# Aircraft Arrival Sequencing


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# Outline

- Motivation
- Problem Statement and Approach
  - Strategies (FCFS, WCG, Optimization Strategies)
  - Constraints and assumptions
  - Performance metrics
- Methods
  - FCFS
  - Optimization Strategies
    - Optimization using MPL
    - Sequential optimization using C++ to call MPL
  - WCG
- Results
  - LaGuardia Case Study
- Conclusions and Future Work
- Questions

# Situation

CATSR

**Stakeholders:** **Concerns:**

Air Traffic Control → Vehicle Throughput

Airlines → Vehicle Delay

Airlines → Airline Fairness

Passengers (PAX) → PAX Delay

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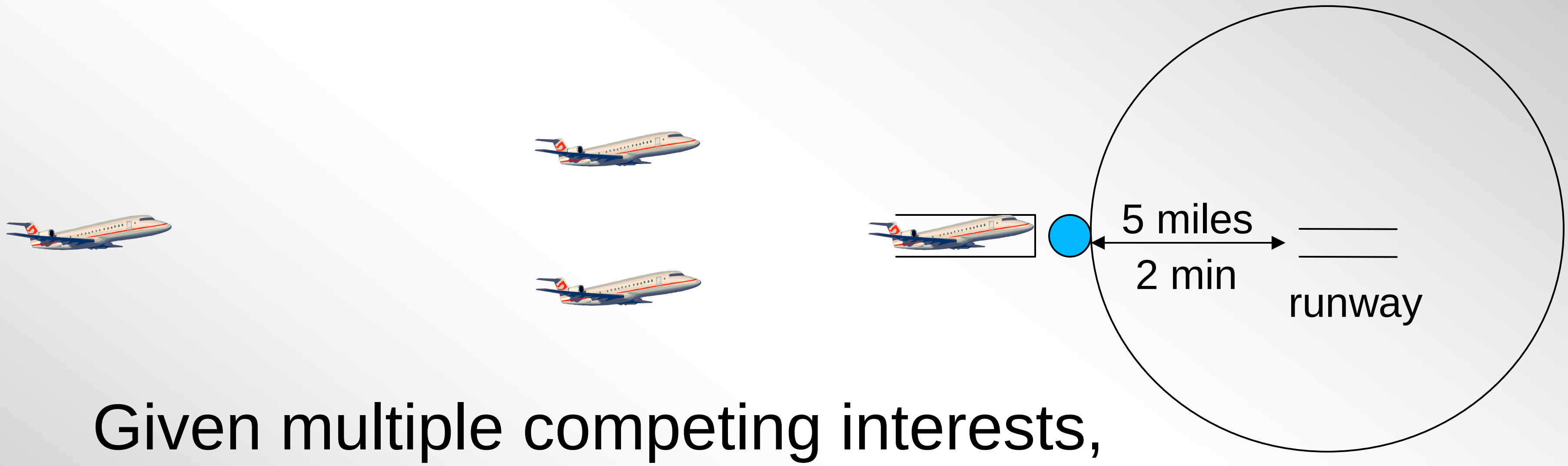
# Motivation

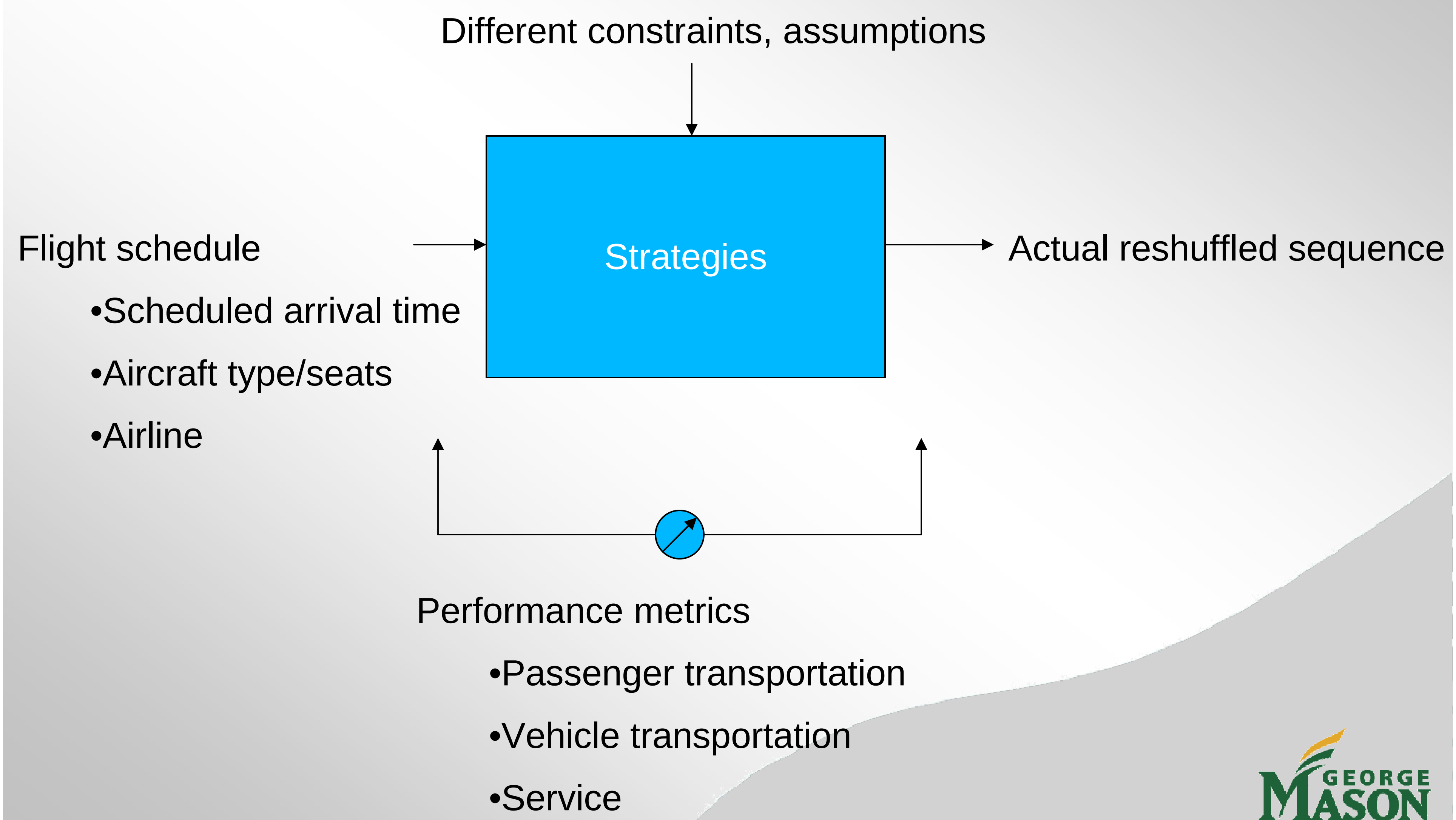
- Air Traffic Control uses first come, first served (FCFS) queueing discipline to sequence arrival aircraft.
- This is not always the best for every stakeholder.
- What strategies might be better?

# Problem Statement




Given multiple competing interests, how can arrivals be sequenced fairly and efficiently?

# Approach Overview



# Strategies for Resequencing

Heuristic Resequencing

1. First come, first served {FCFS}
2. Weight Class Grouping {WCG}

Optimization Strategies for Resequencing

1. Vehicle throughput maximization {V_thrpt}
2. Vehicle delay minimization {V_delay}
3. Passenger delay minimization {P_delay}
4. Airline fairness maximization {A_fair}

# Constraints And Assumptions

- Treating data as deterministic
- All aircraft show up on time before final approach
- No early arrivals allowed
- Aircraft cannot be delayed more than 30 minutes
- All flights seats are full
- Arrival slot size differs by aircraft type because of wake-vortex categories

# Wake-Vortex Categories

Larger aircraft generate stronger turbulence than smaller aircraft.

Larger aircraft can also withstand more turbulence than smaller ones.

Hence, a smaller plane following a larger plane will always require more separation than a larger plane following a smaller plane.

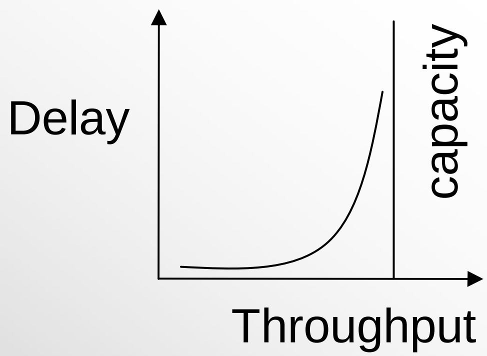
| **Time Separation (sec)** | | Trailing aircraft | | | |
|---|---|---|---|---|---|
| | | Heavy | B757 | Large | Small |
| Leading aircraft | Heavy | 96 | 137 | 157 | 280 |
| | B757 | 96 | 103 | 121 | 271 |
| | Large | 72 | 77 | 83 | 182 |
| | Small | 72 | 77 | 83 | 120 |

Separation standard

*If all planes are Large, then 43 arrivals per hour (in theory)*

# System Metrics

- Throughput = Entities / Unit Time
- Capacity = Upper limit of throughput
- Utilization = Throughput / Capacity




Tradeoff between delay and utilization

# System Metrics

**Flight delay:**

$\text{delay}_i = \text{arrival\_time}_i - \text{sched\_time}_i$

**Ave Veh Delay =** $\dfrac{\sum_i delay_i}{N}$

**Ave PAX Delay** = $\dfrac{\left\{\sum_i PAX_i * delay_i\right\}}{\sum_i PAX_i}$

**Ave PAX Delay per airline** (k) = $\dfrac{\sum_{i \in S_k} PAX_i * delay_i}{\sum_{i \in S_k} PAX_i}$

(for flights in contention with others)

i *is the flight index*

i = 0 to N

N *is the number of flights to be sequenced*

$PAX_i$ = *Total number of Passengers on flight i*

$\mathbf{S}_k$ *is the set of flights of airline k in contention*

# Optimization Strategies: Objective Functions

- *Vehicle throughput* MIN $time_{lastplane}$
  V_thrpt
- *Vehicle delay* MIN $\sum_i delay_i$
  V_delay
- *PAX delay* MIN $\sum_i PAX_i * delay_i$
  P_delay
- *Airline fairness* MIN $\left\{ \underset{k}{Max} \left\{ \frac{\sum_{i \in S_k} PAX_i * delay_i}{\sum_{i \in S_k} PAX_i} \right\} \right\}$
  A_fair
  (spread the penalty)

# MIP (Mixed Integer Program)

Decision variables in Blue: $t_i$ is assigned landing time

$$y_{ij} = \begin{cases} 1 & \text{flight j follows flight i} \\ 0 & \text{otherwise} \end{cases}$$

