Analysis of Gaming Issues in Collaborative Trajectory Options Program (CTOP)

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Outline

- Motivation
- Background on CTOP
- Research Questions
- Optimal Trajectory Options (w/o Gaming)
- Gaming Issues
- Implications

Motivation (1)

- Air transportation is a critical enabler of the global economy…
  - Strong correlation with gross domestic product
  - Air cargo is a leading indicator of economic activity
  - Significant number of direct, indirect, and induced jobs
  - Air transportation provides a basis for economic activity in regions with poor surface and water access
- Future economic growth will require significant efficiency improvements and/or capacity increases

Motivation (2)

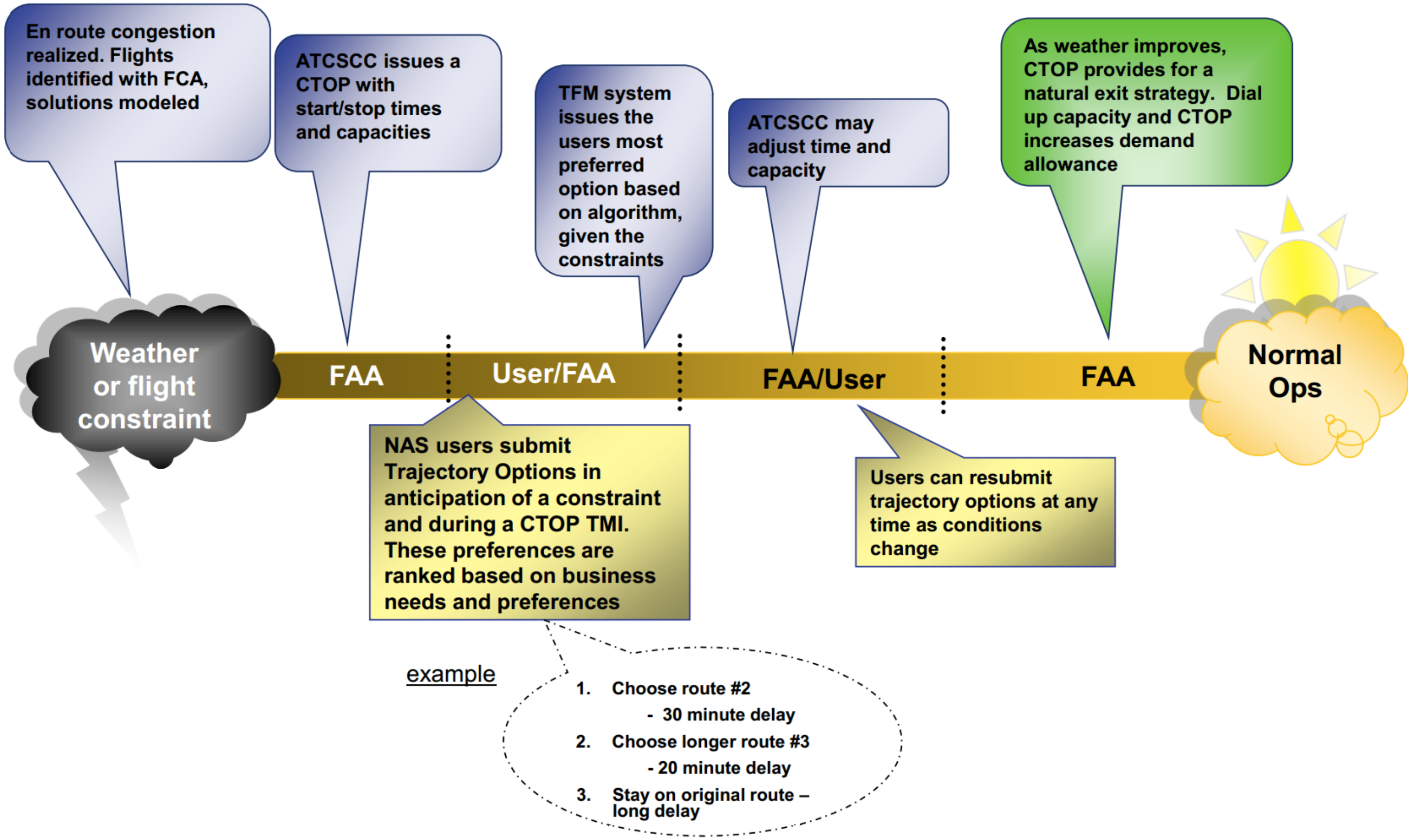
- En route congestion due primarily to…
  - High demand
  - Severe weather
- Two methods traditionally employed to address en-route congestion…
  - Holding flights on the ground
  - Re-routing flights that are airborne
- However… Not able to truly maximize throughput by assigning both delays and reroutes.

Motivation (3)

- CTOP (Collaborative Trajectory Options Program) recently introduced to address this shortcoming…
  - Enables consideration of both ground holding and multiple routes (and also re-routing).
  - Based philosophically on the ration-by-schedule principles of the Ground Delay Program (GDP).
  - Requires consideration of significantly greater number of combinations and permutations.
  - Has proven to be a challenge for many airlines.

CTOP (1)

- How does CTOP work?



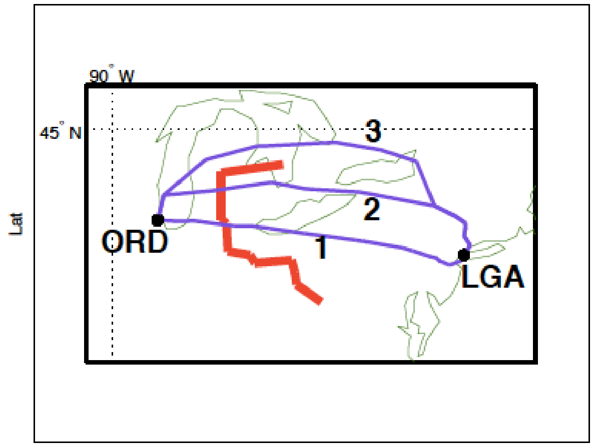
CTOP (2)

- What are airlines required to do?

