# The Effect of Reduced Unimpeded Taxi-Out Times on Departure Delays at Capacity Constrained Airports

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# General Question

- Will reducing the time it takes aircraft to taxi from their gate to the runway reduce departure delays when a queue exists?

# Taxi-out Overview

- Taxi-out phase can be broken into two stages:
  - Pushback from the gate to the runway or departure queue
  - Runway or departure queue to lift-off

- Inefficiencies exist within each stage (i.e., pilot unfamiliarity with taxi route; departure queues)

- Unimpeded taxi-out time represents how long it takes an aircraft when no conflicting traffic is present
  - Not the minimum or optimal time
  - Can be reduced as pilot skills are enhanced

# Safe Flight 21 Program

- Pilots have the option to equip aircraft with cockpit tools which enhance their ability to taxi from the gate to the runway or departure queue

- Moving map display of the airport surface
  - Highly accurate own-ship position
  - Comprehensive digital map of the airport surface (including runways, taxiways, holding areas, ramps, hangars, and prominent structures)

- Monitor progress using the cockpit display and correlate position by reference to outside visual cues

- Other traffic (aircraft and vehicles) will be presented on the display

# Problem Description

- Expectation is that unimpeded taxi-out time will be reduced

1) No queue formed with aircraft waiting at the runway

   Actual taxi-out time = unimpeded time

   → Time savings realized

2) Traffic exists and aircraft must yield or wait

   Actual taxi-out time > unimpeded time

   → Will time savings be realized when queues exist?

   → What if only a subset of aircraft are equipped with the enhancement?

# Deterministic Example

- Assuming universal equipage, time savings achieved regardless of queue size
  - Amount of time waiting in the departure queue is unchanged
  - Enter and depart the queue a fixed increment earlier

| Aircraft | Pushback | Baseline Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Pushback | Reduced Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Savings |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 10.0 | 11.5 | 11.5 | 0.0 | 2.0 | 13.5 | 1.5 | 9.5 | 11.0 | 11.0 | 0.0 | 2.0 | 13.0 | **0.5** |
| 2 | 3.0 | 10.0 | 13.0 | 13.5 | 0.5 | 2.0 | 15.5 | 3.0 | 9.5 | 12.5 | 13.0 | 0.5 | 2.0 | 15.0 | **0.5** |
| 3 | 4.5 | 10.0 | 14.5 | 15.5 | 1.0 | 2.0 | 17.5 | 4.5 | 9.5 | 14.0 | 15.0 | 1.0 | 2.0 | 17.0 | **0.5** |
| 4 | 6.0 | 10.0 | 16.0 | 17.5 | 1.5 | 2.0 | 19.5 | 6.0 | 9.5 | 15.5 | 17.0 | 1.5 | 2.0 | 19.0 | **0.5** |
| 5 | 7.5 | 10.0 | 17.5 | 19.5 | 2.0 | 2.0 | 21.5 | 7.5 | 9.5 | 17.0 | 19.0 | 2.0 | 2.0 | 21.0 | **0.5** |
| 6 | 9.0 | 10.0 | 19.0 | 21.5 | 2.5 | 2.0 | 23.5 | 9.0 | 9.5 | 18.5 | 21.0 | 2.5 | 2.0 | 23.0 | **0.5** |
| 7 | 10.5 | 10.0 | 20.5 | 23.5 | 3.0 | 2.0 | 25.5 | 10.5 | 9.5 | 20.0 | 23.0 | 3.0 | 2.0 | 25.0 | **0.5** |
| 8 | 12.0 | 10.0 | 22.0 | 25.5 | 3.5 | 2.0 | 27.5 | 12.0 | 9.5 | 21.5 | 25.0 | 3.5 | 2.0 | 27.0 | **0.5** |
| 9 | 13.5 | 10.0 | 23.5 | 27.5 | 4.0 | 2.0 | 29.5 | 13.5 | 9.5 | 23.0 | 27.0 | 4.0 | 2.0 | 29.0 | **0.5** |
| 10 | 15.0 | 10.0 | 25.0 | 29.5 | 4.5 | 2.0 | 31.5 | 15.0 | 9.5 | 24.5 | 29.0 | 4.5 | 2.0 | 31.0 | **0.5** |