Data: $M$ is a large constant

$t_{separation}(i,j)$ is known based on plane sizes

MIN Z = *OBJECTIVE FUNCTION*

SUBJECT TO:

$$t_i - t_j \geq t_{separation}(j,i) - M\, y_{ij} \qquad \text{for } j>i$$

$$t_j - t_i \geq t_{separation}(i,j) - M\,(1-y_{ij}) \qquad \text{for } j>i$$

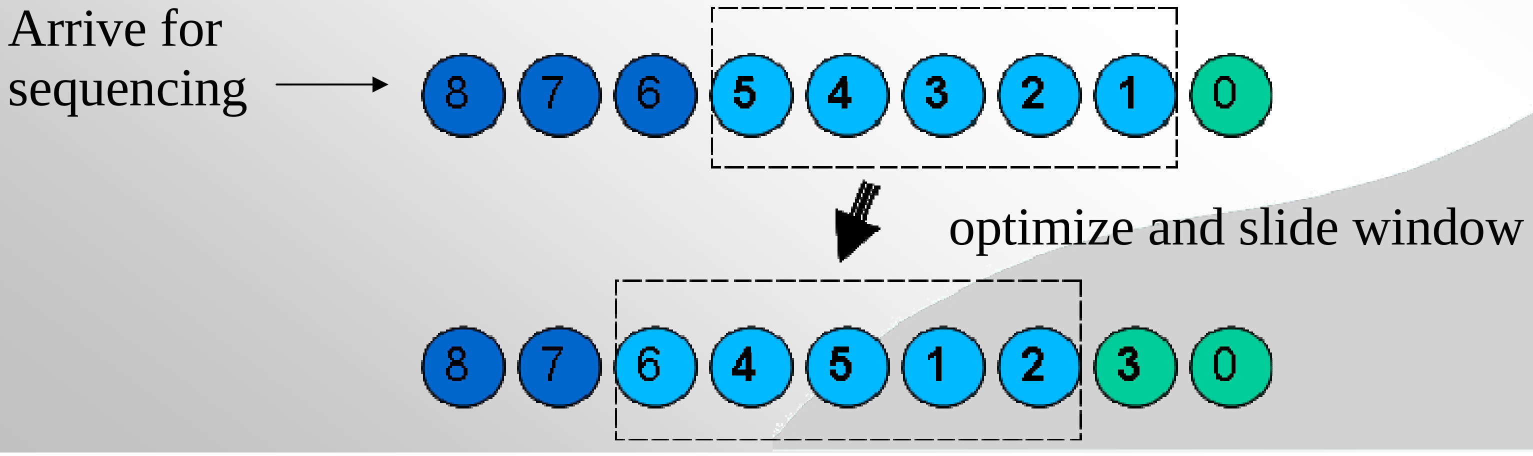
Every pair of planes (independent of relative order) is separated by at least the minimum safety requirement

# Approaches: Optimization Using C++

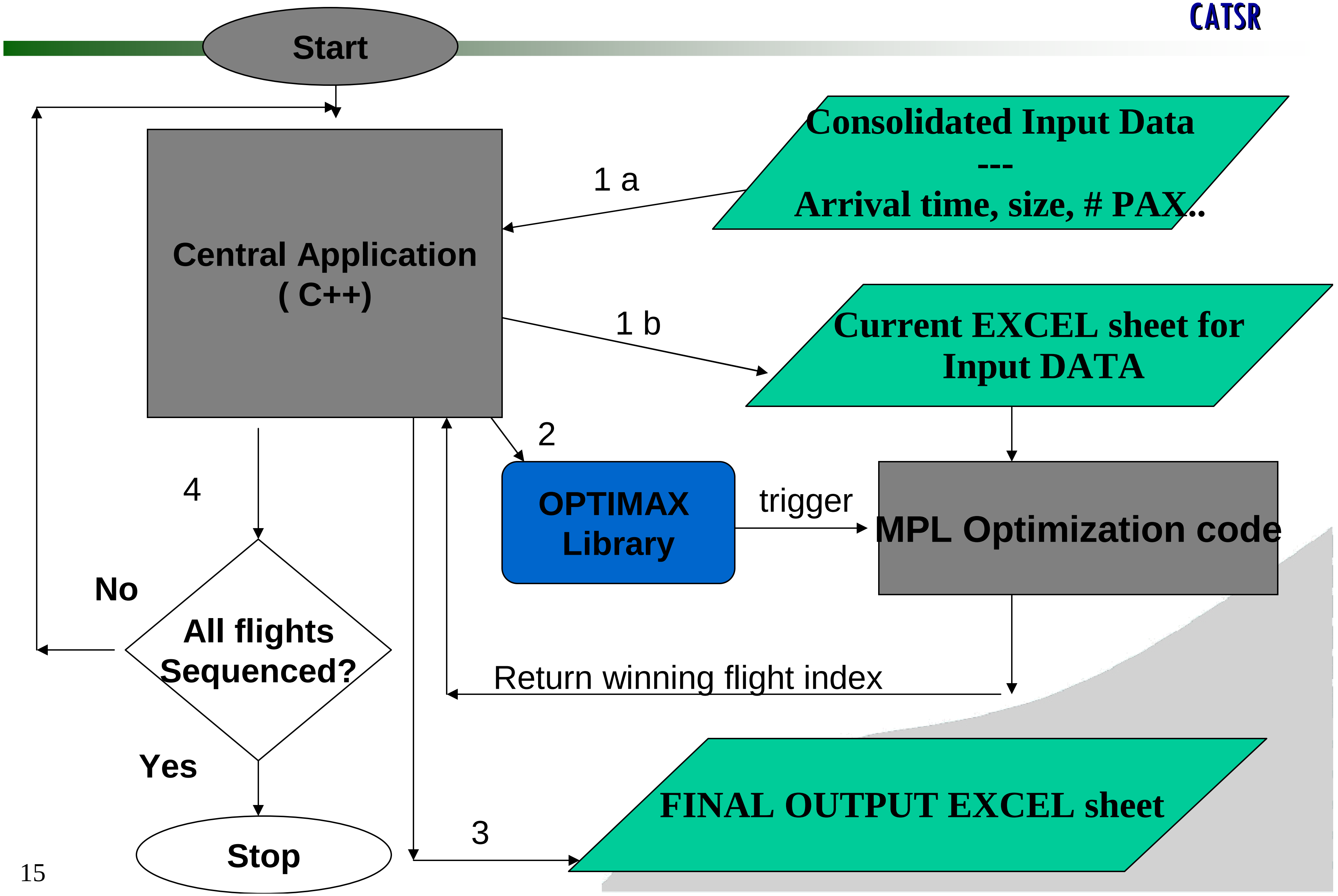
Problem : Computation time for MIP increases rapidly with number of flights considered

Workaround

- Exploit problem structure
- Optimize small windows. Things to consider:
  - Window size
  - Windows should overlap

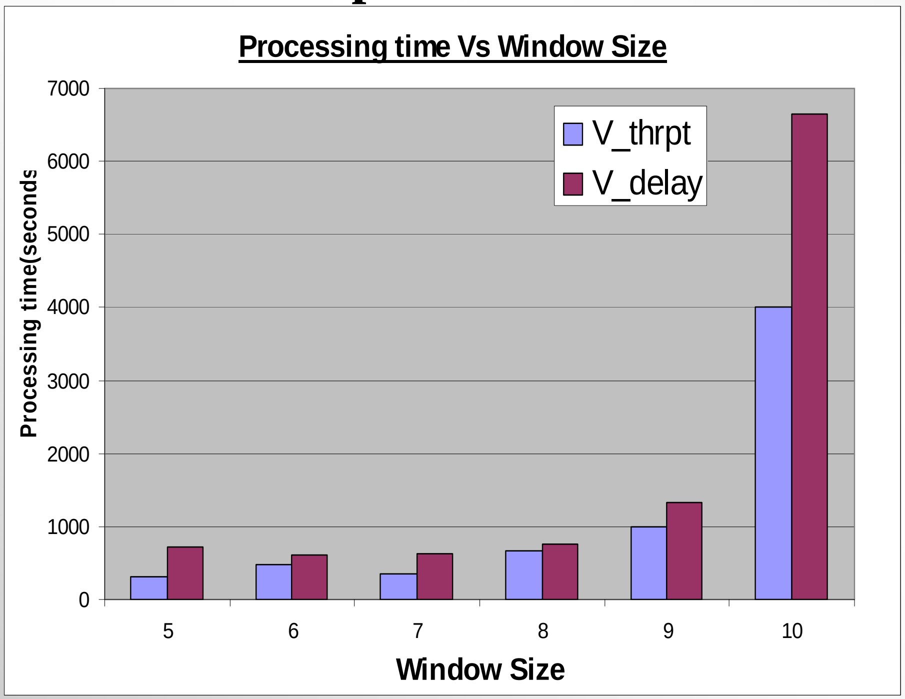


# Sequential Optimization - Flow chart

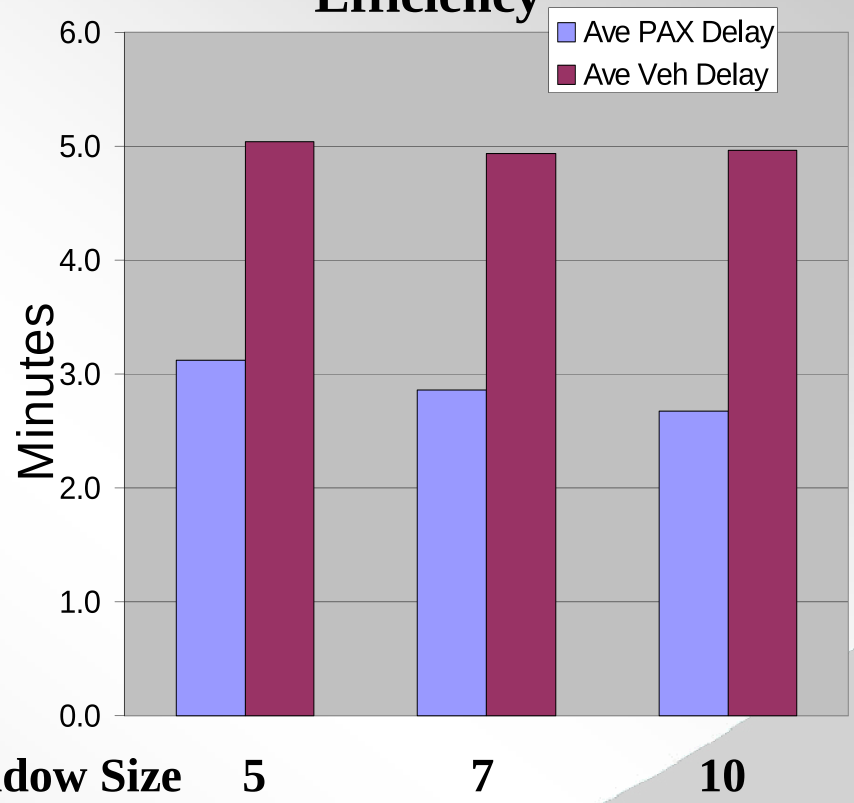


# Window Size: Speed vs Efficiency Trade-Off

**Speed**




**Efficiency**

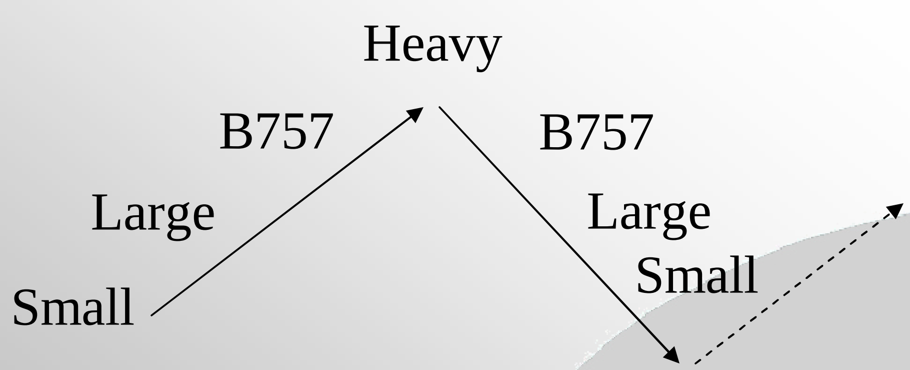



Conclusion: Without compromising too much on Efficiency we make considerable gain in Processing Speed.

