar to the "curse of dimensionality" experiences with real options)
- Limits on communication bandwidth

Pragmatic Approach

- Break the TBO problem into "functional" steps
  - Determine the number of aircraft that can (at a point in the future) traverse each sub-volume of airspace considering traffic and weather uncertainties
  - Determine the "optimal" route for each aircraft subject to volume constraints in each sub-volume
  - Resolve potential conflicts in a fuel and emissions optimal manner when "certain" that conflicts will arise

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Air Traffic Flow Management in the Presence of Uncertainties

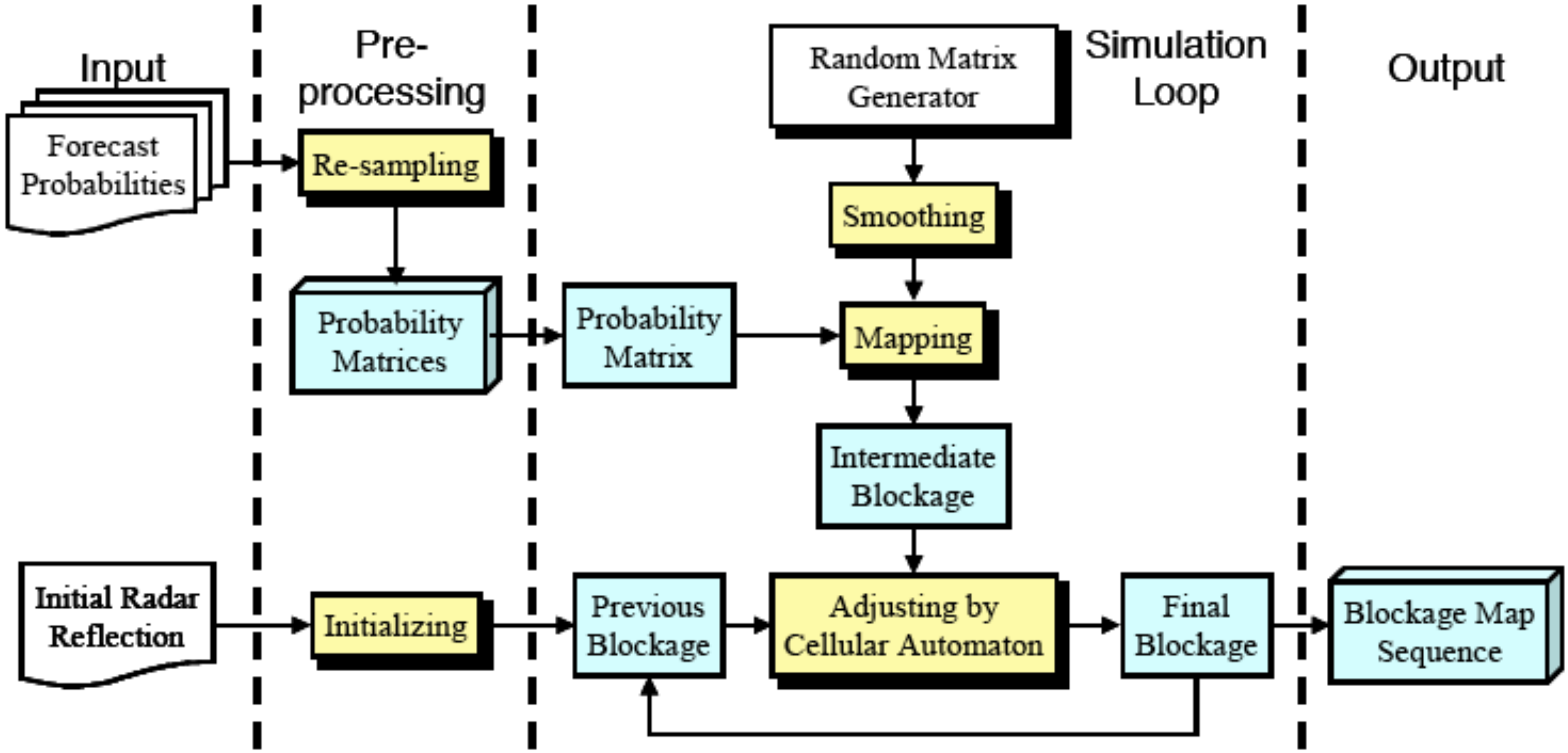
Principal Investigators: John-Paul Clarke

