En Route Speed Control Methods for Transferring Terminal Delay

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Motivation

- In recent years, rising demand for air travel has led to increasing delays in terminal airspace
- While it is possible to increase throughput near the terminal there is a ceiling on such improvement
- In the U.S. Traffic Management Advisor (TMA) imposes speed adjustments on aircraft, however, it only operates out to 200 nm from the arrival airport
- En route speed control of flights could be used to help reduce the amount of traffic at the terminal

Motivating Work

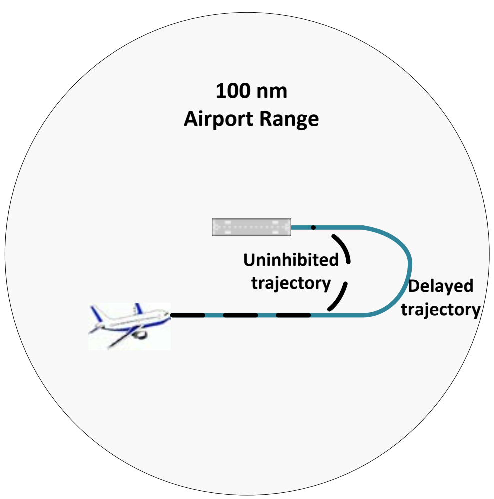
Knorr, Dave, Chen, Xing, Rose, Marc, Gulding, John, Enaud, Phillippe, and Hegendoerfer, Holger, “Estimating ATM Efficiency Pools in the Descent Phase of Flight: Potential Savings in both Time and Fuel,” in 9th USA/Europe Air Traffic Management R&D Seminar, Berlin, Germany June 2011.

Operational Systems and Trials:

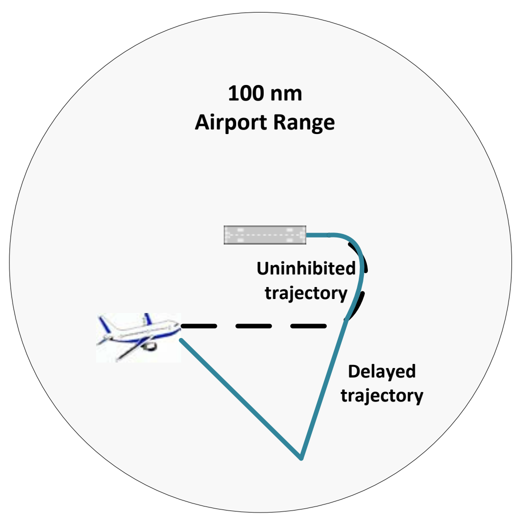
- Attila used at Atlanta, MSP and Charlotte by Delta Airlines
- London Heathrow: System allows airborne holding close to airport to be exchanged for reduced speed during cruise (United Airlines estimates potential to save 45 kg fuel per flight)
- Airservices Australia used speed control at Sydney saving 1 million kg of fuel in 2008
- The Terminal Area Precision Scheduling and Spacing System (TAPSS) system
- The Airline Based En Route Sequencing and Spacing tool (ABESS)

Current Context

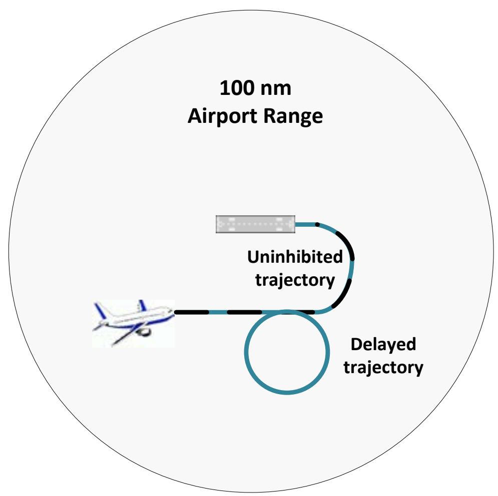
- Delays in the terminal area are typically taken by adding distance to a flight through a multitude of mechanisms including tromboning, vectoring and circular holding patterns.