# Deterministic Example (Cont'd)

- Given less than 100% equipage, time savings is a function of the queue relative to the taxi time reduction
  - 1st aircraft equipped; remaining aircraft not equipped

| Aircraft | Pushback | Baseline Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Pushback | Reduced Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Savings |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 10.0 | 11.5 | 11.5 | 0.0 | 2.0 | 13.5 | 1.5 | 9.5 | 11.0 | 11.0 | 0.0 | 2.0 | 13.0 | **0.5** |
| 2 | 3.0 | 10.0 | 13.0 | 13.5 | 0.5 | 2.0 | 15.5 | 3.0 | 10.0 | 13.0 | 13.0 | 0.0 | 2.0 | 15.0 | **0.5** |
| 3 | 4.5 | 10.0 | 14.5 | 15.5 | 1.0 | 2.0 | 17.5 | 4.5 | 10.0 | 14.5 | 15.0 | 0.5 | 2.0 | 17.0 | **0.5** |
| 4 | 6.0 | 10.0 | 16.0 | 17.5 | 1.5 | 2.0 | 19.5 | 6.0 | 10.0 | 16.0 | 17.0 | 1.0 | 2.0 | 19.0 | **0.5** |
| 5 | 7.5 | 10.0 | 17.5 | 19.5 | 2.0 | 2.0 | 21.5 | 7.5 | 10.0 | 17.5 | 19.0 | 1.5 | 2.0 | 21.0 | **0.5** |
| 6 | 9.0 | 10.0 | 19.0 | 21.5 | 2.5 | 2.0 | 23.5 | 9.0 | 10.0 | 19.0 | 21.0 | 2.0 | 2.0 | 23.0 | **0.5** |
| 7 | 10.5 | 10.0 | 20.5 | 23.5 | 3.0 | 2.0 | 25.5 | 10.5 | 10.0 | 20.5 | 23.0 | 2.5 | 2.0 | 25.0 | **0.5** |
| 8 | 12.0 | 10.0 | 22.0 | 25.5 | 3.5 | 2.0 | 27.5 | 12.0 | 10.0 | 22.0 | 25.0 | 3.0 | 2.0 | 27.0 | **0.5** |
| 9 | 13.5 | 10.0 | 23.5 | 27.5 | 4.0 | 2.0 | 29.5 | 13.5 | 10.0 | 23.5 | 27.0 | 3.5 | 2.0 | 29.0 | **0.5** |
| 10 | 15.0 | 10.0 | 25.0 | 29.5 | 4.5 | 2.0 | 31.5 | 15.0 | 10.0 | 25.0 | 29.0 | 4.0 | 2.0 | 31.0 | **0.5** |

# Deterministic Example (Cont'd)

– 1st aircraft not equipped; remaining aircraft equipped

| Aircraft | Pushback | Baseline Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Pushback | Reduced Time | Enter Queue | Exit Queue | Delay | Service Time | Departure Time | Savings |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 10.0 | 11.5 | 11.5 | 0.0 | 2.0 | 13.5 | 1.5 | 10.0 | 11.5 | 11.5 | 0.0 | 2.0 | 13.5 | 0.0 |
| 2 | 3.0 | 10.0 | 13.0 | 13.5 | 0.5 | 2.0 | 15.5 | 3.0 | 9.5 | 12.5 | 13.5 | 1.0 | 2.0 | 15.5 | 0.0 |
| 3 | 4.5 | 10.0 | 14.5 | 15.5 | 1.0 | 2.0 | 17.5 | 4.5 | 9.5 | 14.0 | 15.5 | 1.5 | 2.0 | 17.5 | 0.0 |
| 4 | 6.0 | 10.0 | 16.0 | 17.5 | 1.5 | 2.0 | 19.5 | 6.0 | 9.5 | 15.5 | 17.5 | 2.0 | 2.0 | 19.5 | 0.0 |
| 5 | 7.5 | 10.0 | 17.5 | 19.5 | 2.0 | 2.0 | 21.5 | 7.5 | 9.5 | 17.0 | 19.5 | 2.5 | 2.0 | 21.5 | 0.0 |
| 6 | 9.0 | 10.0 | 19.0 | 21.5 | 2.5 | 2.0 | 23.5 | 9.0 | 9.5 | 18.5 | 21.5 | 3.0 | 2.0 | 23.5 | 0.0 |
| 7 | 10.5 | 10.0 | 20.5 | 23.5 | 3.0 | 2.0 | 25.5 | 10.5 | 9.5 | 20.0 | 23.5 | 3.5 | 2.0 | 25.5 | 0.0 |
| 8 | 12.0 | 10.0 | 22.0 | 25.5 | 3.5 | 2.0 | 27.5 | 12.0 | 9.5 | 21.5 | 25.5 | 4.0 | 2.0 | 27.5 | 0.0 |
| 9 | 13.5 | 10.0 | 23.5 | 27.5 | 4.0 | 2.0 | 29.5 | 13.5 | 9.5 | 23.0 | 27.5 | 4.5 | 2.0 | 29.5 | 0.0 |
| 10 | 15.0 | 10.0 | 25.0 | 29.5 | 4.5 | 2.0 | 31.5 | 15.0 | 9.5 | 24.5 | 29.5 | 5.0 | 2.0 | 31.5 | 0.0 |