Funded by: NASA Ames Research Center

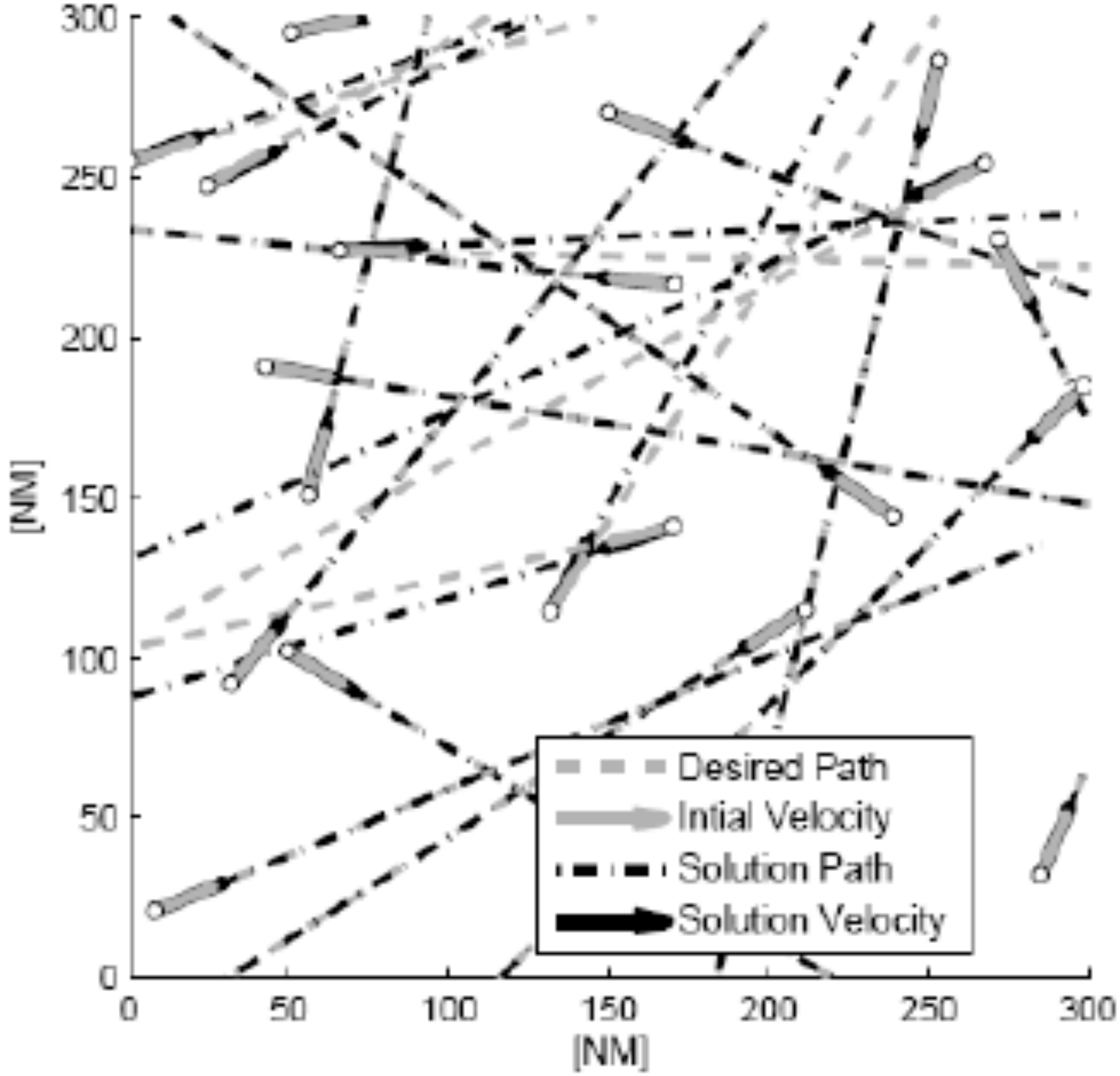
Determining Airspace Capacity

- Step 1: Develop set of airspace blockage scenarios for given volume of airspace that are "consistent" with probabilistic convective weather forecast
- Step 2: Derive "probabilistic capacity" at future times using Monte Carlo simulation of efficient (fuel-optimal) conflict resolution algorithm in scenarios from Step 1.
- Step 3: Determine number of aircraft to send towards volume of airspace using two-stage stochastic program and probabilistic capacities from Step 2.

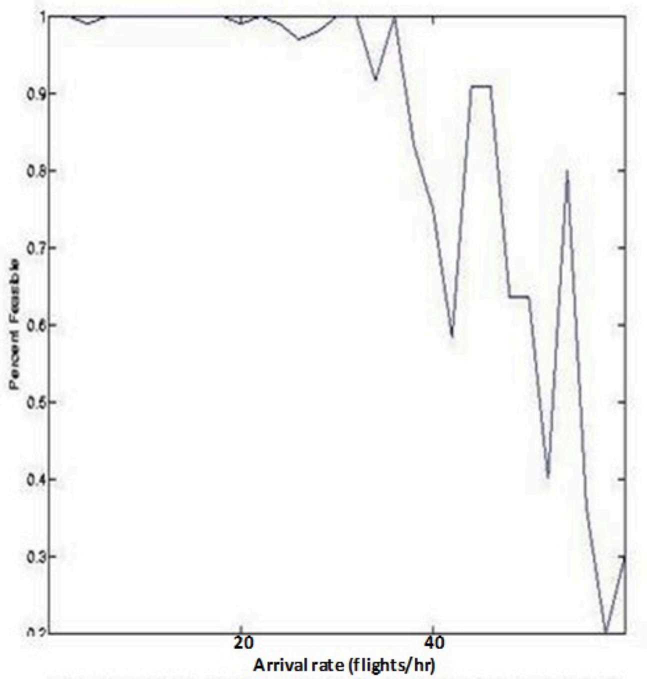
Capacity – Step 1



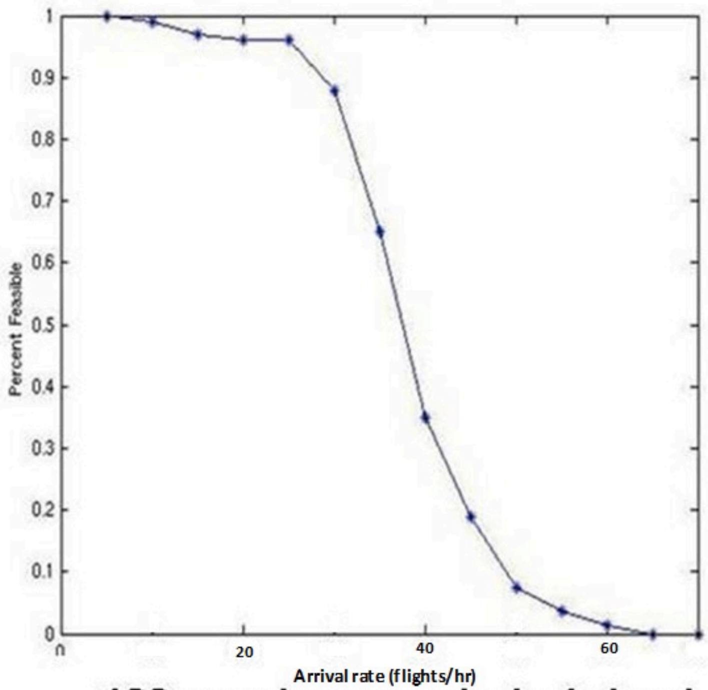
Capacity – Step 2



Capacity – Step 2 (cont'd)