Flight operators need to submit TOS messages to express their preference.

Index	Trajectory	Relative Trajectory Cost (RTC)	ETA
1	ORD..ELX..JHW..RKA..LGA	0 (min)	1:25
2	ORD..TVC..RKA..LGA	30 (min)	2:00
3	ORD..ASP..YYZ..ROC..RKA..LGA	40 (min) (NOSLOT)	N/A

ORD–LGA



Definition

Adjusted cost (AC) =
RTC + Required Ground Delay

If there is only one slot at 2:00...
FAA will assign option 2(AC=30+0)

CTOP (3)

- How does the CTOP allocation scheme compare to the scheme for Ground Delay Programs (GDP)?

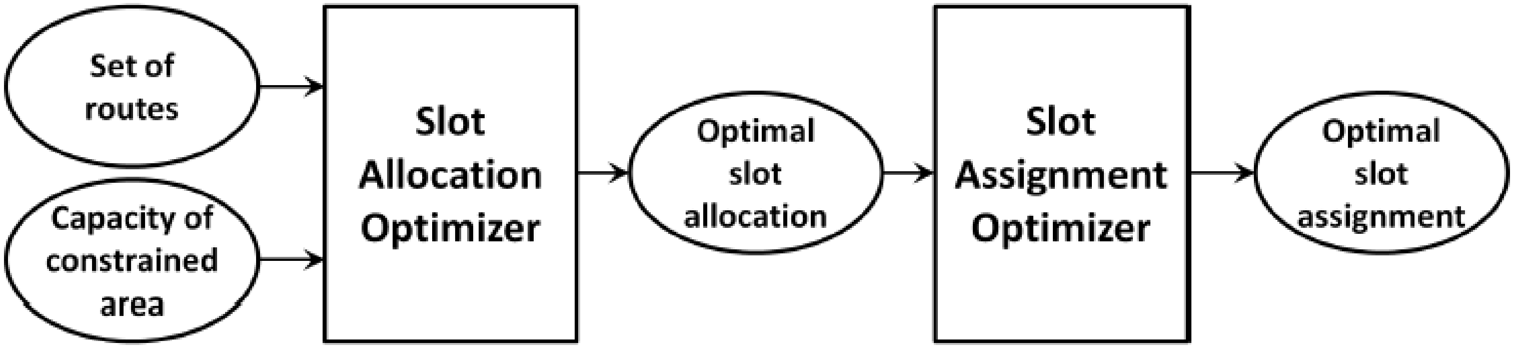
1. Determine flights included in the CTOP demand.
2. Determine flights that are part of CTOP demand but are exempt.
3. Assign trajectories to exempt flights first.
4. Sort remaining flights by Initial Arrival Time (IAT) at the CTOP.
5. Once at a time, in IAT order, assign flights to their most preferred option possible based on adjusted cost, which is sum of relative trajectory cost and required ground delay, using the available capacity that remains after assigning prior flights.
6. Send assignments to Flight Operators.

Research Questions

- What are the optimal trajectory options to submit?
  - What trajectory options should an airline submit to obtain the "best" slots given the FAA's CTOP assignment algorithm?
  - How should flights be subsequently assigned to slots to minimize the impact of en route capacity shortage and maximize revenue?
- Should an airline try to game the system?
  - What is the best strategy given all the possible actions that other airlines can make?

Optimal Trajectory Options (1)

- Two Stage Algorithm
  - 1st stage: Find best slots (given capacity constraints and likely actions by other operators) to minimize cost.
  - 2nd stage: Find best slot assignments (given slots from 1st stage) to maximize revenue.

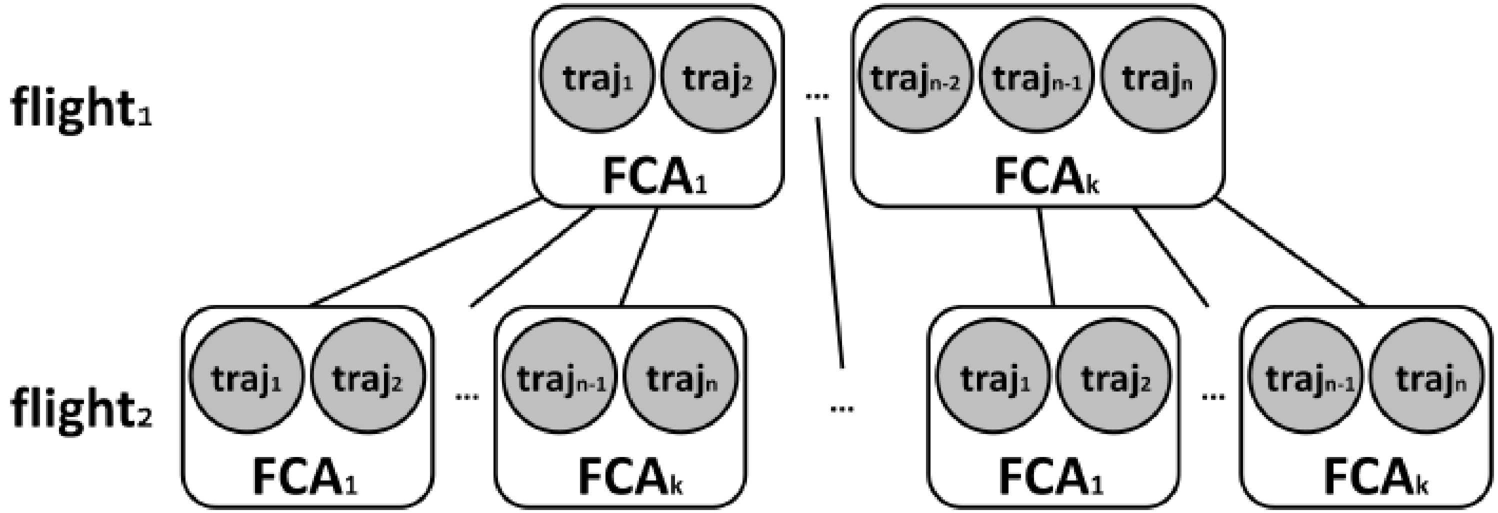


Optimal Trajectory Options (2)

- In the 1st Stage…
  - Find optimal FCA slot allocations that…
    - Minimize total costs
  - For the given…
    - Set of aircraft within a planning horizon
    - Definition and capacity of Flow Constraints Areas (FCA)
    - Set of trajectory candidates
  - By considering…
    - Expected action of other operators
    - Possible trajectory combinations

Optimal Trajectory Options (3)

- "Greedy" algorithm utilized…
  - Instead of considering all trajectory combinations, only the earliest feasible slots of each FCA are considered by grouping trajectories based on FCA entrance.