Tromboning



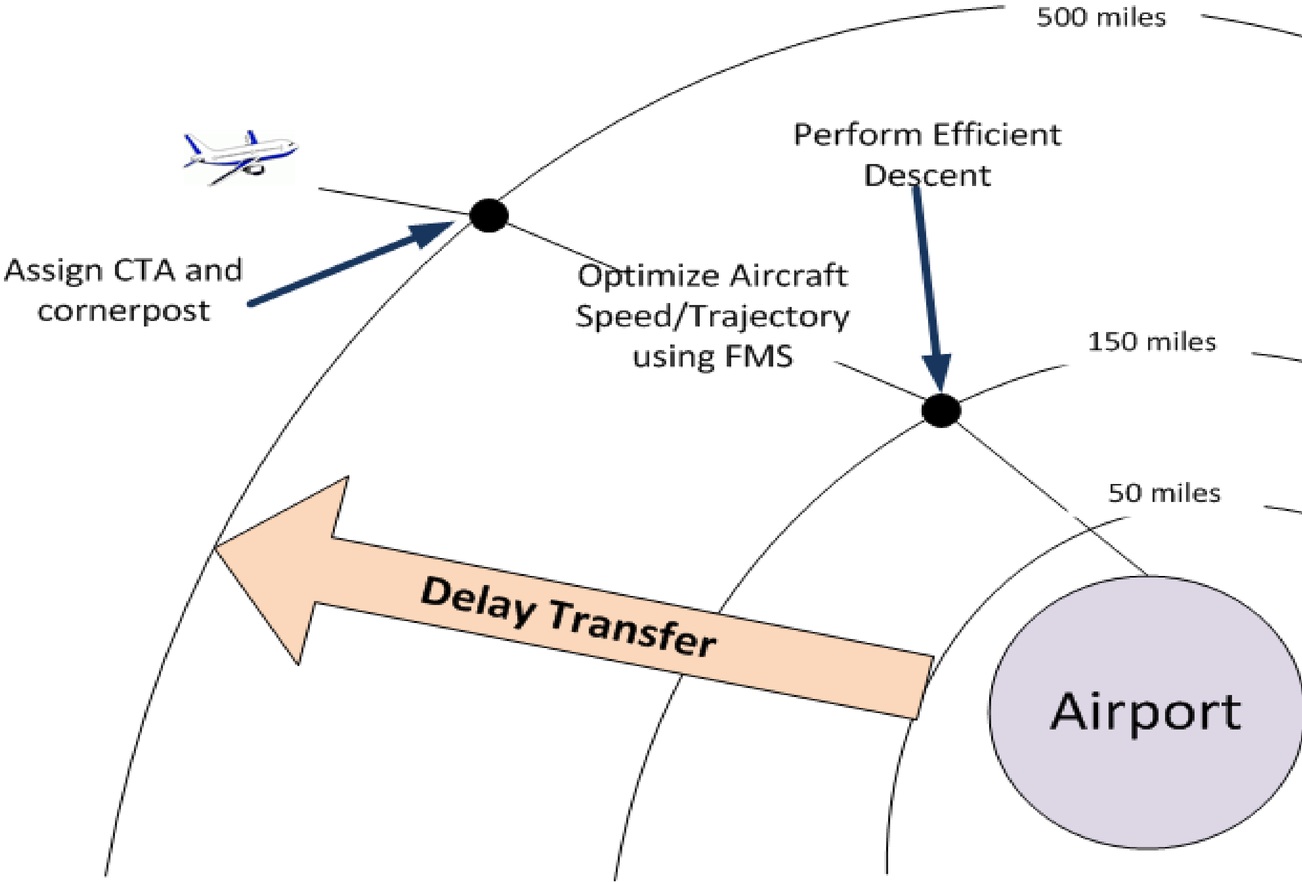
Vectoring



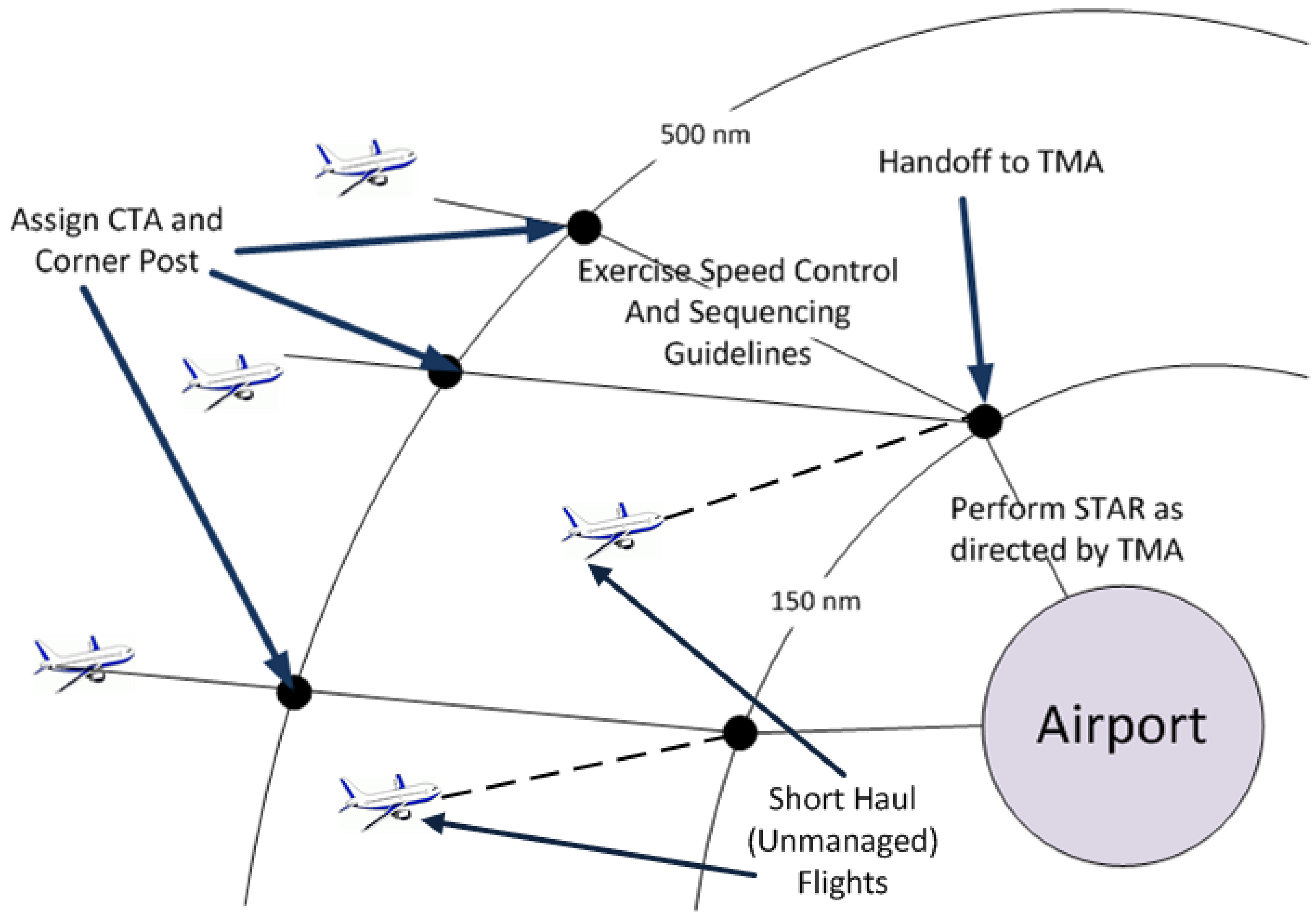
Circular Holding Pattern

Approach

- Develop a process for transferring delay away from the terminal by assigning a Controlled Time of Arrival (CTA) at 500 nm



Operational Context



Strategy

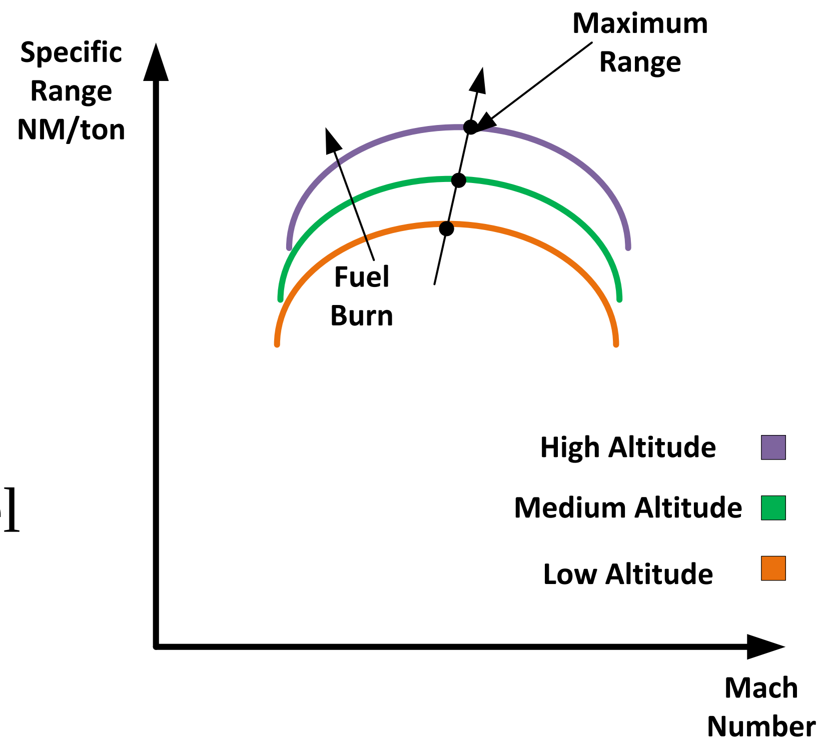
- Design a process for sending and receiving data between systems and carriers/command centers
- Develop a model to coordinate flights en route to transfer and eliminate terminal delay
  - Model seeks to maximize fuel savings while maintaining a high throughput rate
  - Controlled times of arrival (CTAs) are assigned dynamically based on periodic information updates