10 samples per arrival rate level



100 samples per arrival rate level

Capacity – Step 3

- Input data including bounds on decision variables
  - M : set of flights, *m* as the index
  - S : set of time periods; *s*, *t*, *u* as the index
  - b_m : scheduled departure period of flight *m*
  - Δk_m : regular flying period of flight *m* to the sector
  - Δs_m : maximum number of periods flight *m* can be ground-delayed
  - Δt_m^+ : maximum number of periods flight *m* can be scheduled to arrive early
  - Δt_m^- : maximum number of periods flight *m* can be scheduled to arrive late
  - Δh_m : maximum number of periods flight *m* can be air-held

Capacity – Step 3 (cont'd)

- **Costs and capacity**

  g_m^s : ground-delay cost for flight *m* if it is sent at time *s*

  $c_m^{t-s-\Delta k_m}$: speed-change cost for flight *m* if it is sent at time *s* and arrived the sector at time *t*

  a_m^{u-t} : air-hold cost for flight *m* if it arrives the sector at time *t* and enters the sector at time *u*

  d_m^t : diversion cost for flight *m* which diverts at time *t*

  C^u : sector capacity at time *u*

- Variables

  x_m^{st} : 1 if flight *m* is sent at time *s* and arrives the sector at time *t*; 0 otherwise

  p_m^{tu} : 1 if flight *m* arrives the sector at time *t* and enters the sector at time *u*; 0 otherwise

  q_m^t : 1 if flight *m* arrives the sector and diverts at time *t*; 0 otherwise

Capacity – Step 3 (cont'd)

$$\min \sum_{m\in M}\left\{\sum_{s=b_m}^{b_m+\Delta s_m}\sum_{t=s+\Delta k_m-\Delta t_m^+}^{s+\Delta k_m+\Delta t_m^-}\left[\left(g_m^s+c_m^{t-s-\Delta k_m}\right)\cdot x_m^{st}\right]+\sum_{t=b_m+\Delta k_m-\Delta t_m^+}^{b_m+\Delta s_m+\Delta k_m+\Delta t_m^-}\left[E\left[d_m^t\cdot Q_m^t(\xi)\right]+\sum_{u=t}^{t+\Delta h_m}\left(a_m^{u-t}\cdot E\left[P_m^{tu}(\xi)\right]\right)\right]\right\}$$

$$s.t. \quad \sum_{m\in M}\sum_t p_m^{tu}(\xi)\le C^u \qquad \forall u$$

$$q_m^t(\xi)+\sum_{u=t}^{t+\Delta h_m}p_m^{tu}(\xi)=\sum_s x_m^{st} \qquad \forall t,m$$

$$\sum_{s=b_m}^{b_m+\Delta s_m}\sum_{t=s+\Delta k_m-\Delta t_m^+}^{s+\Delta k_m+\Delta t_m^-}x_m^{st}=1 \qquad \forall m$$

$$x_m^{st} \quad binary \qquad \forall s,t,m$$

$$p_m^{tu}(\xi),q_m^t(\xi) \quad binary \qquad \forall t,u,m$$

Computational Study (Number of Period Considered = 11)

flights depart in	# of flight	Solve to Optimality			Rolling Horizon Method			
		objective value	Time (sec)	period	modified objective value	Time (sec)	# iteration	% from optimal
period 1-2	27	2,644.95	11.12	5-13	2,644.95	12.00	1	0.00%
period 1-3	28	2,647.95	371.96	5-16	2,647.95	13.00	1	0.00%
period 1-4	31	3,403.17	422.59	5-16	3,403.17	13.00	1	0.00%
period 1-5	35	3,417.01	1,247.56	5-18	3,422.91	18.00	1	0.17%
period 1-6	41	n/a	n/a	5-19	4,298.91	21.00	2	n/a
	44				4,306.51	23.00	3	n/a
period 1-7	48	n/a	n/a	5-19	8,467.54	29.00	3	n/a