**Hence, windowing works!!**

# Same Weight Class Grouping

- Objective is to provide a strategy that gives
  - better performance than FCFS
  - faster implementation than optimization strategies
- Heuristics to sequence aircraft landing
  1. Similar to knapsack heuristics
  2. If there is a gap between adjacent flights, use FCFS
  3. If there is not a gap between adjacent flights
     - choose same weight class aircraft if available
     - choose next weight class aircraft if same weight class unavailable



# Same Weight Class Grouping

- Reasoning behind the heuristic
  - Arbitrary sequence of different weight class aircraft requires long separation overall
  - Grouping same weight class requires shorter time to land all aircraft

# RESULTS

Case Study:

New York's LaGuardia Airport

June 1st, 2006

# Example Resequencings

CATSR

For the given sequence: S←L←B←S

(assuming they have same scheduled arrival time)

| Strategy | Resultant Sequence: |
|---|---|
| FCFS: | S←L←B←S |
| V_thrpt: | S←S←L←B |
| V_delay: | S←S←L←B |
| P_delay: | B←L←S←S |
| WCG: | S←S←L←B |

S: Small

L: Large

B: B757

# LGA Case Study: Input Data

| FAACARRIER | FLTNO | ETMS_EQPT | DEP_LOCID | ARR_LOCID | SCHINTM |
|---|---|---|---|---|---|
| TCF | 6453 | E170 | DFW | LGA | 00:04 |
| CHQ | 3028 | E145 | PHL | LGA | 00:16 |
| FFT | 514 | A319 | DEN | LGA | 06:15 |
| DAL | 1905 | MD88 | BOS | LGA | 06:59 |
| COM | 618 | CRJ1 | DCA | LGA | 06:59 |
| USA | 2158 | A319 | DCA | LGA | 06:59 |
| PDT | 4110 | DH8B | MHT | LGA | 07:00 |
| USA | 2115 | A319 | BOS | LGA | 07:07 |
| CHQ | 3108 | E145 | BWI | LGA | 07:12 |
| AWI | 3716 | CRJ2 | PHL | LGA | 07:12 |
| EGF | 867 | E135 | BGR | LGA | 07:15 |
| CJC | 4880 | SF34 | ITH | LGA | 07:15 |
| CHQ | 3276 | E145 | RIC | LGA | 07:17 |
| EGF | 863 | E135 | CMH | LGA | 07:18 |
| … | … | … | … | … | … |

ASPM data, June, 1, 2006

| Time Separation (sec) | | Trailing aircraft | | | |
|---|---|---|---|---|---|
| | | Heavy | B757 | Large | Small |
| Leading aircraft | Heavy | 96 | 137 | 157 | 280 |
| | B757 | 96 | 103 | 121 | 271 |
| | Large | 72 | 77 | 83 | 182 |
| | Small | 72 | 77 | 83 | 120 |

Separation standard

| Aircraft type | Weight catogory |
|---|---|
| A319 | L |
| A320 | L |
| A321 | L |
| B190 | S |
| B712 | L |
| B732 | L |
| B733 | L |
| B734 | L |
| B735 | L |
| B737 | L |
| B738 | L |
| B752 | B757 |
| B763 | L |
| … | … |

Aircraft weight category

| ETMS_NAME | TYPICAL_SEATS | EDMS_AIRFRAME |
|---|---|---|
| A124 | 8 | B747-200 |
| A300 | 250 | A300-600 |
| A30062 | 266 | A300-B4-622R |
| A306 | 266 | A300-B4-605R |
| A30B | 250 | A300B |
| A310 | 220 | A310 |
| A318 | 107 | A318 |
| A319 | 124 | A319 |
| A32 | 164 | A320 |
| A320 | 164 | A320 |
| A32023 | 150 | A320-200 |
| A321 | 199 | A321 |
| A32123 | 199 | A321 |
| A330 | 295 | A330 |
| A33034 | 295 | A330-300 |
| … | … | … |

Number of seats

# Input: Flight Schedule

| FAACARRIER | FLTNO | ETMS_EQPT | DEP_LOCID | ARR_LOCID | SCHINTM |
|---|---|---|---|---|---|
| TCF | 6453 | E170 | DFW | LGA | 00:04 |
| CHQ | 3028 | E145 | PHL | LGA | 00:16 |
| FFT | 514 | A319 | DEN | LGA | 06:15 |
| DAL | 1905 | MD88 | BOS | LGA | 06:59 |
| COM | 618 | CRJ1 | DCA | LGA | 06:59 |
| USA | 2158 | A319 | DCA | LGA | 06:59 |
| PDT | 4110 | DH8B | MHT | LGA | 07:00 |
| USA | 2115 | A319 | BOS | LGA | 07:07 |
| CHQ | 3108 | E145 | BWI | LGA | 07:12 |
| AWI | 3716 | CRJ2 | PHL | LGA | 07:12 |
| EGF | 867 | E135 | BGR | LGA | 07:15 |
| CJC | 4880 | SF34 | ITH | LGA | 07:15 |
| CHQ | 3276 | E145 | RIC | LGA | 07:17 |
| EGF | 863 | E135 | CMH | LGA | 07:18 |
| … | … | … | … | … | … |

ASPM data, June, 1, 2006

# Input: Aircraft Separation Standard

CATSR

| **Time Separation (sec)** | | Trailing aircraft | | | |
|---|---|---|---|---|---|
| | | Heavy | B757 | Large | Small |
| Leading aircraft | Heavy | 96 | 137 | 157 | 280 |
| | B757 | 96 | 103 | 121 | 271 |
| | Large | 72 | 77 | 83 | 182 |
| | Small | 72 | 77 | 83 | 120 |

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# Input: Aircraft Weight Category

| Aircraft type | Weight category |
|---|---|
| B738 | Large |
| B752 | B757 |
| B763 | Large |
| C560 | Small |
| C750 | Large |
| CL60 | Small |
| CRJ1 | Large |
| … | … |