Performance Objectives

- Conserve fuel and transfer delay: Transfer delay from the terminal area to the en route portion of the flight, where it can be more efficiently absorbed
- Throughput: Maintain a high level of throughput and seek to increase throughput whenever possible
- Equity: Assigning CTAs, will perturb the natural order of the arriving flights. It is important to ensure that any flight prioritization be carried out in an equitable manner

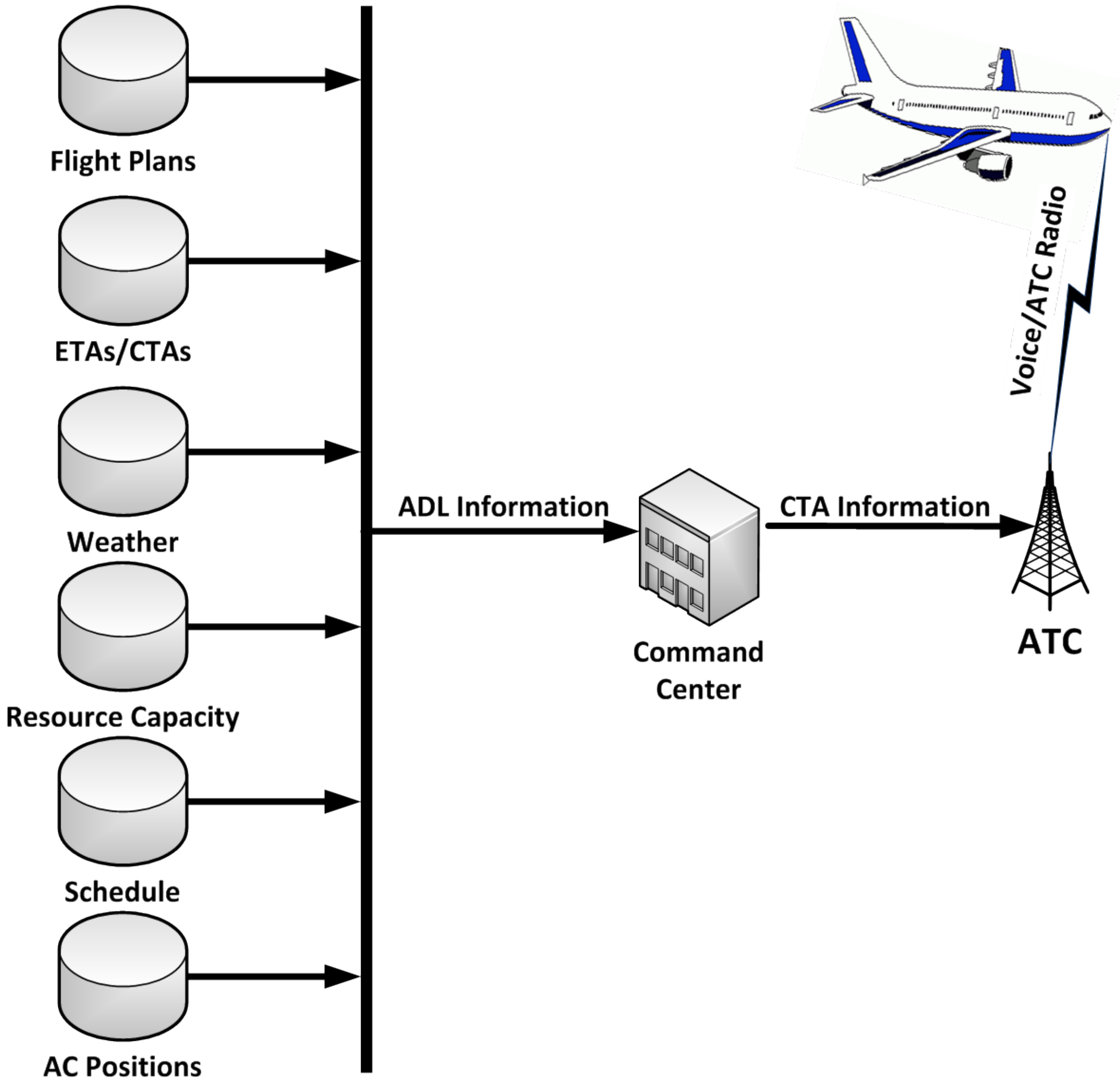
Fuel Usage Characteristics

- Fuel efficiency is a concave function of speed
- Increasing function of altitude
- General Characteristics:
  - Cost Curves are relatively flat
  - Slowing down during cruise increases Specific Range
  - Delay transfer from lower to higher altitudes reduces fuel consumption
- Two primary mechanisms for fuel savings
  - Less distance is traveled by aircraft resulting in lower overall fuel burn
  - Delay is more efficiently absorbed at higher altitude