Optimal Routing

Aircraft Operations for Minimum Environmental Impact

Stephen Altus, PhD
Jeppesen, A Boeing Company
San Jose, CA
Geoffrey C. Bower
Stanford University, Department of Aeronautics & Astronautics
Stanford, CA

JEPPESEN
A BOEING COMPANY

Optimal Routing

Flight Planning Objective Functions

One way to include the atmospheric impact is to rely on an intelligent emission taxing scheme

Minimize: $Cost = C_{fuel} + C_{time} + C_{overflight} + C_{spill} + C_{emissions\ tax}$

If no official scheme exists, operators can define their own weighting based on cultural values and operational goals

Alternatively, we could do multi-objective optimization for cost and environment – a current aircraft design research topic

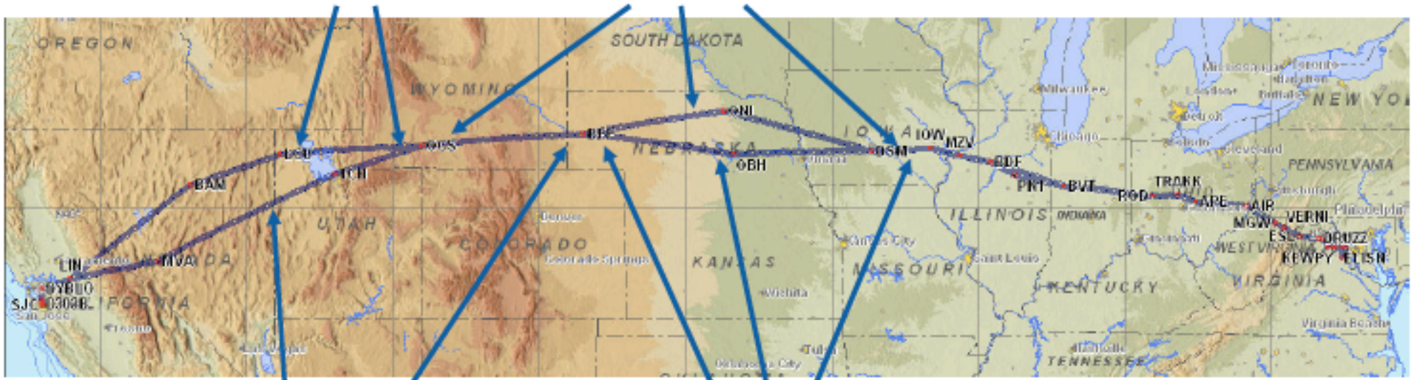
Optimal Routing

Flight planning for min NO_x: system allowed to vary route, altitudes

- SJC-IAD
- 150-seat aircraft, 30,000lb payload
- Mach 0.78, NWS RUC winds & temperatures

Minimum-NO_x route: Fuel 25,746lb; NO_x 337lb

FL330 to OCS FL350



FL350 to BFF FL370

Minimum-fuel route: Fuel 25,663lb; NO_x 389lb

Optimal Routing

Minimum Cost vs. minimum NO_x varying speed, altitudes, route

- SJC-IAD, optimal routes matched in this case
- 150-seat aircraft, 30,000lb payload
- NWS RUC winds & temperatures

Scenario	Min Cost CI = 50	Min NOx
Altitudes	FL350 for 1393nm, then FL370	FL310 for 206nm, then FL330
Speeds	Mach .778 - .783	Mach .760
Fuel	24,576 lb	25,193 lb
NO_x (Cruise only)	416 lb	394 lb
Advantage	2.4% less fuel 1% less time	5.3% less NO_x