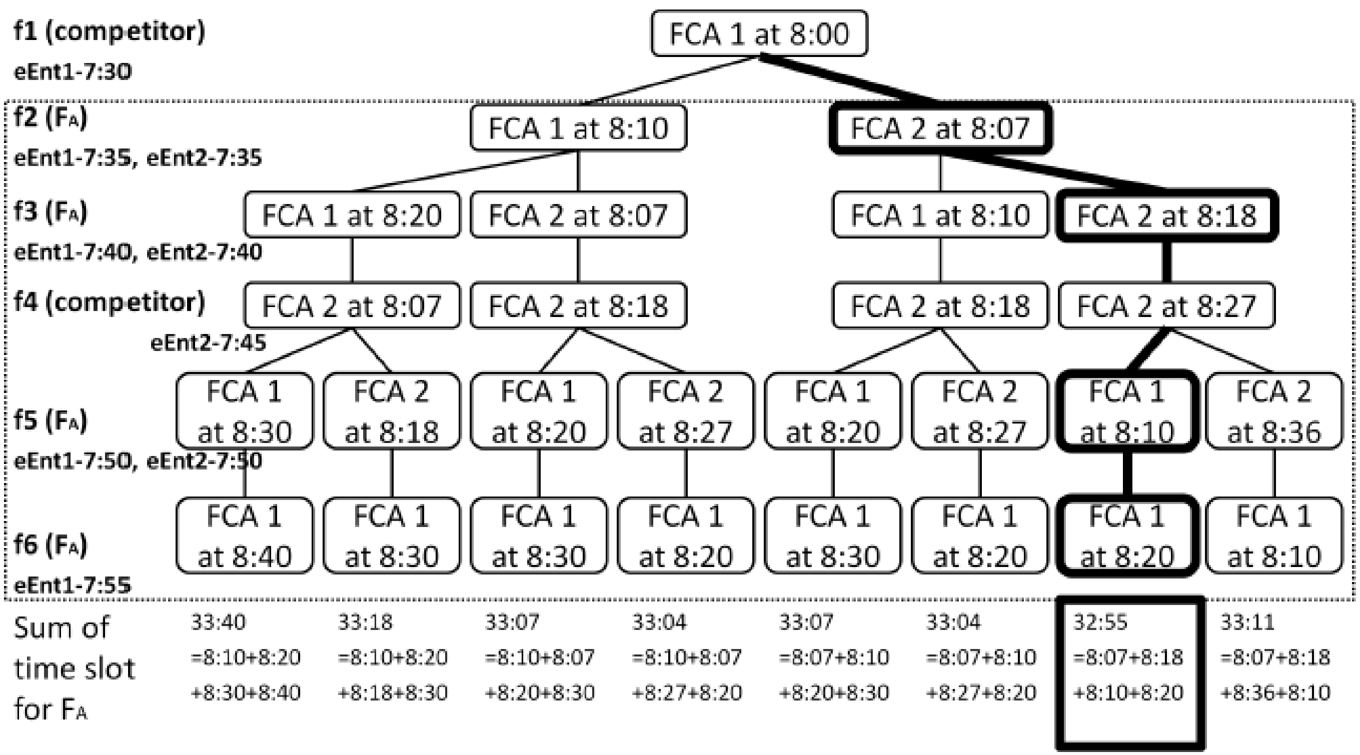


Optimal Trajectory Options (4)

Sort flights based on the earliest IAT regardless of the FCAs
$f = 0$
while ($f \neq$ end of a planning horizon) **do**
    if all trajectories of a flight f enter the same FCA **then**
        Do a slot allocation based on greedy strategy
        (the earliest feasible slot)
    else
        Branch further by investigating the earliest feasible slot
        for each trajectory and choosing the earliest trajectory for each FCA
        as a candidate for slot allocations
    end if
    $f = f + 1$
end while
Choose the best trajectory combination which has the minimum cost.