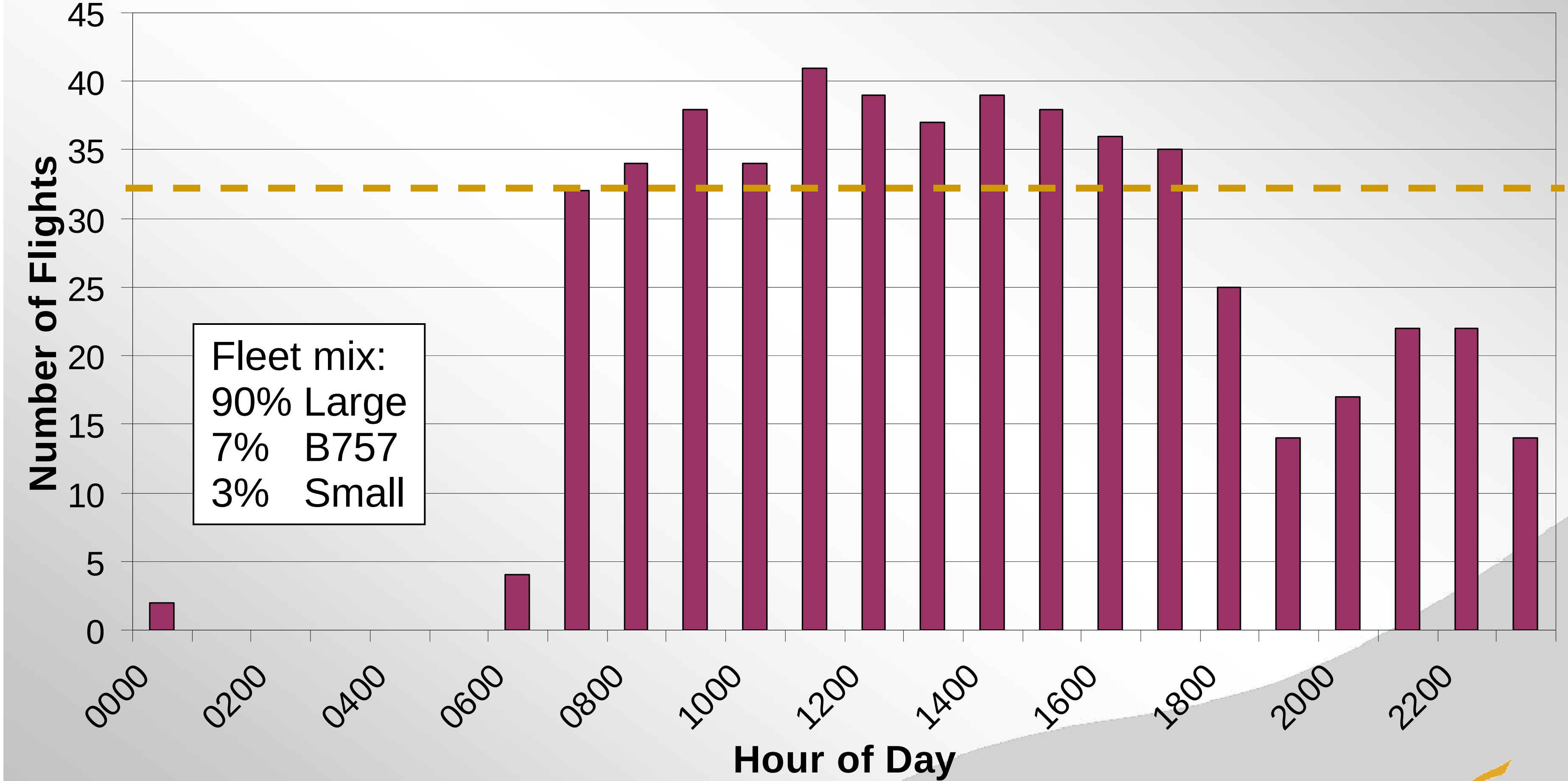
Aircraft weight category

# Input: Aircraft Seat Information

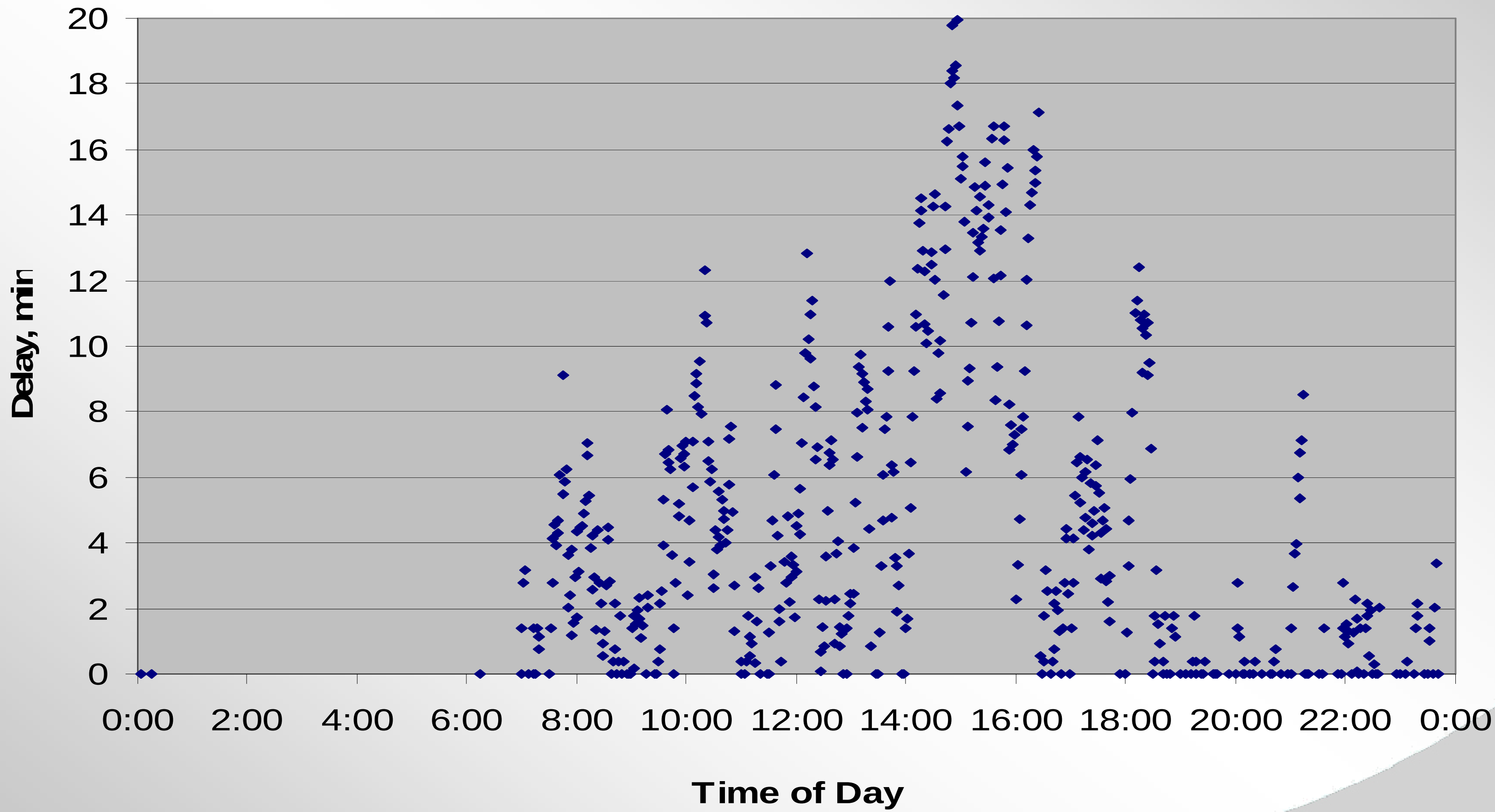
| ETMS_NAME | TYPICAL_SEATS | EDMS_AIRFRAME |
|---|---|---|
| A124 | 8 | B747-200 |
| A300 | 250 | A300-600 |
| A30062 | 266 | A300-B4-622R |
| A306 | 266 | A300-B4-605R |
| A30B | 250 | A300B |

Number of seats

# Pre-Scheduled LGA Arrival Rate



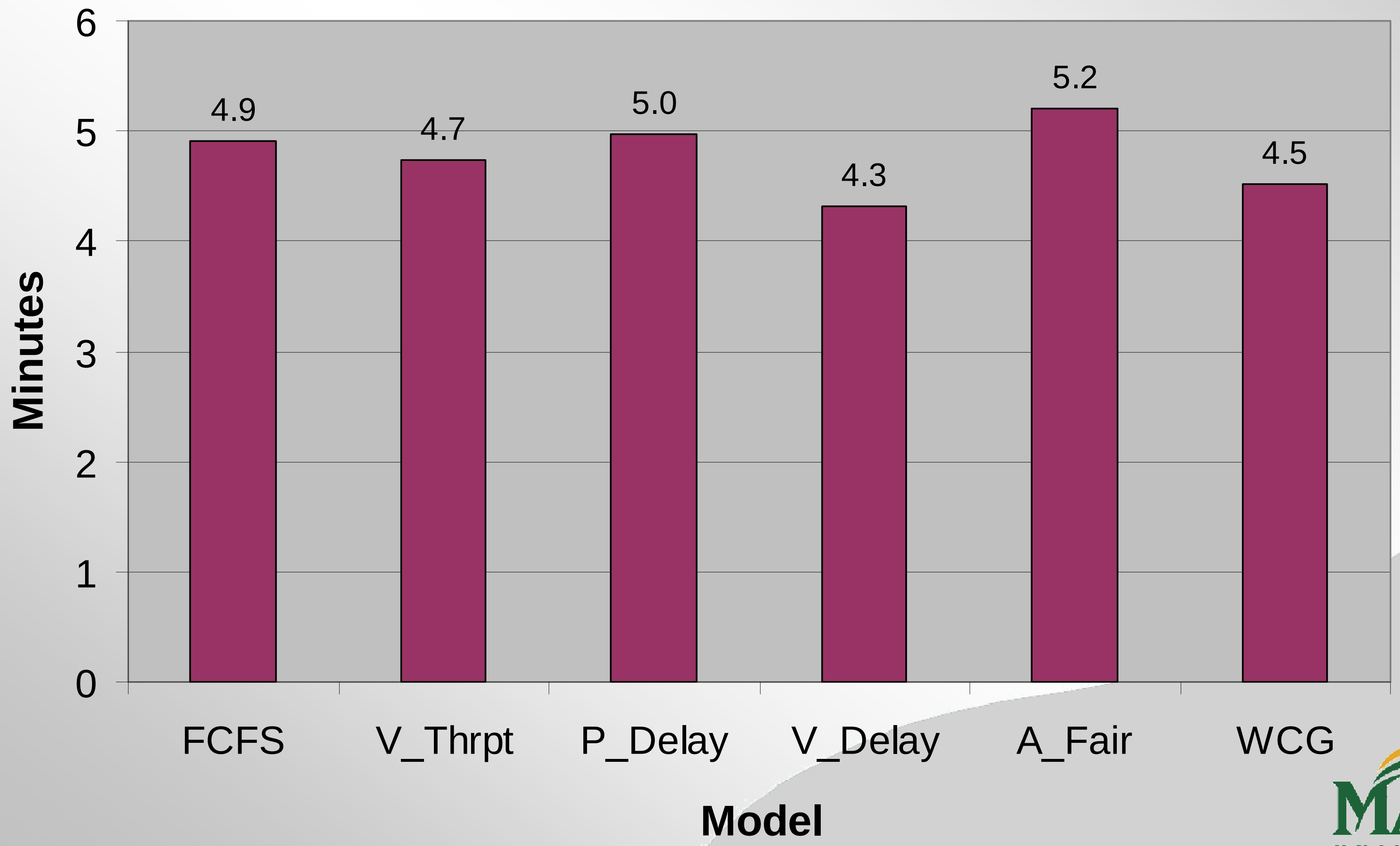
# Benchmark: LGA Results (FCFS)