Fuel Optimal Conflict Resolution

PARTNER

Partnership for AiR Transportation Noise and Emission Reduction

An FAA/NASA/TC-sponsored Center of Excellence

NEXTGEN EN ROUTE TRAFFIC OPTIMIZATION TO REDUCE FUEL BURN AND EMISSIONS

(Project 5)

Lead Investigators: Prof. John-Paul Clarke, Prof. Karen Feigh
Georgia Tech Project Manager: Atri Dutta
FAA Project Manager: László Windhoffer

This work was funded by the US Federal Aviation Administration, Under FAA Award Nos.: 07-C-NE-GIT, Amendment No. 017.

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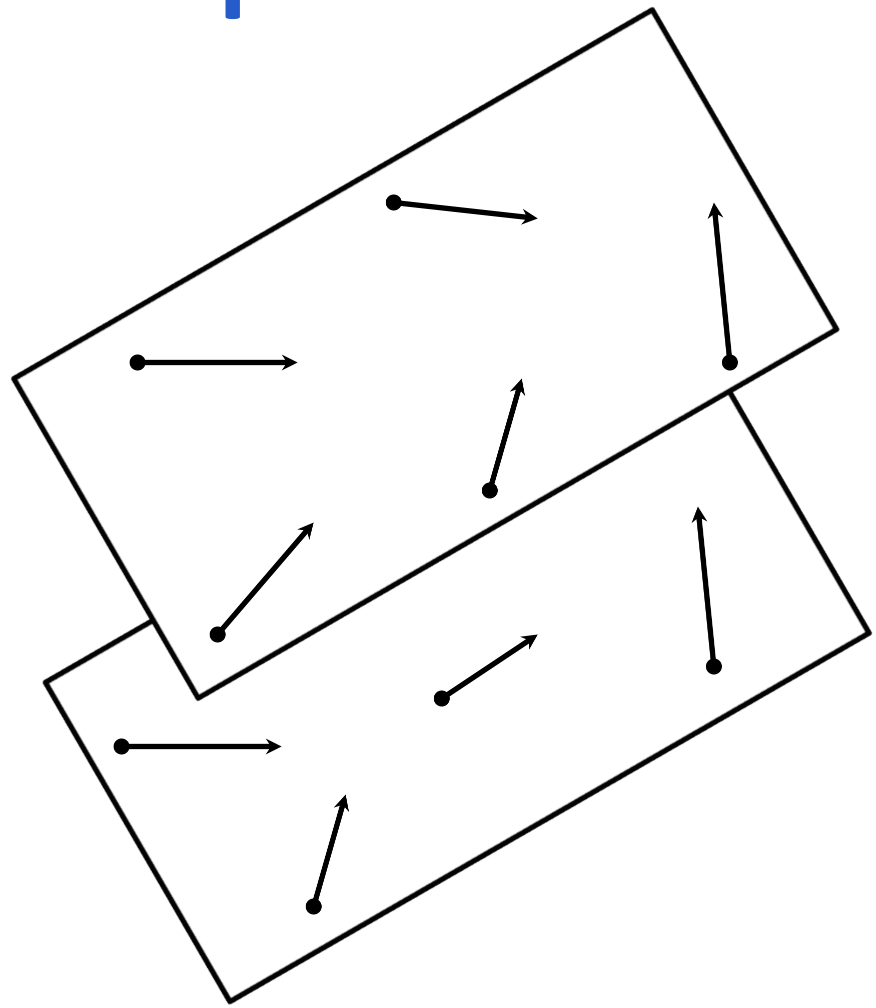
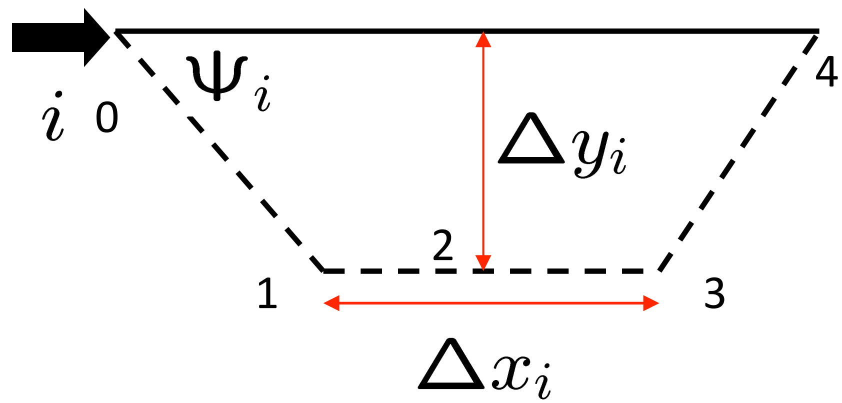
Problem Description