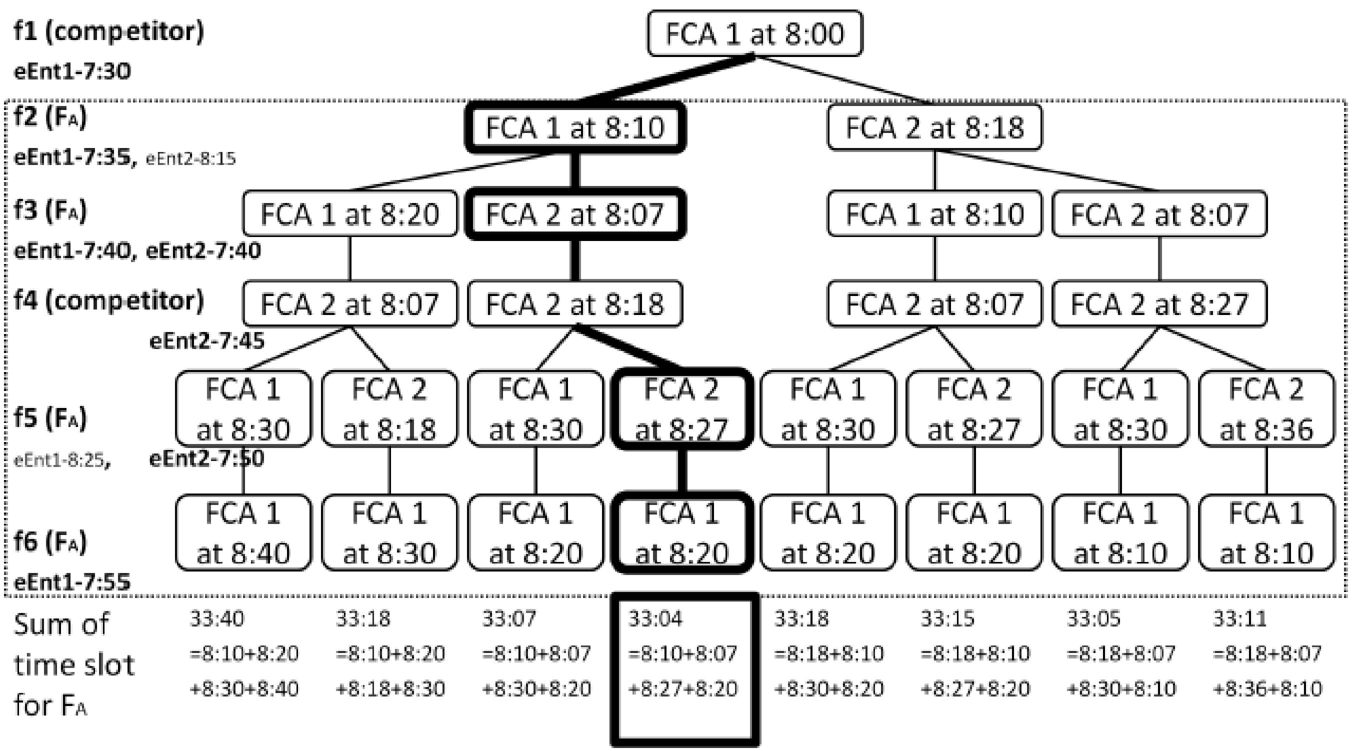
Optimal Trajectory Options (5)

- Available slots at FCA 1 - 8:00, 8:10, 8:20, 8:30, 8:40
- Available slots at FCA 2 - 8:07, 8:18, 8:27, 8:36, 8:45



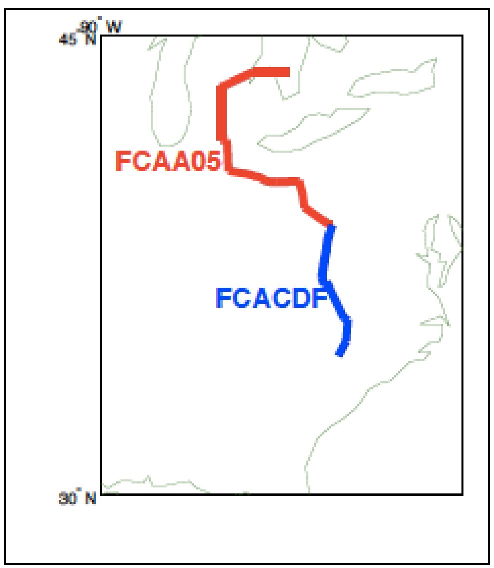
Optimal Trajectory Options (6)

- Available slots at FCA 1 - 8:00, 8:10, 8:20, 8:30, 8:40
- Available slots at FCA 2 - 8:07, 8:18, 8:27, 8:36, 8:45

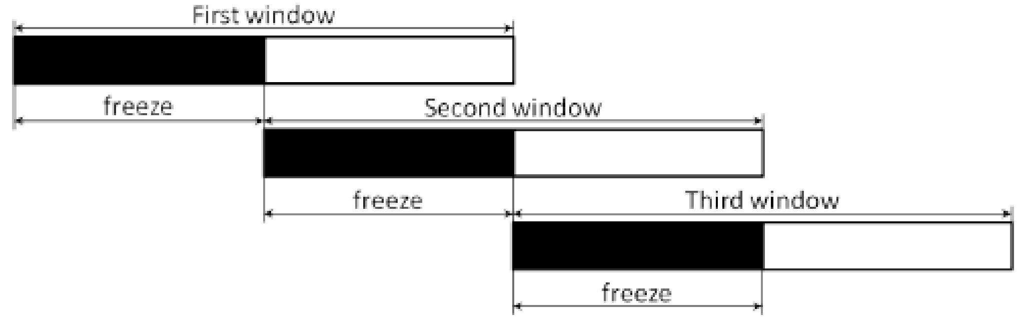


Optimal Trajectory Options (7)

- The FAA's CTOP message is extracted.
  - Constrained Areas: FCAA05, FCACDF
  - The number of our flights: 106, the number of other flights: 266
  - Total number of available slots of FCAA05 and FCACDF: 175 slots