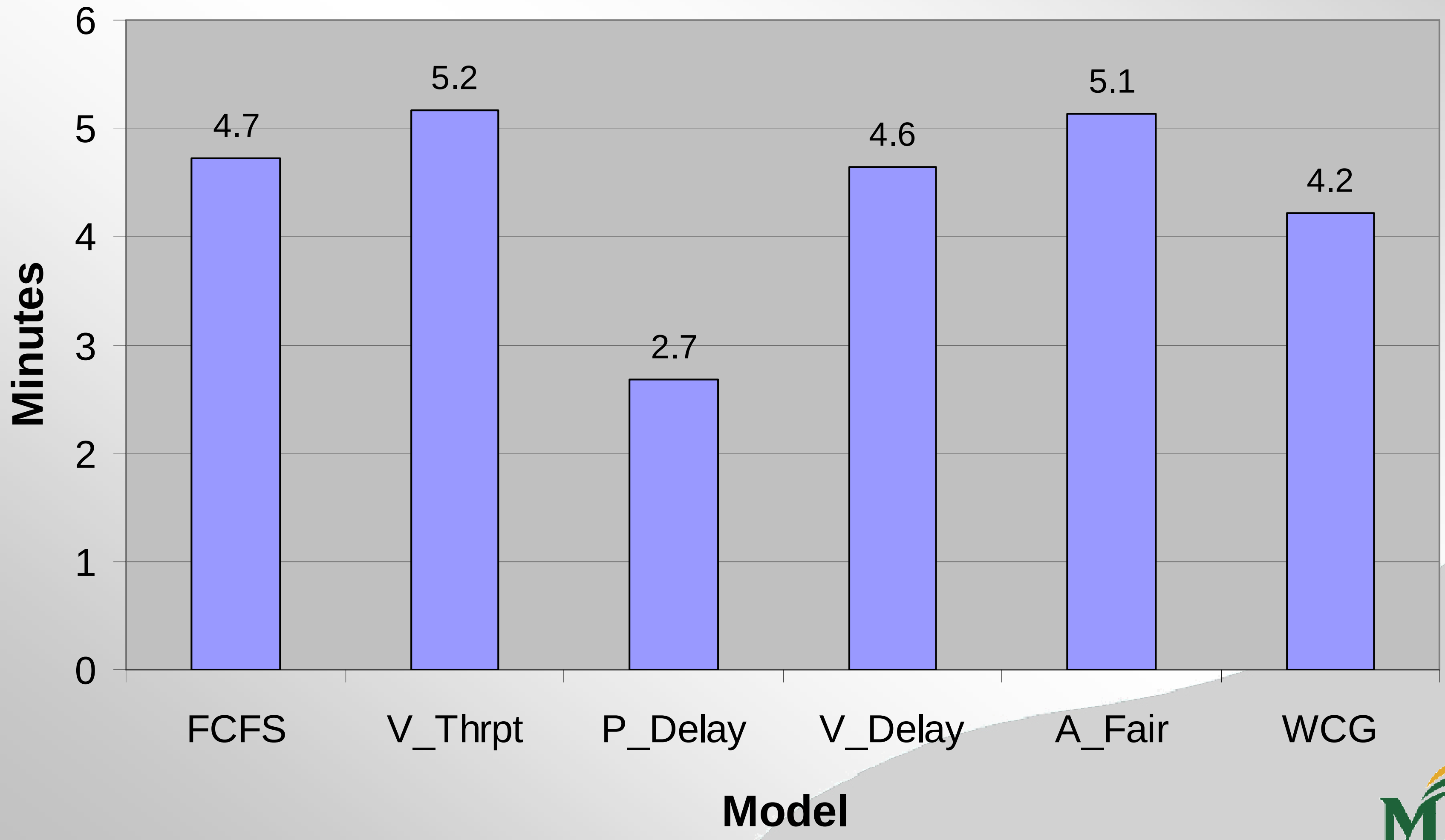

**Ave flight delay: 4.9 min**
**Ave pax delay: 4.7 min**

**85% of flights delayed and 39% have delay >5 min**

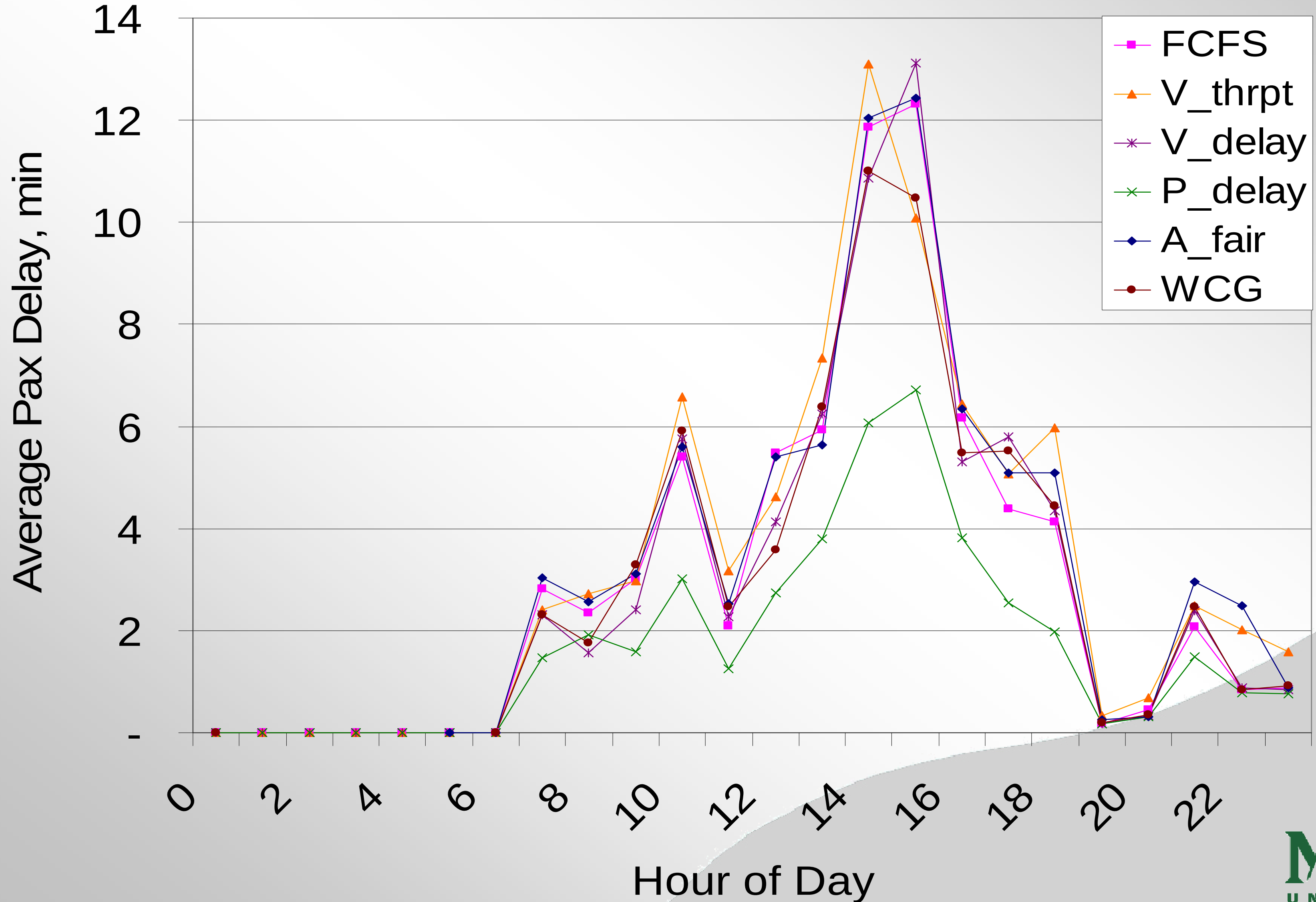
# LGA Results: Vehicle (Flight) Delay



# LGA Results: PAX Delay

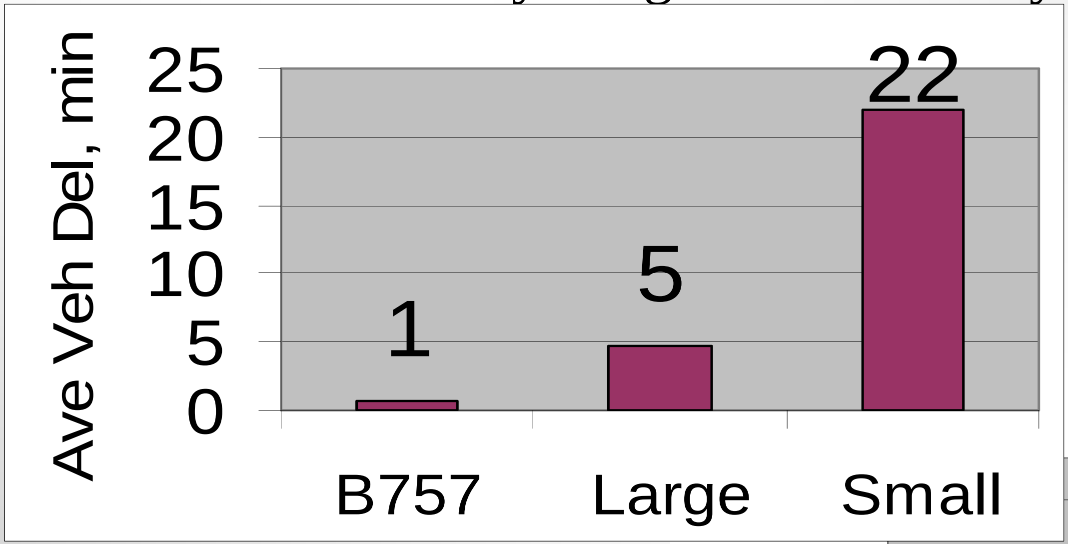


# LGA Hourly PAX Delay

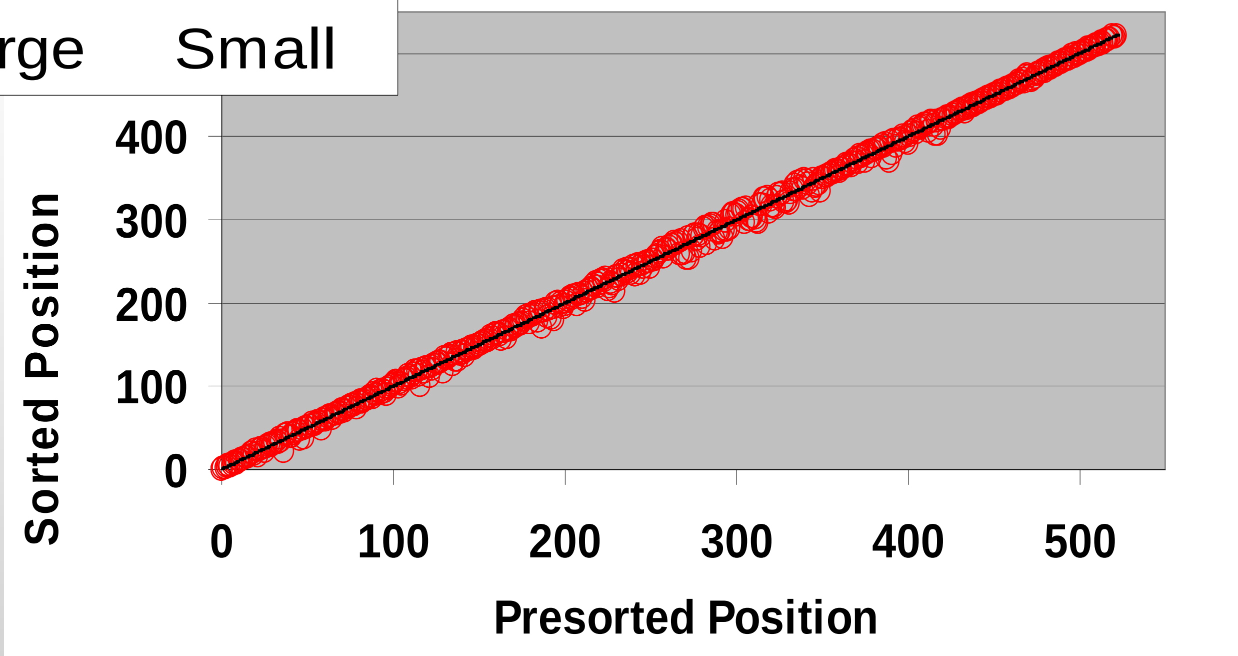


# Pax Delay: P_delay Results

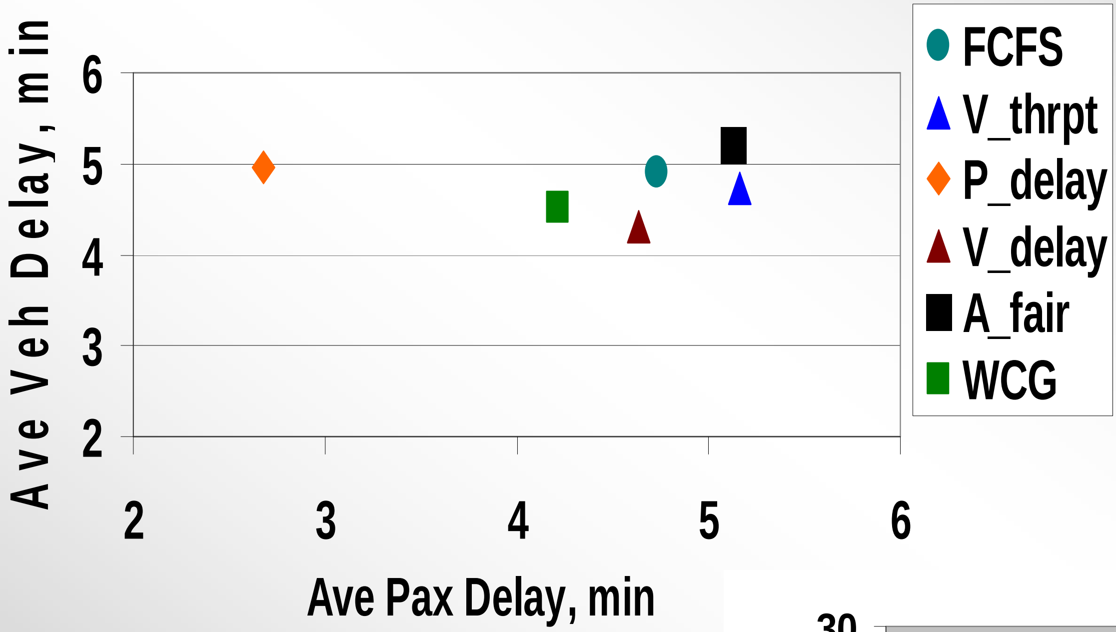
Where does P_delay assign the most delay?