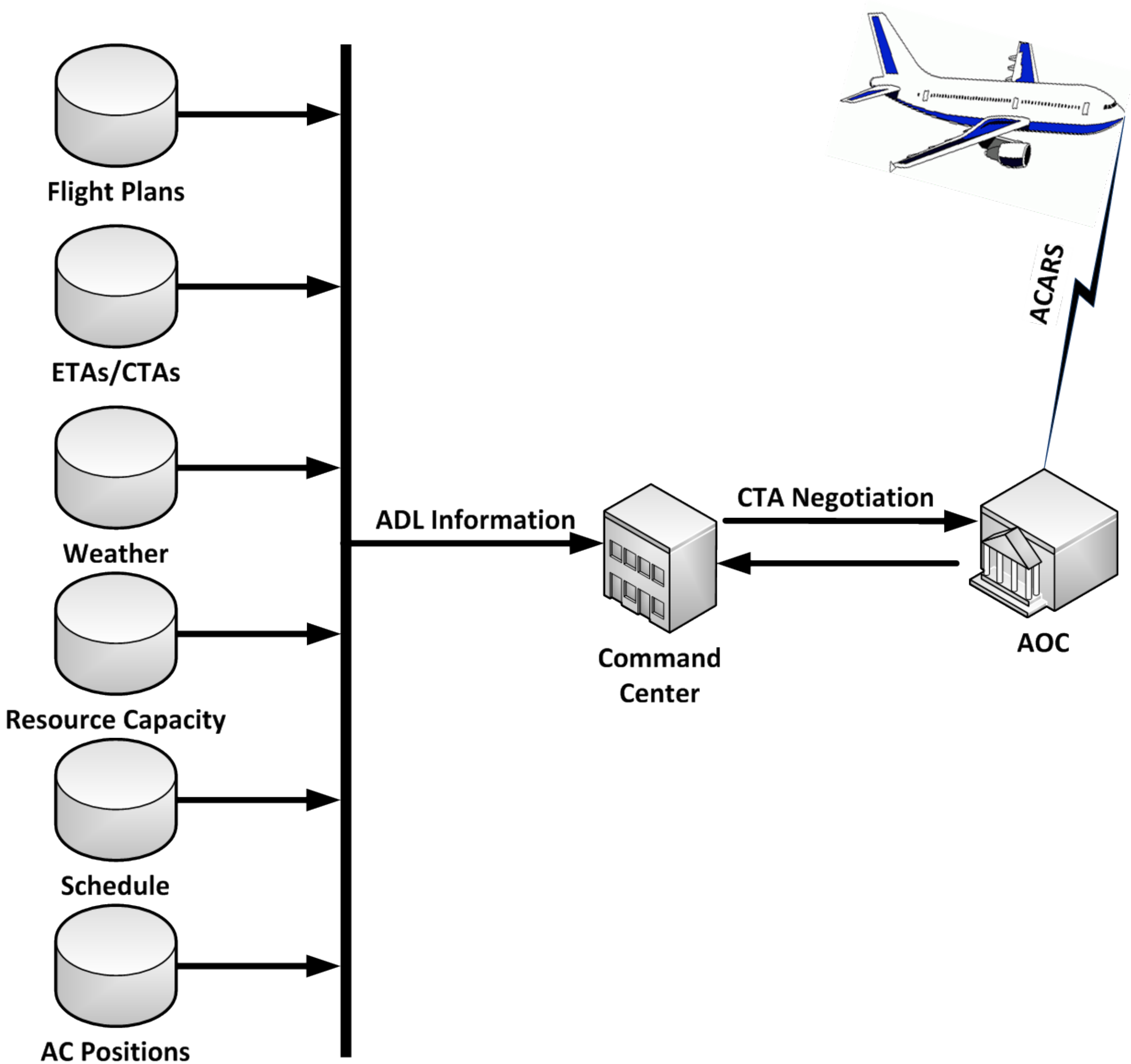


Absorbing delay en route ➔ Slowing down
Absorbing delay in terminal area ➔ Path Extension
➔ En route delay is essentially free

Information Flow: Central Control Approach

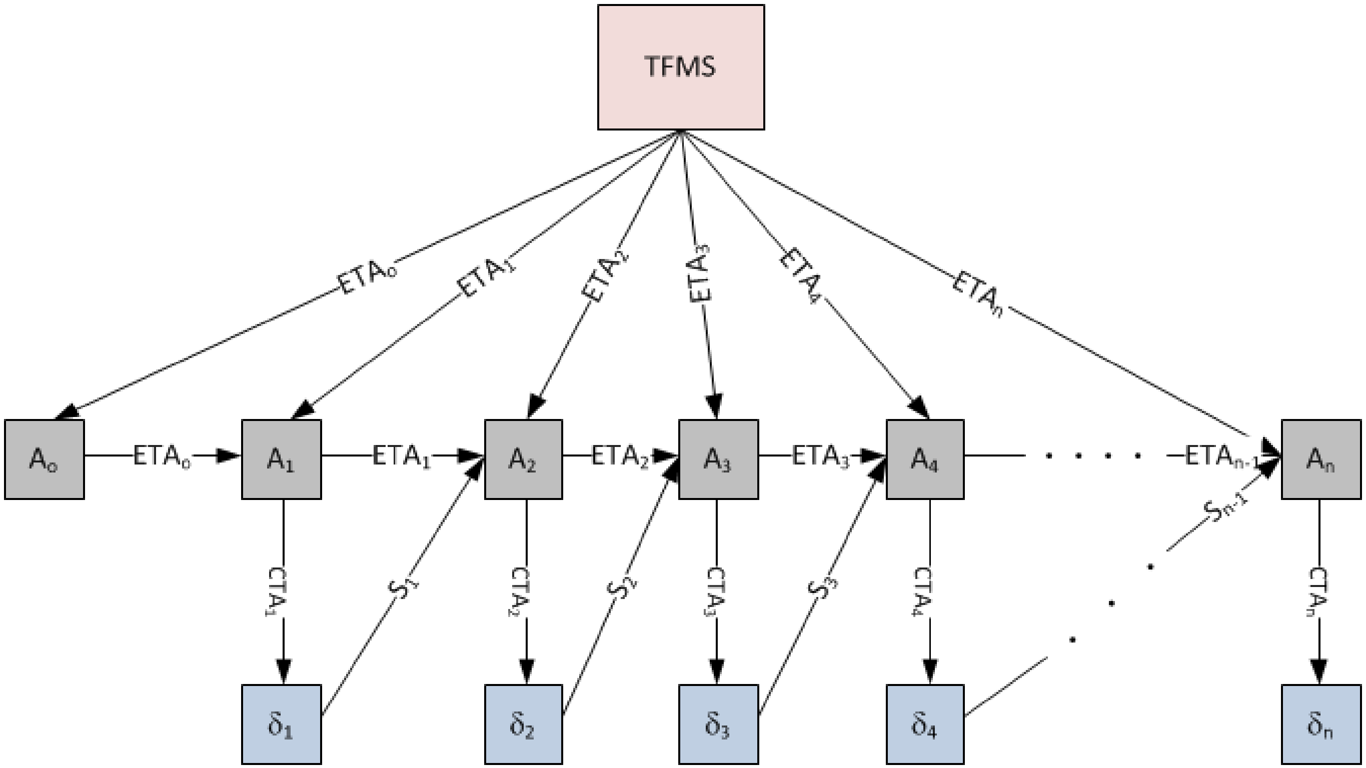


Information Flow: Collaborative Approach



Dynamic Framework

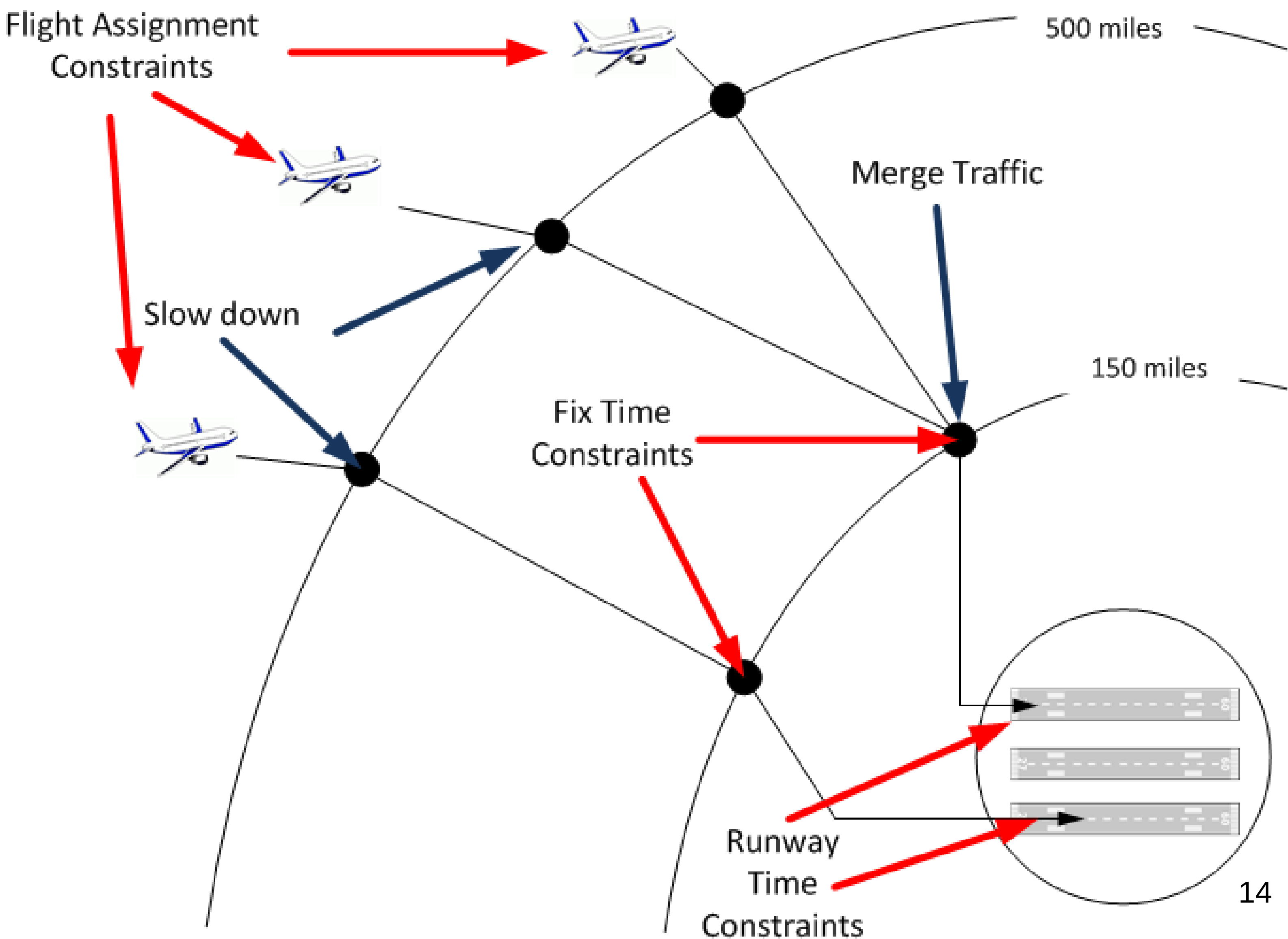
- Model dynamically assigns CTAs over a rolling horizon
  - CTA assignments to individual aircraft are not revisited
  - Assignments are made to banks of flights every 15-30 minute period
- TFMS provides periodic updates of ETAs
- Assigned CTAs define assignment constraints in future periods