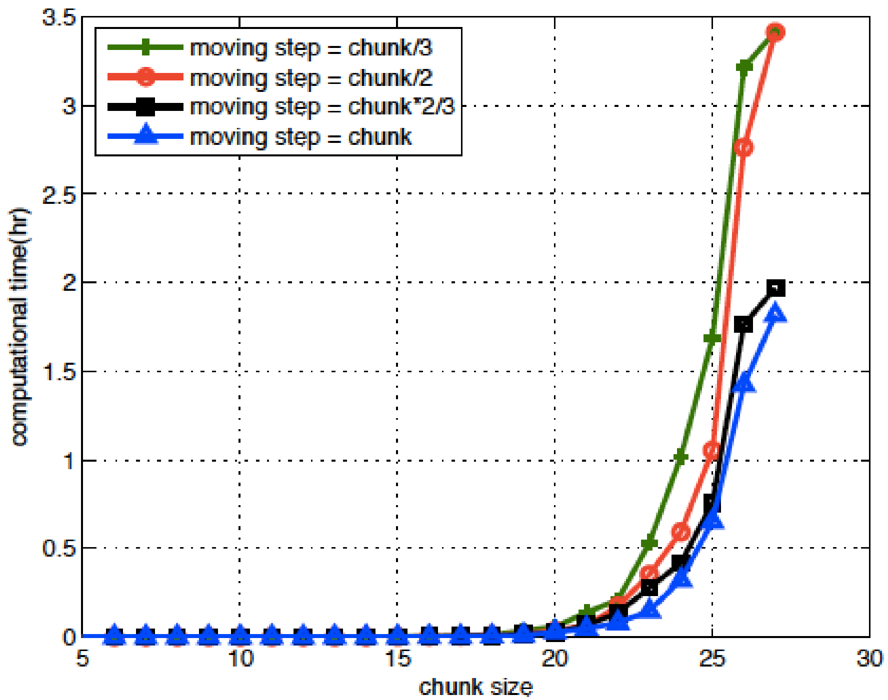


1^{st} stage rolling horizon



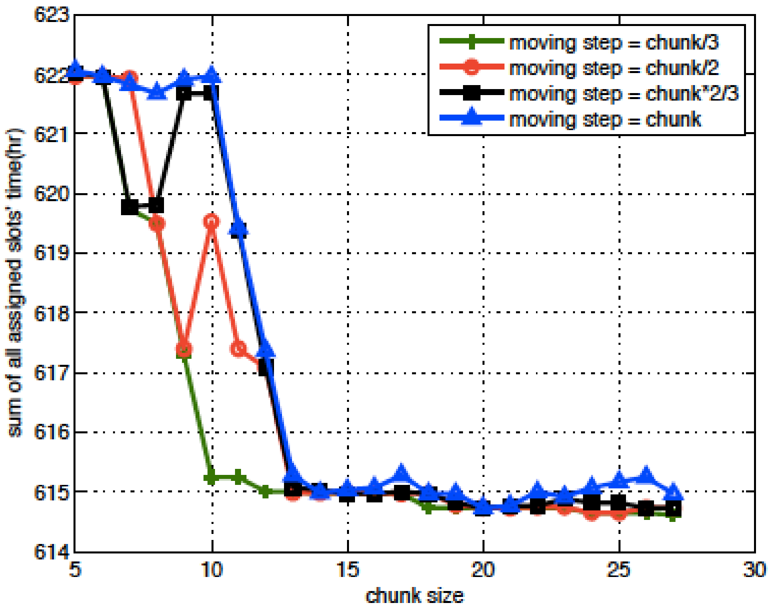
Optimal Trajectory Options (8)

- Chunk size on x axis represents the number of flights which enter multiple FCAs in each planning window. Thus, it can be interpreted as the size of each optimization window.

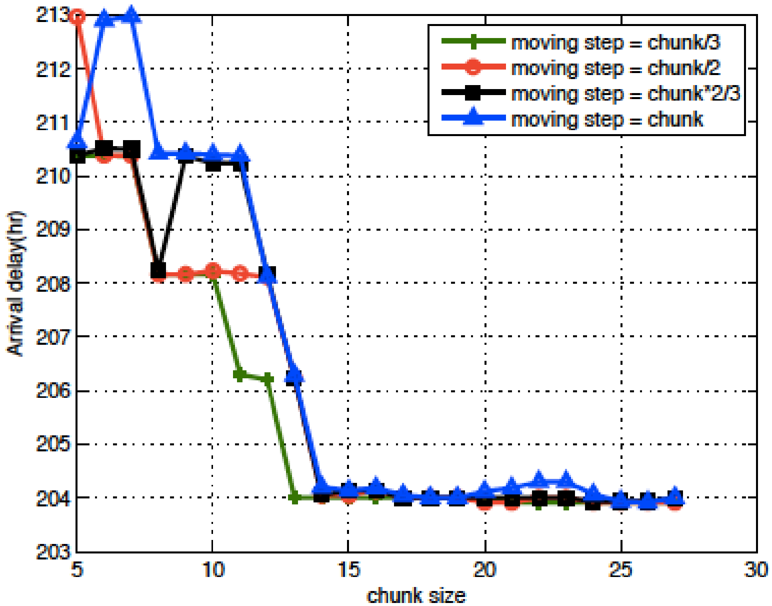


Optimal Trajectory Options (9)