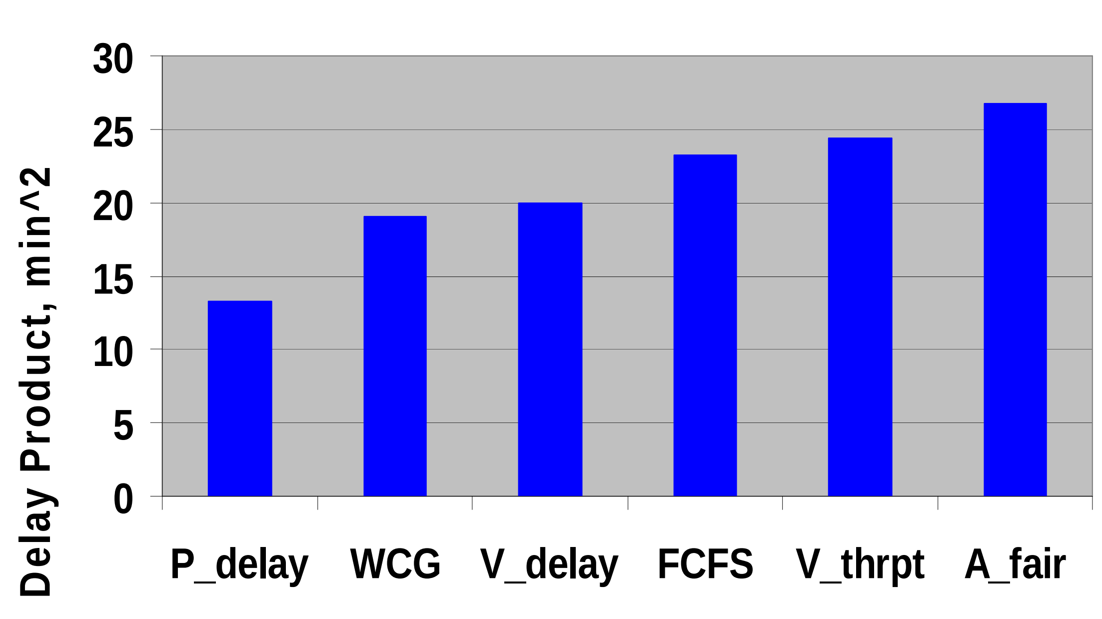

Amount of Re-Sequencing



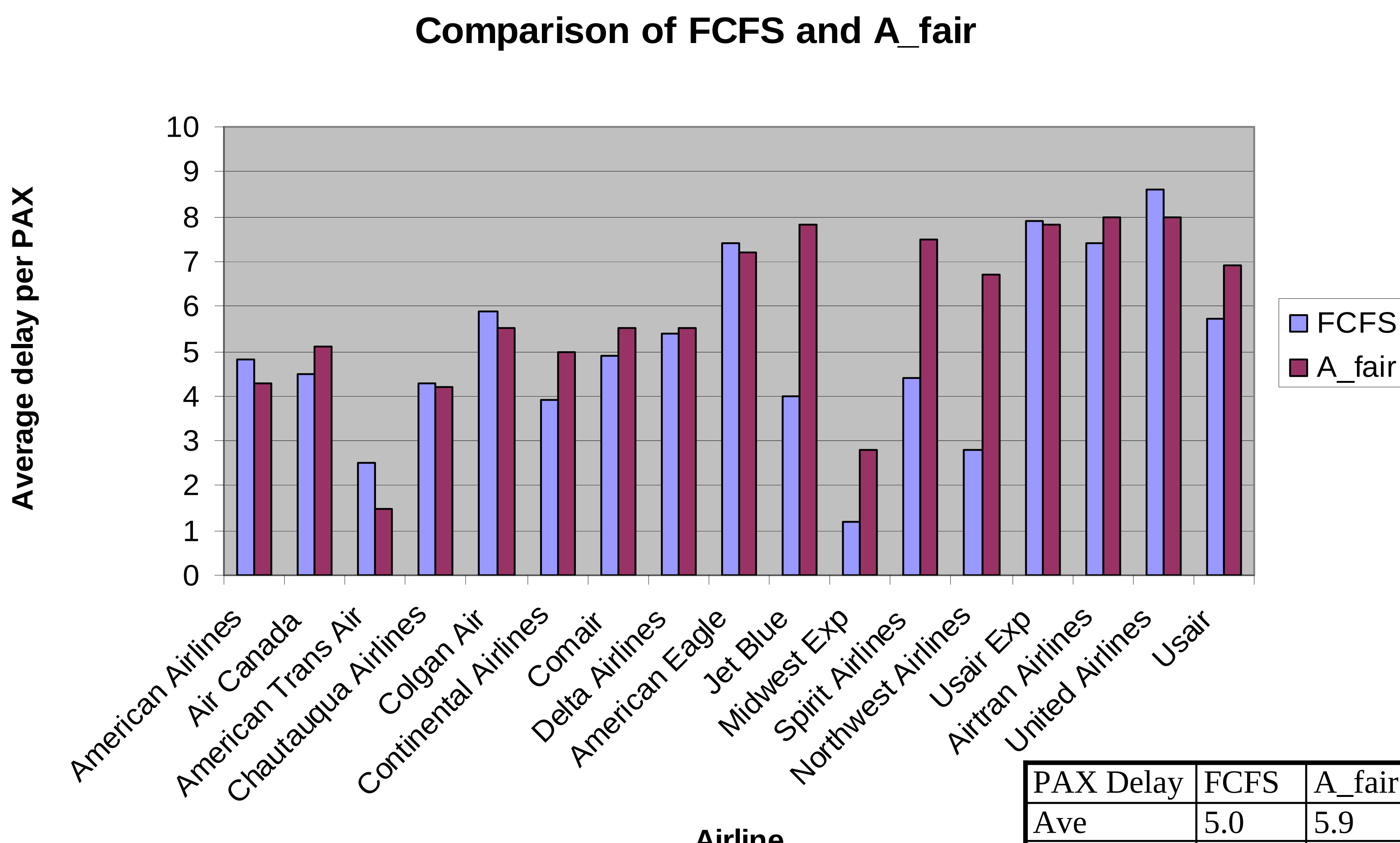
# PAX Delay And Vehicle Delay




Ave Veh Del * Ave PAX Delay



# LGA: Airline Fairness




| PAX Delay | FCFS | A_fair |
|---|---|---|
| Ave | 5.0 | 5.9 |
| Range | 7.4 | 6.5 |

# Conclusions

- Little to no gains seen over FCFS for V_trpt, V_delay, A_fair, and WCG
  - Input data is very homogenous
  - LGA is operating at or near capacity for most of the day
- Airline fairness maximization gives worst performance in terms of vehicle delay and passenger delay
  - Constraints are imposed without considering delay metrics
- PAX_delay model shows gains at the cost of smaller flights
  - Delaying small aircraft (3% of the fleet mix) reduces average passenger delay significantly.

# Improvements and Future Work

- Optimize multiple weighted objectives at once
- Allow flights to arrive early by a small amount
- Weight A_Fair by number of flights scheduled
- Look for a more heterogeneous data set
- Only process slots where there are collisions
- Increase number of flights that get fixed at each iteration

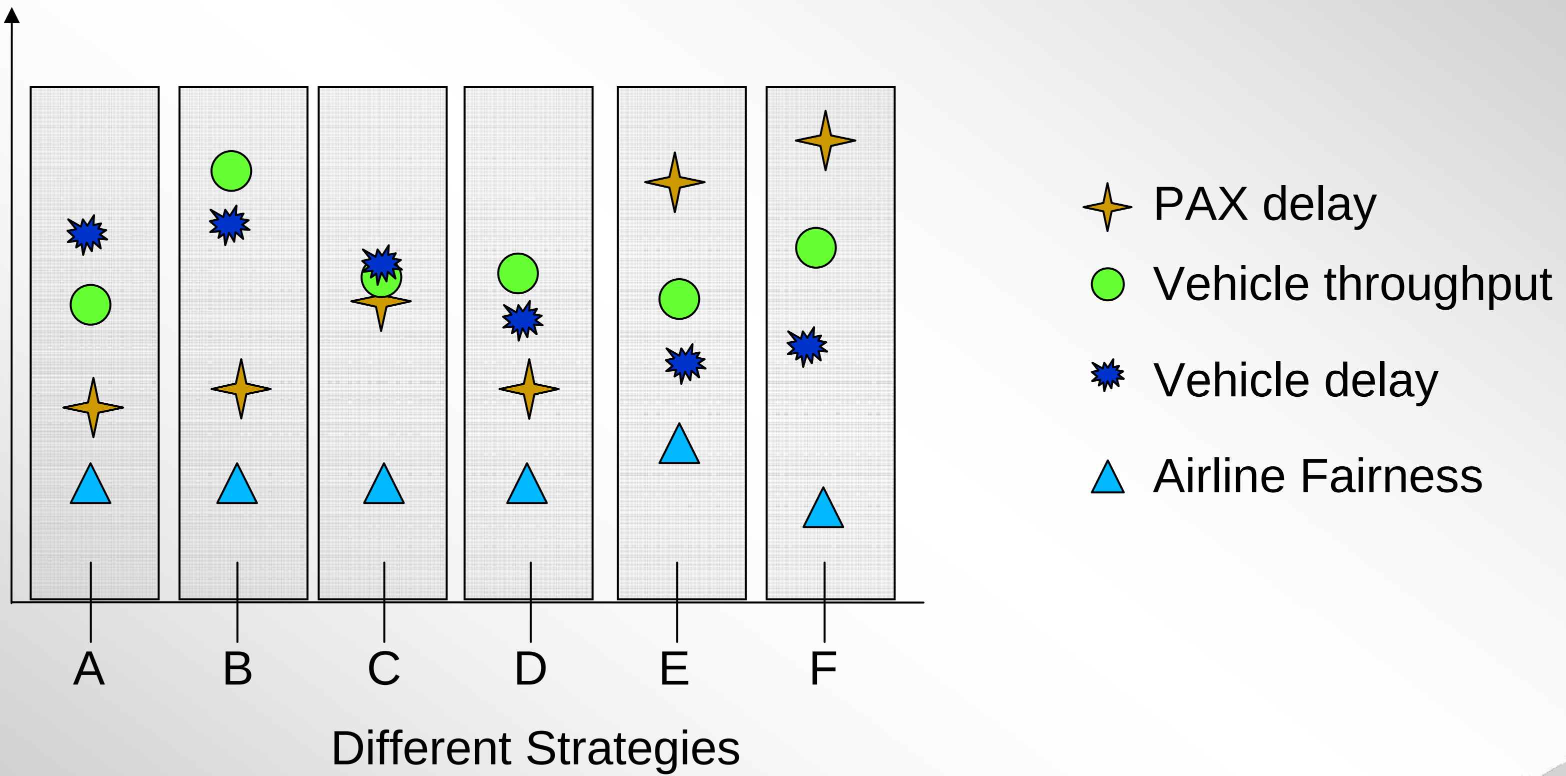
# Acknowledgements

Thanks to our sponsors, Dr. Shortle and Dr. Sherry from GMU's Center for Air Transportation Systems Research for their continued guidance and encouragement through the semester and to Dr. Laskey for helping us improve our presentation and keeping us on track.