# General Model

- Single runway configuration reduces the taxi-out process to a tandem or series queue
- First station starts at the gate and ends when the aircraft enters the departure queue and is defined as a G/G/C queue
  - "Gs" stand for general distributions used to represent inter-arrival times and service times respectively
  - C is the maximum number of aircraft that can simultaneously taxi-out without adding additional delays
- Second service station consists of a single runway and is defined as a G/G/1 queue
  - Arrivals into the second station are aircraft that are exiting the first station
  - Service time consists of aircraft take-off

# General Model (Cont'd)

- Waiting area is assumed to be infinite and that aircraft wait at the runway
  - In reality, aircraft may hold at the gate rather than waiting at the runway
  - However, overall wait is the same using the simplifying assumption
- When more than one runway exists, can segment system into several tandem queues and the analysis still applies

# Heavy Traffic Scenario

- Under heavy traffic, aircraft depart their gates and enter the runway queue at a rate close to but not exceeding runway capacity

- Using the equilibrium queuing theory, the average wait in the queue for any G/G/1 queue is:

$$W_q = \frac{\lambda\left(\sigma_A^2 + \sigma_B^2\right)}{2\left(1 - \lambda/\mu\right)}$$

  - $\lambda$ is the arrival rate (i.e., average number of aircraft arriving to the runway queue during a unit of time)
  - $\mu$ is the service rate (i.e., average capacity during a unit of time)
  - $\sigma^2_A$ is the variance of the inter-arrival time (i.e., time between arrivals to the runway queue)
  - $\sigma^2_B$ is the variance of the service time (i.e., take-off time)

# Heavy Traffic Scenario (Cont'd)

- From the equation, $\lambda$ is the arrival rate into the departure queue
  - Same as the rate at which aircraft depart their gates
  - Independent of unimpeded taxi-out time
- Service time is the take-off or runway occupancy time and is also independent of unimpeded taxi-out time
- Variance of inter-arrival times into the queue is the only parameter to influence the wait in queue
  - If variance is unchanged, then the average wait in the departure queue remains the same and the time savings is realized
  - If variance increases, then the average wait increases offsetting the reduction in unimpeded taxi-out times
  - If variance decreases, then the average wait decreases further reducing total taxi-out time

# Special Case

- Changes to the unimpeded taxi-out distribution have no effect on the waiting time in the second station assuming:
  - Aircraft pushback according to a Poisson process
  - Unimpeded taxi-out time is exponentially distributed
  - No feedback or returning of an aircraft back to the gate is allowed

- Arrival into the second queue is Poisson with the same distribution for which aircraft enter the first queue (pushback)

- Overall time in the system is reduced by the reduction in unimpeded taxi-out time

# Mixed Equipage

- If equipage is less than 100%, then unimpeded taxi-out time follows a mixed distribution
  - Mean equals the weighted average of the means for the equipped and unequipped populations
  - Variance equals the weighted average of the variances for the equipped and unequipped populations plus a positive term assuming a change in unimpeded taxi-out time

$$h(x) = \begin{cases} f(x)\; with & prob = p \\ g(x)\; with & prob = 1 - p \end{cases}$$