- min{total slot times}



- min{total arrival delay}

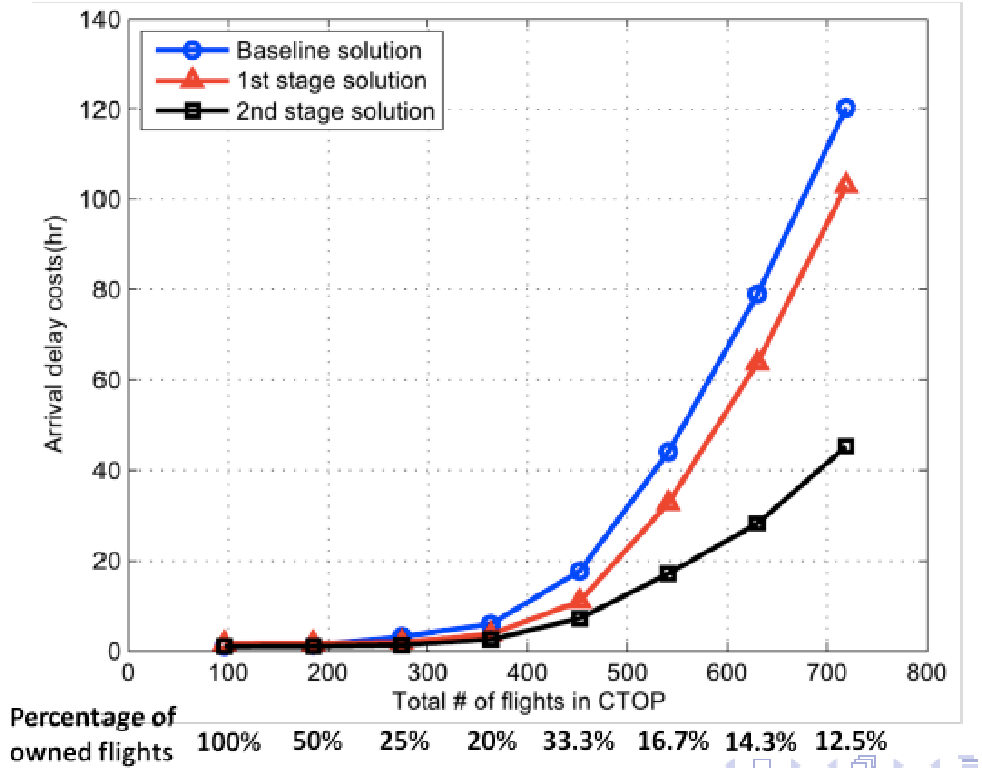


Optimal Trajectory Options (10)

- In the 2nd Stage…
  - Find optimal slot assignments that…
    - Satisfy the given slot capacity constraints
    - Minimize total costs
  - For the given…
    - Slot allocations
    - Full set of trajectory candidates
    - Schedule of flights
  - By…
    - Swapping the slot internally
    - Routing out (NOSLOT) specific flights

Optimal Trajectory Options (11)

- Minimizing total arrival delays
- Simulations with different schedule are executed by injecting more other users' flights while the number of owned flights is fixed.



Gaming Issues (1)

- Airlines must submit trajectory options with limited knowledge of CTOP demand.
  - i.e. limited knowledge of other airline flights and strategies
- One rational assumption in the presence of no information is that the other airlines will submit NOSLOT options.
  - However airlines could do something else and could even game the system.
- Need to consider the range of actions of other airlines and also potential gaming.

Gaming Issues (2)

- Key question… Is there a Nash equilibrium?

Airline A \ Airline B			
	NOSLOT (1054) NOSLOT (510)	NOSLOT (1054) 1 Trajectory + NOSLOT (513)	NOSLOT (1054) B 2 Trajectories + NOSLOT (471)
	1 Trajectory + NOSLOT (1012) NOSLOT (510)	1 Trajectory + NOSLOT (1033) 1 Trajectory + NOSLOT (477)	1 Trajectory + NOSLOT (1102) 2 Trajectories + NOSLOT (489)
	2 Trajectories + NOSLOT (980) A NOSLOT (510)	2 Trajectories + NOSLOT (1002) 1 Trajectory + NOSLOT (511)	2 Trajectories + NOSLOT (1007) 2 Trajectories + NOSLOT (481)

Gaming Issues (3)

- Consider the following demand case and scenarios…

Cases

Scenarios	A 50% B 50%	A 67% B 33%	A 75% B 25%
	1- (25|75) 2- (75|25)	1- (33|67) 2- (100|0)	1- (50|50) 2- (100|0)
	1- (50|50) 2- (50|50)	1- (67|33) 2- (67|33)	1- (75|25) 2- (75|25)
	1- (75|25) 2- (25|75)	1- (100|0) 2- (33|67)	1- (100|0) 2- (50|50)

Gaming Issues (4)

- Assuming Airline A knows…

	Airline B		
Airline A	NOSLOT (1054) NOSLOT (510)	[redacted]	[redacted]
	1 Trajectory + NOSLOT (1012) NOSLOT (510)	[redacted]	[redacted]
	2 Trajectories + NOSLOT (980) NOSLOT (510)	[redacted]	[redacted]

Gaming Issues (5)

- The "known" case-scenario combinations are…

Case 1 – Scenario 1 (A = 0, B = 0)	Case 1 – Scenario 1 (A = 1, B = 0)	Case 1 – Scenario 1 (A = 2, B = 0)
Case 1 – Scenario 2 (A = 0, B = 0)	Case 1 – Scenario 2 (A = 1, B = 0)	Case 1 – Scenario 2 (A = 2, B = 0)
Case 1 – Scenario 3 (A = 0, B = 0)	Case 1 – Scenario 3 (A = 1, B = 0)	Case 1 – Scenario 3 (A = 2, B = 0)
Case 2 – Scenario 1 (A = 0, B = 0)	Case 2 – Scenario 1 (A = 1, B = 0)	Case 2 – Scenario 1 (A = 2, B = 0)
Case 2 – Scenario 2 (A = 0, B = 0)	Case 2 – Scenario 2 (A = 1, B = 0)	Case 2 – Scenario 2 (A = 2, B = 0)
Case 2 – Scenario 3 (A = 0, B = 0)	Case 2 – Scenario 3 (A = 1, B = 0)	Case 2 – Scenario 3 (A = 2, B = 0)
Case 3 – Scenario 1 (A = 0, B = 0)	Case 3 – Scenario 1 (A = 1, B = 0)	Case 3– Scenario 1 (A = 2, B = 0)
Case 3 – Scenario 2 (A = 0, B = 0)	Case 3 – Scenario 2 (A = 1, B = 0)	Case 3– Scenario 2 (A = 2, B = 0)
Case 3 – Scenario 3 (A = 0, B = 0)	Case 3 – Scenario 3 (A = 1, B = 0)	Case 3 – Scenario 3 (A = 2, B = 0)

Gaming Issues (6)

- And the SG-CTOP payoff is…

$$D(C, S, M) = dy \qquad (1)$$

Where:

- D(C,S,M) = estimated delay in minutes (dy) for *Airline A* in…
  - Case (C),
  - Scenario (S), and
  - Move (M) by *Airline A*;
  - when move by *Airline B* is equals 0 (NOSLOT).
- Move by *Airline A* is…
  - 0 = NOSLOT,
  - 1 = one trajectory plus NOSLOT option, and
  - 2 = two trajectories plus NOSLOT option.