CTA Assignment Model Parameters

- F –set of all flights
- Ω_f –set of eligible fixes for flight f
- R –set of all runways
- S_{if} – set of all slots for flight f at fix
- S_{rf} – set of all slots for flight f at runway r
- λ – weight assigned to each term in the objective criteria
- β – A discount factor applied to the second assignment period at each iteration
- c_{fks}^{ir}- the system delay cost of assigning flight f to slot k at fix i and slot s at runway r
- d_{fks}^{ir}- the fuel cost of assigning flight f to slot k at fix i and slot s at runway r
- $x_{fks}^{irn} = \begin{cases} 1 \text{ if flight } f \text{ is assigned to slot } k \text{ at fix } i \text{ and slot } s \text{ at runway } r \text{ in period } n \\ 0 \text{ otherwise} \end{cases}$

CTA Constraint Identification



CTA Assignment Integer Program (IP)

$$\min \sum_{\substack{f\in F, k\in S_{if},\\ i\in\Omega_f, s\in S_{rf},\\ r\in R}} \lambda c_{fks}^{ir1} x_{fks}^{ir1} + (1-\lambda) d_{fks}^{ir1} x_{fks}^{ir1} + \beta\left(\lambda c_{fks}^{ir2} x_{fks}^{ir2} + (1-\lambda) d_{fks}^{ir2} x_{fks}^{ir2}\right)$$

$S.T$

$$\sum_{\substack{k\in S_{if}, i\in\Omega_f,\\ s\in S_{rf}, r\in R}} x_{fks}^{ir2} + x_{fks}^{ir2} = 1 \quad \forall f \in F$$

Every flight is assigned to a slot

$$\sum_{\substack{f\in F, s\in S_{rf},\\ r\in R}} x_{fks}^{ir1} + x_{fks}^{ir2} \le 1 \quad \forall k \in S_{if}, \forall i \in \Omega_f$$

No arrival time at a fix is assigned to more than 1 flight

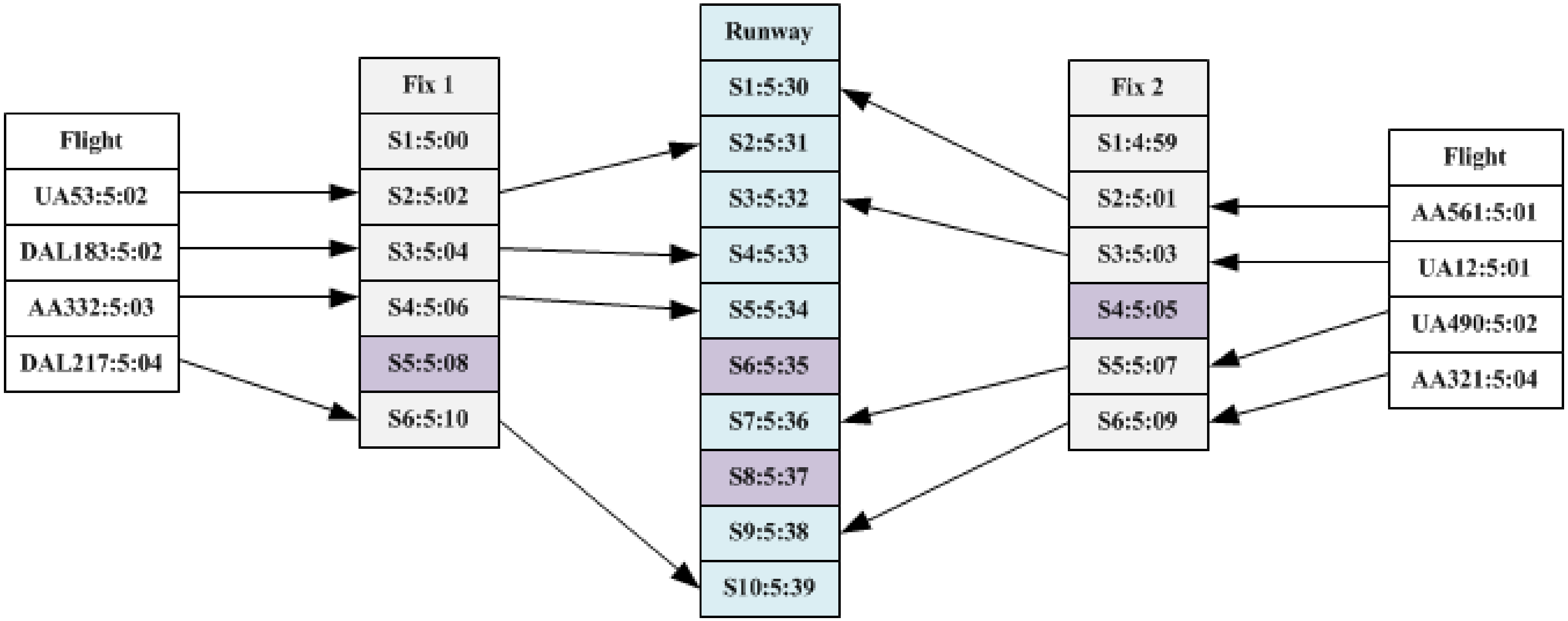
$$\sum_{\substack{f\in F, k\in S_{if},\\ i\in\Omega_f}} x_{fks}^{ir1} + x_{fks}^{ir2} \le 1 \quad \forall s \in S_{rf}, \forall r \in R$$