# Questions

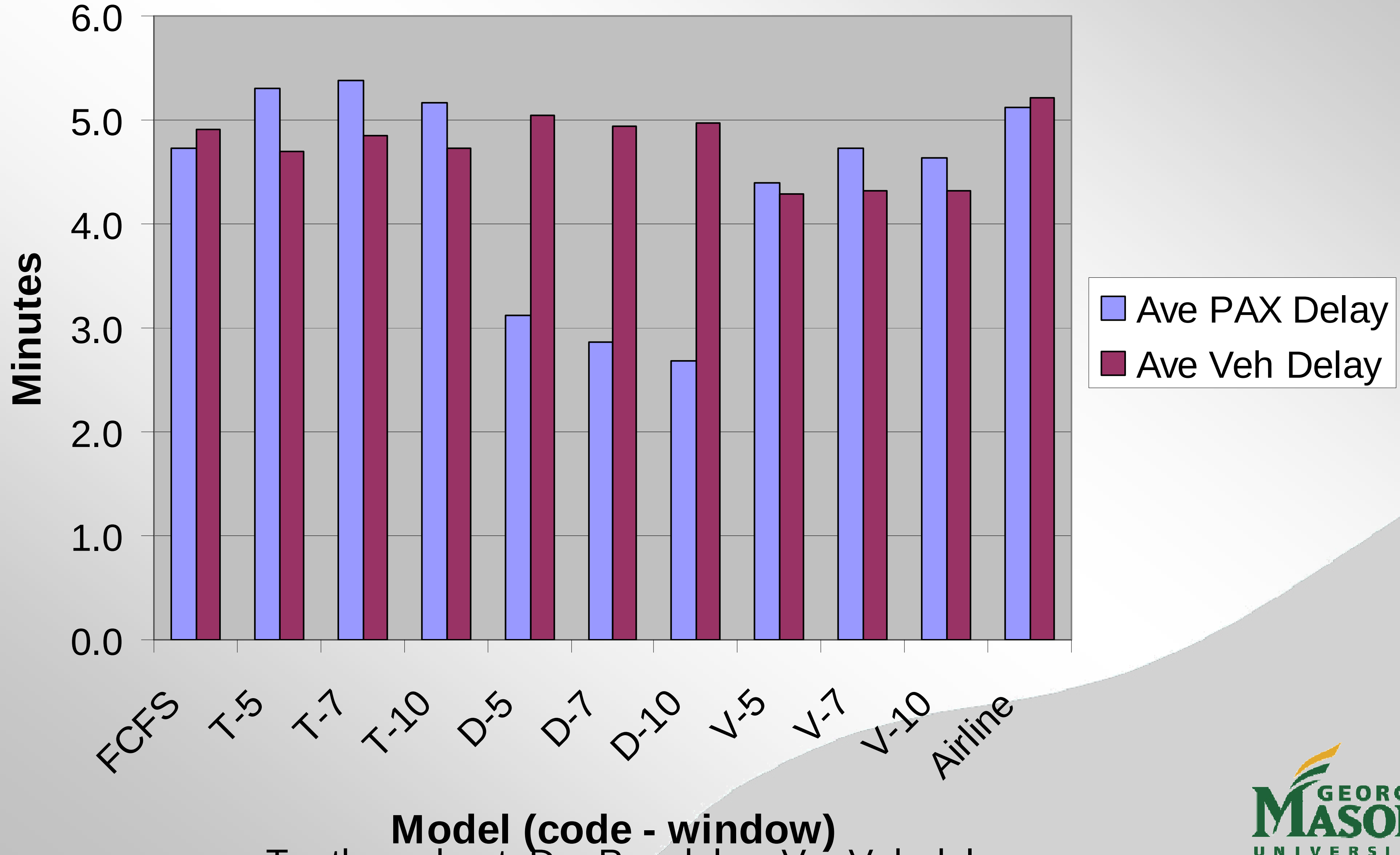
# Back up

# Multi Objective Optimization




A strategy represents a different approach to solving the problem such as FCFS.

# LGA Schedule, Delay




T = throughput, D = Pax delay, V = Veh delay

# LGA Case Study: Complexity

FT = FCFS with throughput opt
FD = FCFS with delay opt
FTD = FCFS with delay and throughput opt
T = throughput opt
D = delay opt
TD = delay and throughput opt

Run statistics: [for non-FCFS: number of integer variables ~ $O(N^2)$ ]

| MODEL | FLIGHTS | SOLN TIME, SEC |
|---|---|---|
| FT | 50 | 30 |
| FD | 40 | 30 |
| FTD | 40 | 30 |
| T | 20 | 10 |
| D | 15 | 1 |
| TD | 15 | 1 |

# Research

Analysis of Sequencing and Scheduling Methods for Arrival Traffic, 1990

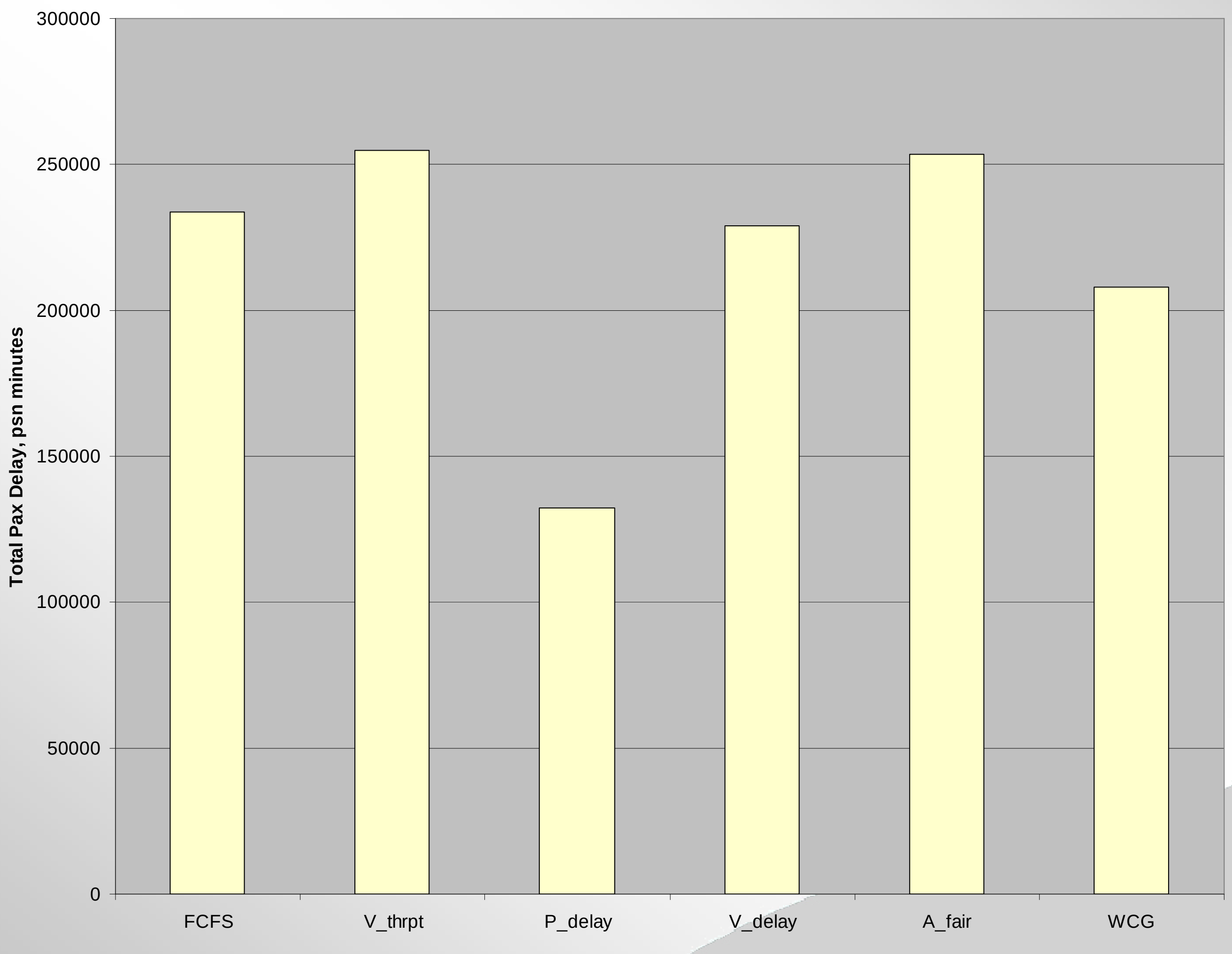
Polynomial Time Feasibility Condition for Multi-Class Aircraft Sequencing on a Single Runway Airport, 2004

Air Transportation: A Tale of Prisoners, Sheep and Autocrats, 2007

Equitable Allocation of Limited Resources, 2003

Potential Benefits of a Time-based Separation Procedure to maintain the Arrival Capacity of an Airport in strong head-wind conditions

# LGA results: passenger delay in a year



# Inter-arrival landing time constraint

Constraint based on specified number of nautical miles

| Separation in nm | | Second to Land: Large | Second to Land: Heavy |
|---|---|---|---|
| First to land | Large | 3 | 3 |
| | Heavy | 5 | 4 |