Gaming Issues (7)

$$M(C,S) = \left(\frac{D(C,S,\alpha) + (4 * D(C,S,\beta)) + D(C,S,\chi)}{6}\right) \quad (2)$$

$$S(C,S) = M(C,S) - (D(C,S,\alpha) - D(C,S,\beta)) \quad (3)$$

$$H(C,TS) = \frac{\sum_{K_{1 \to TS}} [\sum_{M_{0 \to 2}} D(C,K,M)]}{TS} \quad (4)$$

$$F(TC,TS) = \sum_{C_{1 \to TC}} [H(C,TS) - |S(C,S)|] \quad (5)$$

Where:

-TC = Total number of Cases.

-TS = Total number of Scenarios.

-M(C,S) = Estimated delay for each case and scenario.

-S(C,S) = Estimated deviation for each case and scenario.

-H(C,TS) = Estimated mean delay for each case.

-F(TC,TS) = Relationship among all estimated delays associated with moves by *Airline A* when move by *Airline B* is 0 (NOSLOT).

Gaming Issues (8)

$$E(TC,TS) = \sum_{C_{1\to TC}} \left[\sum_{S_{1\to TS}} (D(C,S,\beta) - D(C,S,\alpha)) \right] \quad (6)$$

$$\text{SG}_{Payoff} = \left[E(TC,TS) + \left(|E(TC,TS)| * \frac{F(TC,TS)}{10^{-4}} \right) \right] \quad (7)$$

$$\begin{cases} \text{SG}_{Payoff} \leq 0, \text{ GM} = 2 \text{ Trajectories} + \text{NOSLOT} \\ \text{SG}_{Payoff} > 0, \text{ GM} = 1 \text{ Trajectory} + \text{NOSLOT} \end{cases}$$

Where:

-E(TC,TS) = Delay difference between one trajectory plus NOSLOT and two trajectories plus NOSLOT.

-SG_{Payoff} = SG-CTOP's payoff value.

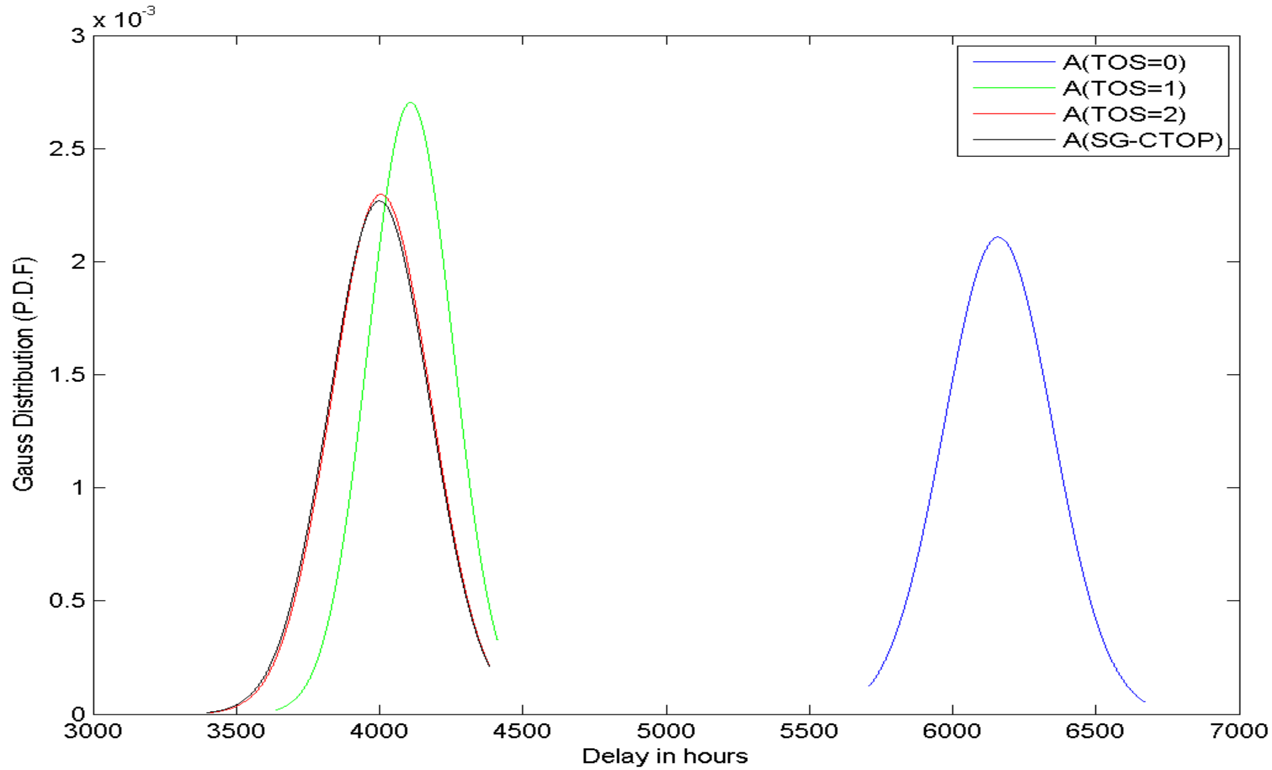
If SG_{Payoff} is higher than 0, game move (GM) is to send one trajectory plus NOSLOT for each flight, otherwise send two trajectories plus NOSLOT.

Gaming Issues (9)

- Evaluating the following game strategies…
  - NOSLOT for all flights
  - One trajectory plus NOSLOT option for all flights
  - Two trajectories plus NOSLOT option for all flights
  - Game move based on SG-CTOP payoff function
- In every game over 100 rounds where…
  - CTOP period from hour 6 to hour 8
  - FCA capacity of 3 or 5 aircraft per 15 minutes
  - Real data from 331 flights from Miami, Dallas, Chicago, San Francisco, Los Angeles and Las Vegas to New York metropolitan area.