No arrival time at a runway is assigned to more than 1 flight

$$x_{fks}^{ir1}, x_{fks}^{ir2} \in \{0,1\}$$

Assignment variables are binary

Illustration of Assignment Process



- Flights are given an assignment time at a fix and a runway using IP model
- Some runway and fix slots will be occupied by unmanaged flights
  - Model slots are designed with slack to accommodate these interruptions
  - Nonetheless these unmanaged injections can cause delay (not explicitly accounted for in the model)

Experimental Test Conditions

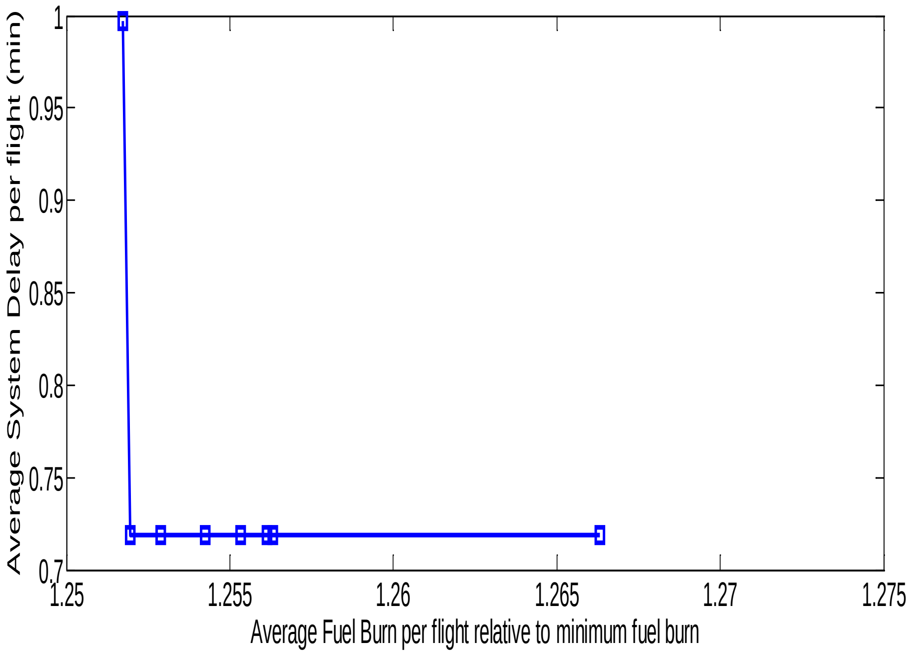
- Data Source: TFMS and ASDX files
- Airport: ATL
- Date of Flights: May 1st, 2012
- Total of Collection: 2:00pm-6:00 pm, Data was processed in 15 minute intervals
- Conditions: Clear Skies, Low winds
- Aircraft Speeds Ranged from Mach 0.72-0.85
- 4 Arrival Fixes
- 2.5 Arrival Runways (Third Runway operated at half capacity)

Traffic Simulation Modeling

- Simulation with randomization was used to inject unmanaged flights and variable timing of trajectories
- Modeling of TMA and terminal routing
  - Find necessary wake vortex time separation
  - Allocate Runway arrival times based on a FCFS queuing process
  - Flights are routed to the earliest available runway slot once they arrive at a fix
  - Travel times for Runways and fixes are computed based on average times
  - No overtakes were allowed

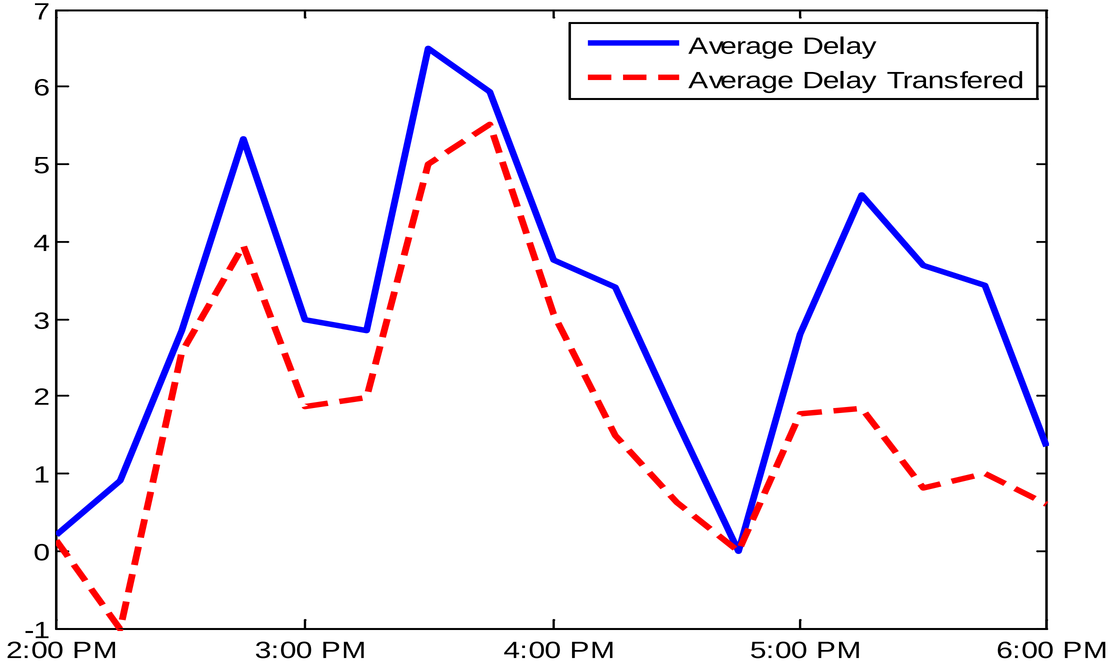
System Throughput vs. Fuel Efficiency

- Weighted our objective function at 11 combinations of fuel and throughput
- Trade suggests that substantial gains in throughput can be attained with minor loss to fuel efficiency