- Given
  - N aircraft
  - Initial location
  - Initial heading
  - Intended exit location
  - Time to reach exit point
- Allow
  - Speed, heading, and altitude changes
- Required
  - Conflict resolution
  - Min fuel burn

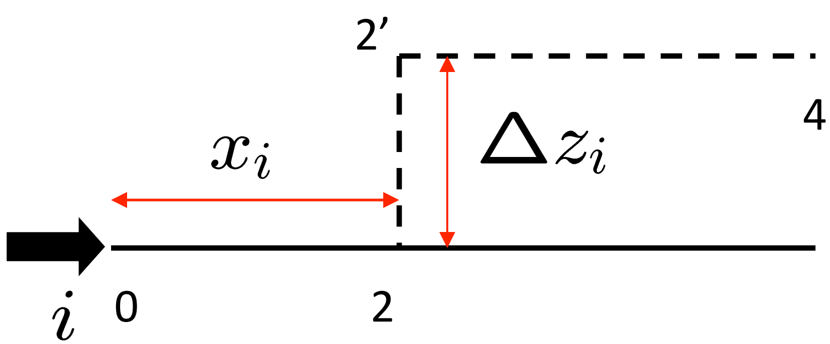


Conflict Resolution Strategy

- Heading changes
  - Two required for providing a lateral separation
  - Third required to turn back to intended exit point



(Horizontal Plane)

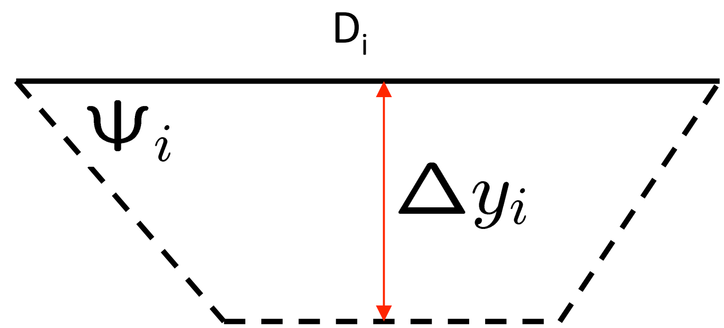


(Vertical Plane)