We consider it based on time (varies with wind speed and direction

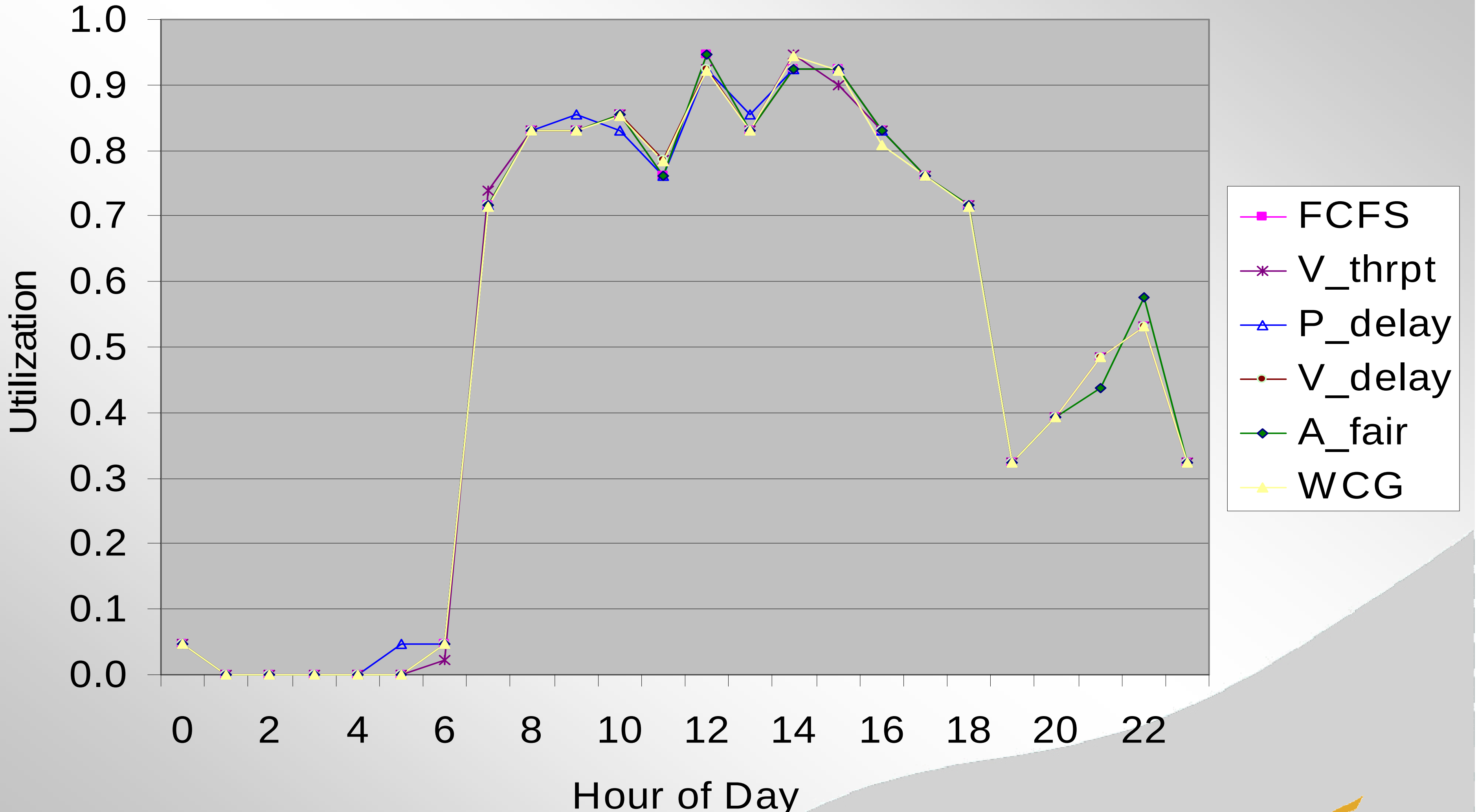
| Separation in sec | | Second to Land: Large | Second to Land: Heavy |
|---|---|---|---|
| First to land | Large | 78 | 78 |
| | Heavy | 125 | 104 |
| No wind | | | |

| Separation in sec | | Second to Land: Large | Second to Land: Heavy |
|---|---|---|---|
| First to land | Large | 91 | 91 |
| | Heavy | 145 | 122 |
| 20 Knot head wind | | | |

HLHL inter-arrival delay is ~5½ min

Single shift to HHLL delay becomes ~5 min

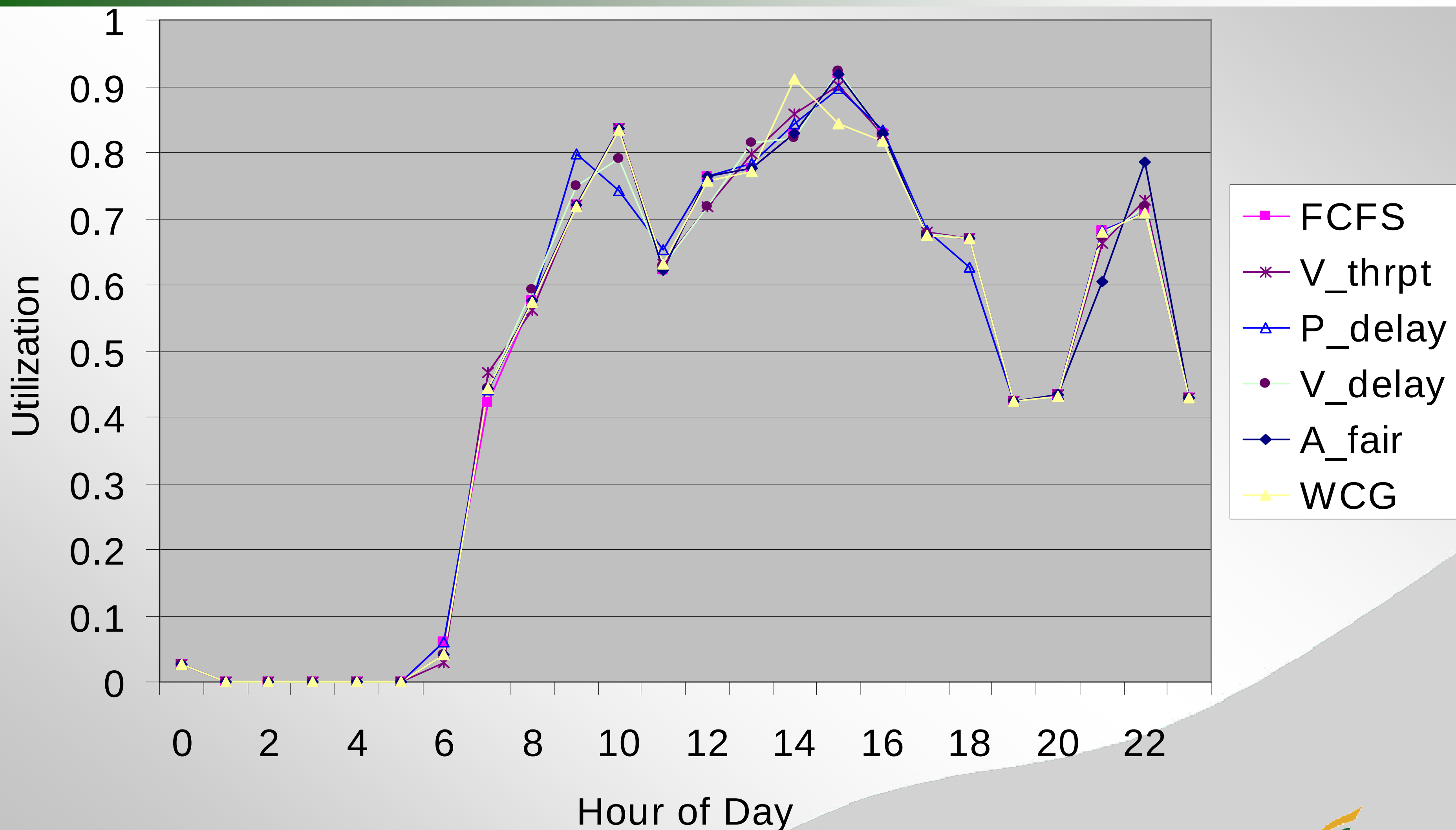
# LGA: Vehicle Utilization




Overall utilization = 0.511 for all models
Hourly throughput varies by 1-2 flights

Assumes:
Veh capacity = 40 /hr
(all Large)

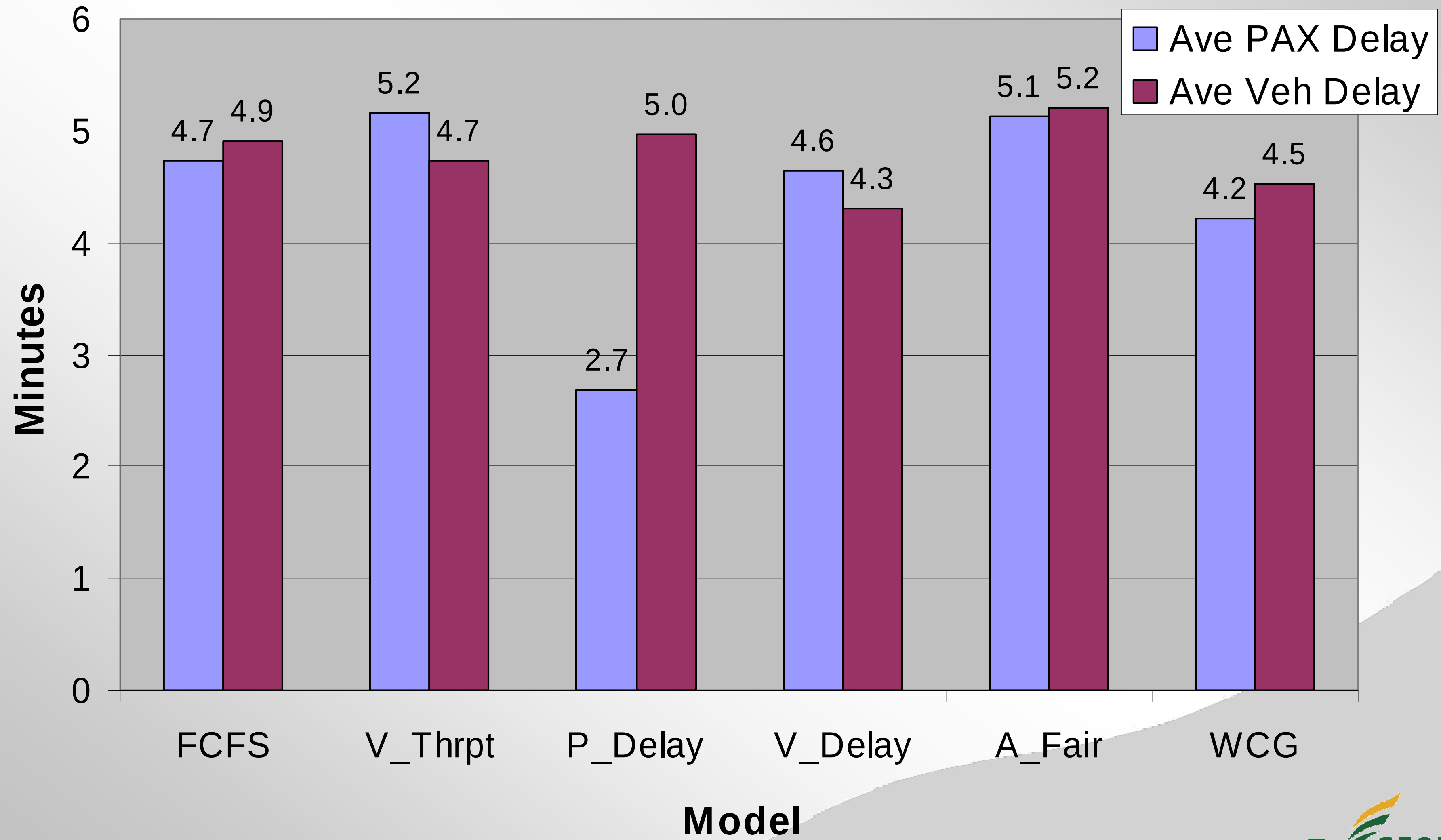
# LGA: Pax Utilization




Overall utilization = 0.483 for all models

Assumes: Veh capacity = 40 /hr (all Large) and 100 pax/veh

# LGA Results: Delay



# LGA: Airline Fairness