Delay Transfer Performance

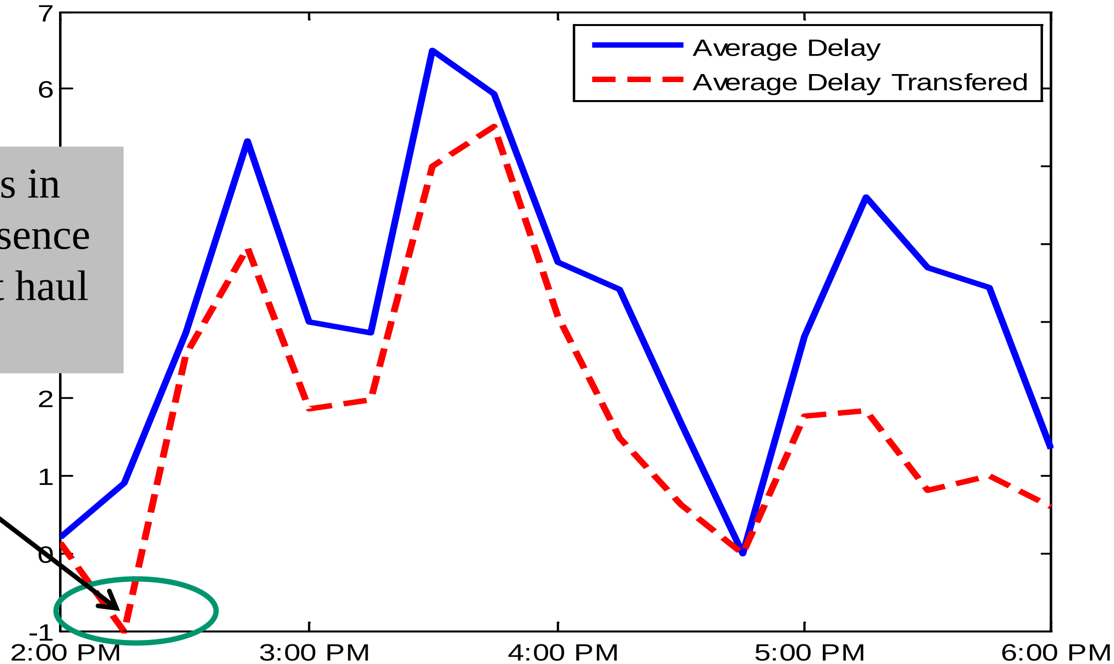
- Model transfers the majority of the terminal delay to en route



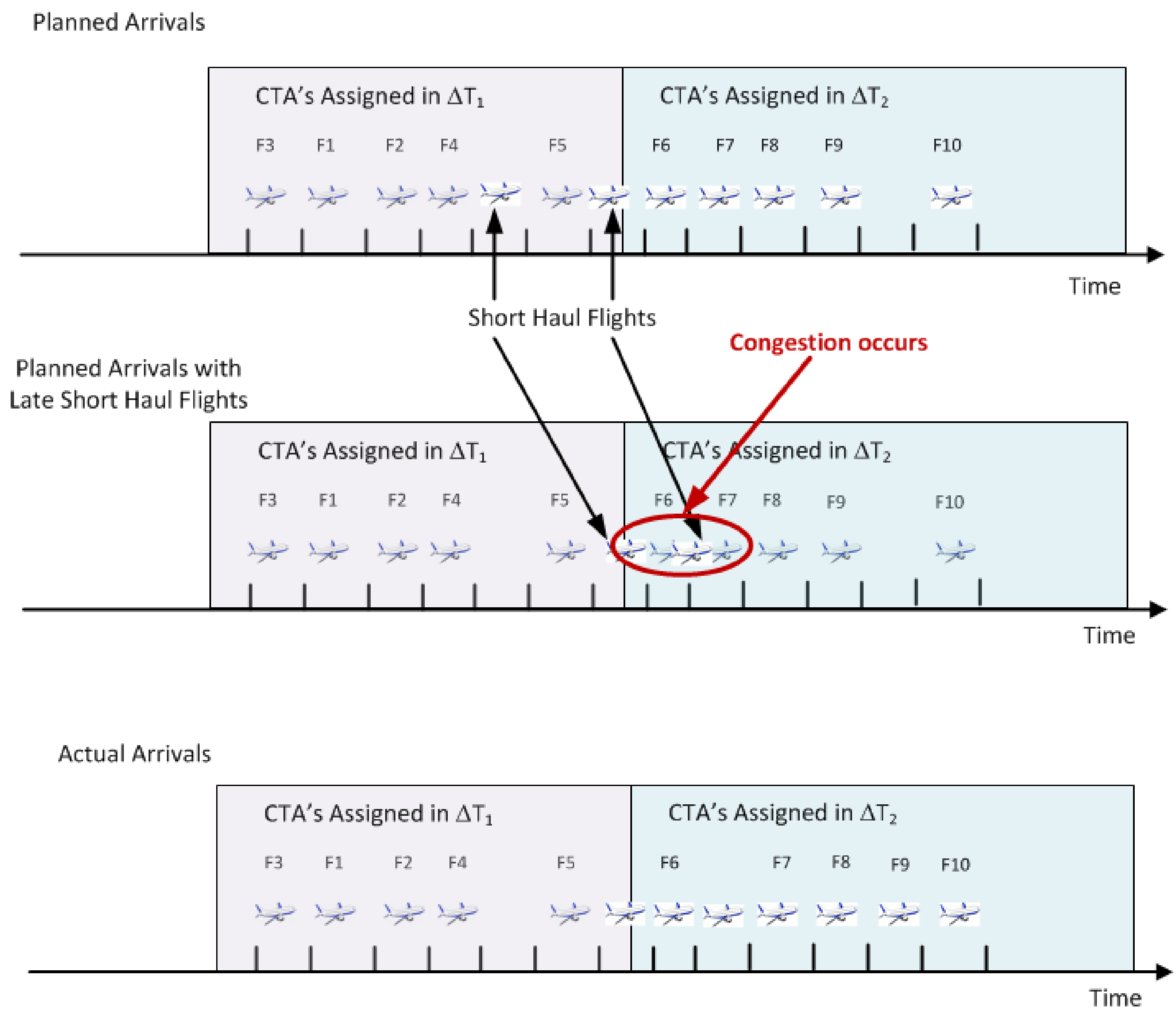
Delay Transfer Performance

- Model transfers the majority of the terminal delay to en route

Negative transfer is in large part due to presence of late arriving short haul flights



Delay Transfer Performance



Compliance

- Implementation of information transfer architecture will likely affect compliance
- Simulation modified to allow some flights to arrive at their original ETA
- Delay transfer can be achieved at modest rates of compliance

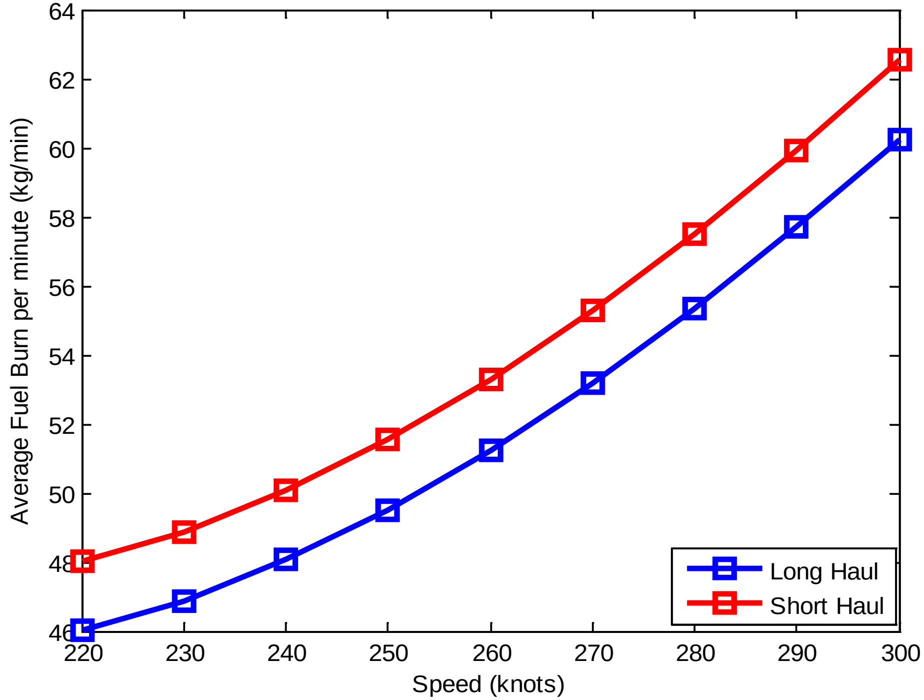
Compliance Level %	Average Delay Transfer (min)	Percentage of Total Delay Transferred
100.00	1.69	58
90.00	1.26	43
80.00	1.31	45
70.00	1.41	48
60.00	1.01	34
50.00	1.02	35
40.00	0.95	33
30.00	-0.40	-14