- Altitude change
  - One per aircraft during flight through center

Other Constraints

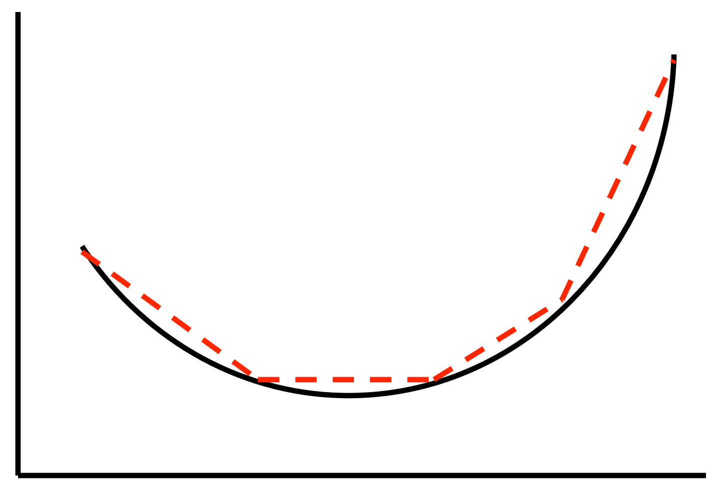
- Time constraints
  - Total time taken over the altered trajectory of each path must be within pre-specified value



- Speed constraints
  - Speed over a particular linear segment is constant and within pre-described limits
- Geometry constraints
  - Projected length of the path is distance between the initial and final points on path
  - Linearized constraint to include in MILP framework

Cost Function

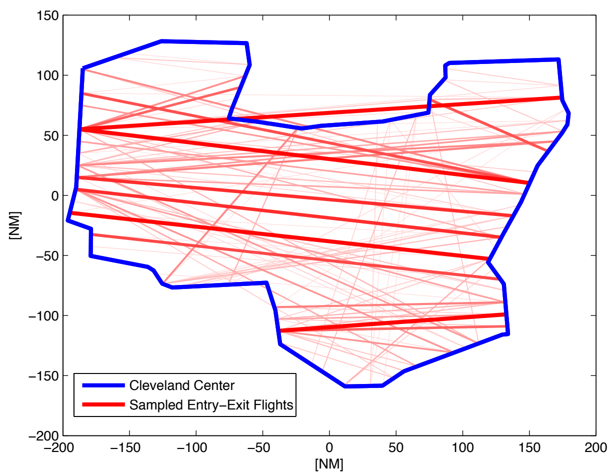
- Fuel Expenditure
  - Convex function of speed
  - Can be approximated by piecewise linear functions to incorporate within the MILP framework

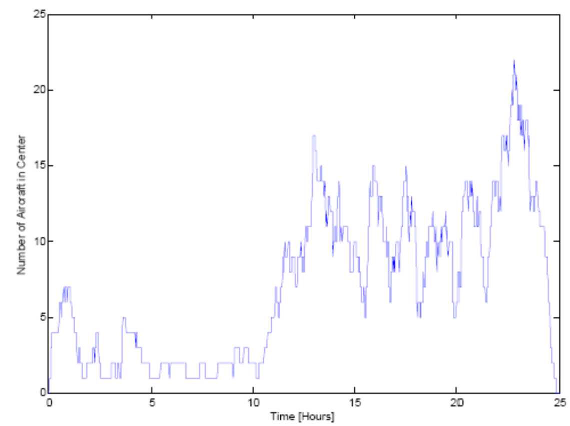


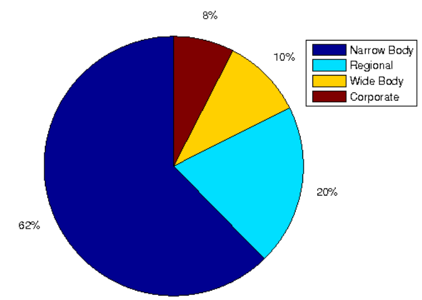
- Minimize total fuel expended during the flight of the aircraft in their altered routes

Case Study: Cleveland ARTCC

- 24hr Period - Sunday, May 1, 2005
  - FL36 (Westbound) – Nominal day in NAS







Case Study: Results

- Lower Bound on Fuel Savings: 1.4 %
- If aircraft fly at suboptimal speeds (0% or 15% below optimal): 3.37% and 6.13%
- Flights > 350NM, (24% of all flights): 2.1%.

Summary

- Current en route operations sub-optimal
- Centralized, deterministic, trajectory-based operations untenable
- Pragmatic approach where operations divided into functional steps shows great promise