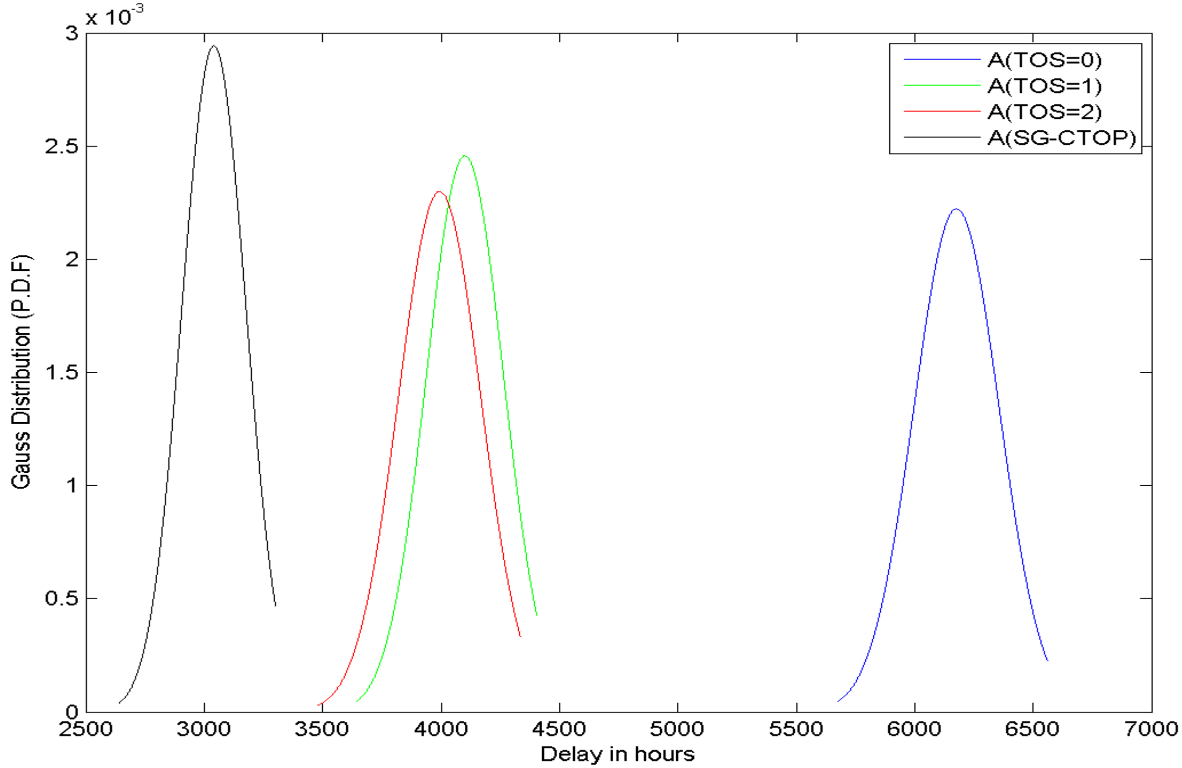
Gaming Issues (10)

- PDF for all cases after 100 SG-CTOP rounds



Gaming Issues (11)

- PDF for Case 1 after 100 SG-CTOP rounds



Gaming Issues (12)

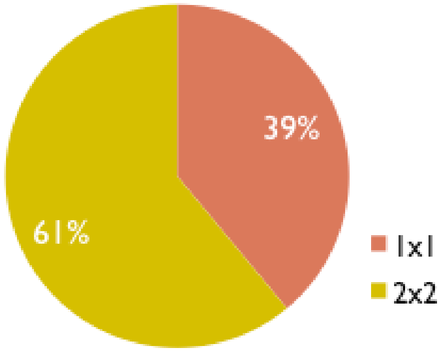
- SG-CTOP achieved a better, or equal, result in all cases (up to 14%).

	TOS Strategies			
	NOSLOT	1 + NS	2 + NS	SG-CTOP
Delay in Hours (Case 1,2,3)	6149	4086	3950	3950
Delay in Hours (Case 1)	5196	3193	2992	2795
Delay in Hours (Case 2)	6960	4572	4479	4339
Delay in Hours (Case 3)	7791	5240	5182	4580

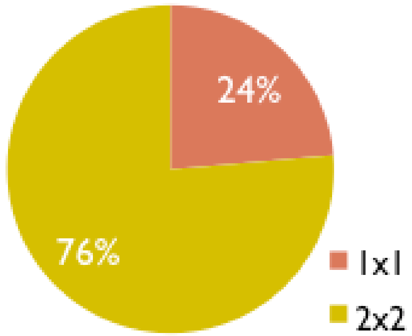
Gaming Issues (13)

- Nash equilibrium can be achieved, but the proportion of times that a given strategy is optimal varies based on fraction of demand.

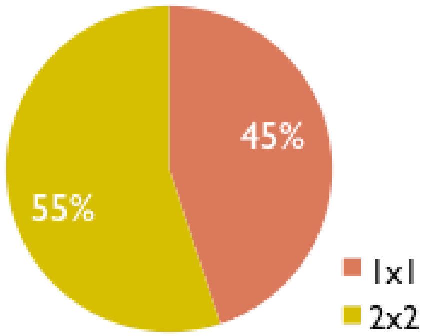
All Cases



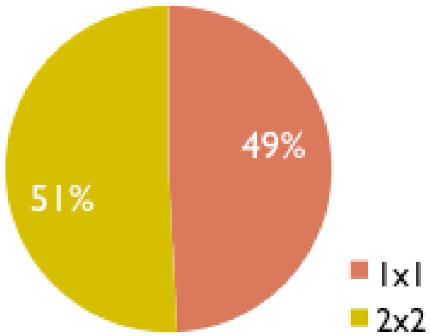
Case 1 (50%-50%)



Case 2 (67%-33%)



Case 3 (75%-25%)



Implications

- Sound decision-making during CTOP requires…
  - Optimization algorithm
  - Game theoretic decision framework
- Nash equilibrium can be achieved…
  - But proportion of times that a given strategy is optimal varies based on fraction of demand.
- Nash equilibrium is often week…
  - Opportunity for airlines to increase the cost of other carriers with only a small increase in their own cost.