Quantifying Fuel Burn Benefits for Delay Transfer

- Challenge: Determine the fuel savings realized per minute of delay transferred
- Fuel burn savings will depend on speed of terminal vectoring and altitude
- A sensitivity analysis was conducted to measure the range of benefits that could be realized
- An empirical CDF was generated from TFMS data to gauge the distribution of flight altitudes in terminal airspace
- BADA fuel burn model was used to calculate fuel consumption at each altitude

Sensitivity of Fuel Savings to Terminal Airspeed

- Statistical analysis of TFMS data used to characterize nonlinear relationship for fleet mix into ATL
- Difference in long and short haul savings is attributable to different fleet mix



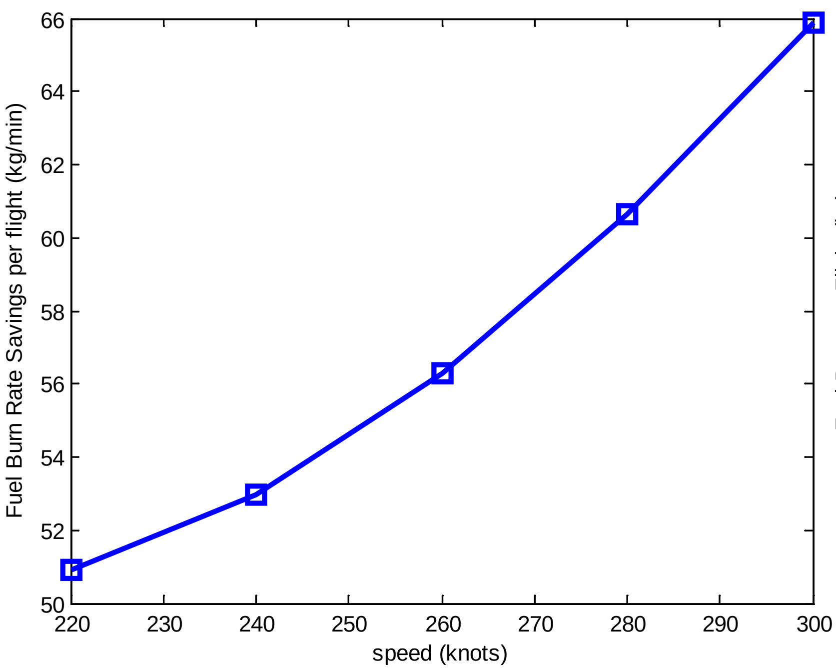
Fuel Burn Savings Calculations

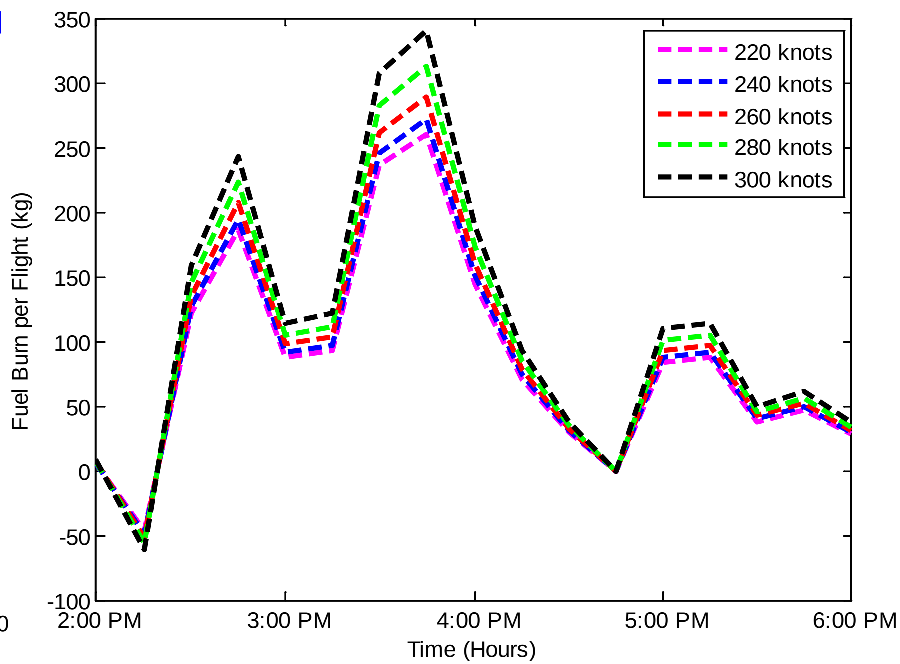
- Slight difference in the manner in which benefit is realized between long and short haul flights
  - Long haul flights benefit by transferring delay between altitudes – delay is largely free
  - Short haul flights benefit from eliminating delay in terminal airspace – delay is completely free and travel time is improved
- Short haul flights account for more of total fuel savings

Speed (knots)	Fuel Burn Savings kg/min (Long Haul)	Fuel Burn Savings kg/min (Short Haul)	Fuel Burn Savings kg/min
220.00	50.63	51.18	50.93
240.00	52.69	53.24	50.70
260.00	55.98	56.55	54.01
280.00	60.31	60.91	58.35
300.00	65.55	66.18	63.61

Average Fuel Burn Savings

- Delay Transfer yields noticeable improvement in fuel burn consumption
- Average savings exceeds 76 kg of fuel regardless of speed





Extensions to Collaborative Decision Making

- Proposed scheme could in principle be extended to support CDM
- FAA could apportion slots to carriers in lieu of a system-wide objective function
- Carriers could allocate and substitute slots to flights based on their internal priorities
- Allocation adjustments could be made to promote equity and enforce compliance based on systematic monitoring

Summary and Future Work

- Analysis suggests that our model has strong potential to reduce terminal delay
- Need to consider introducing ground delays to actively manage the unmanaged flights
- Developing additional ways to allocate equity to airlines
- Dynamic slot sizing could be used to provide adjustments for short haul flights
- Exploring alternatives to the IP slot approach
  - Other Non IP Greedy multi-criteria algorithms can be used to handle the problem
  - Developed a dynamic programing algorithm to establish more precision in spacing between flights
- IP model and other algorithms need to be tested in simulation to develop broader and more definitive conclusions