$$\mu_h = \mu_f \cdot p + \mu_g \cdot (1 - p)$$

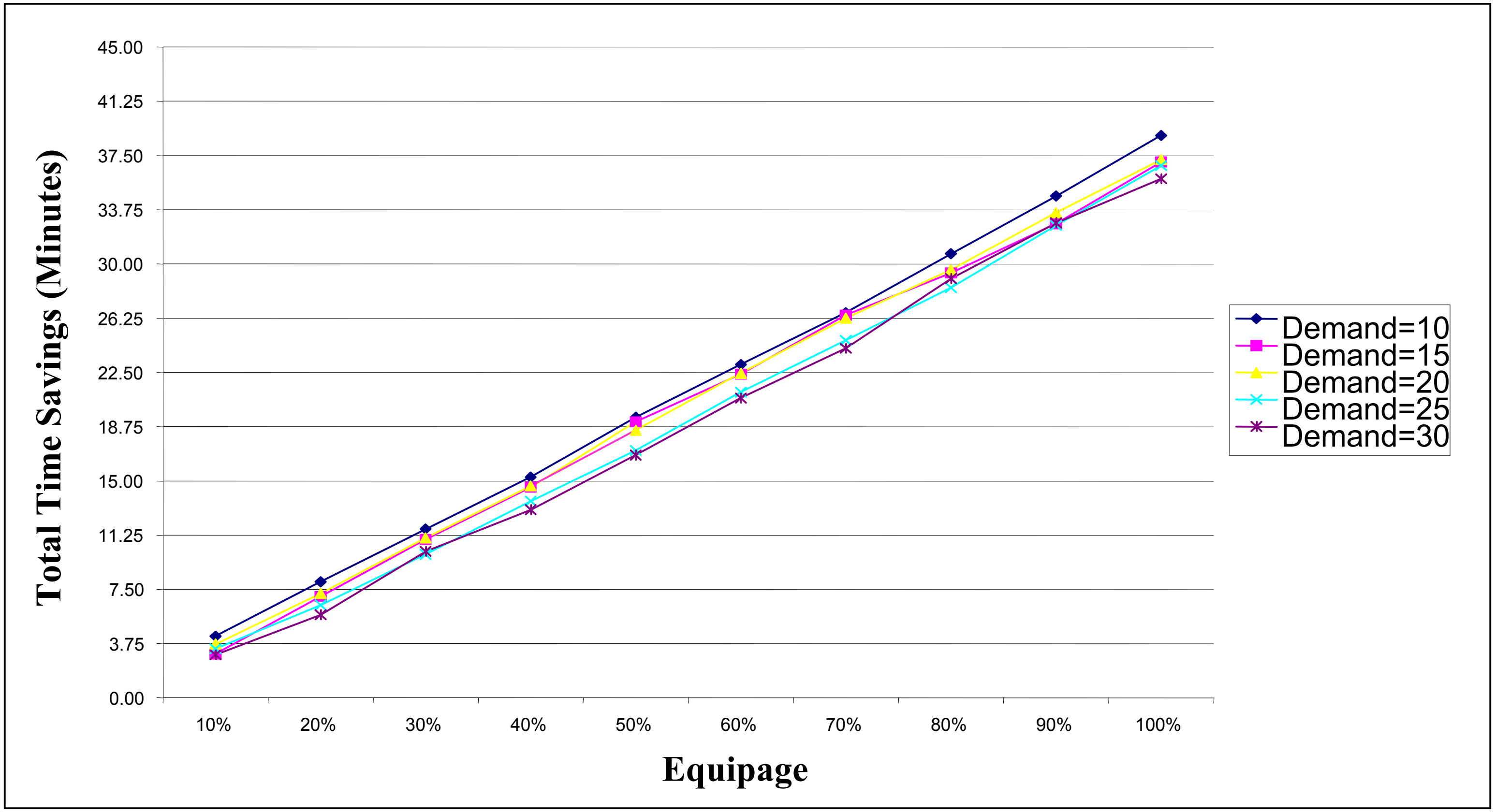
$$\mathrm{var}_h = \mathrm{var}_f \cdot p + \mathrm{var}_g \cdot (1 - p) + \left(\mu_f - \mu_g\right)^2 \cdot p \cdot (1 - p)$$

# Discrete Event Simulation

- 150 scenarios
  - Capacity = 32 departures per hour
  - Demand = 10, 15, 20, 25, and 30 aircraft per hour
  - Baseline time from gate to runway queue = 10 minutes
  - Unimpeded taxi-out time reduction
    - Mean times reduced by .25, .50, and 1.00 minutes
    - Variance not changed
  - Equipage = 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%

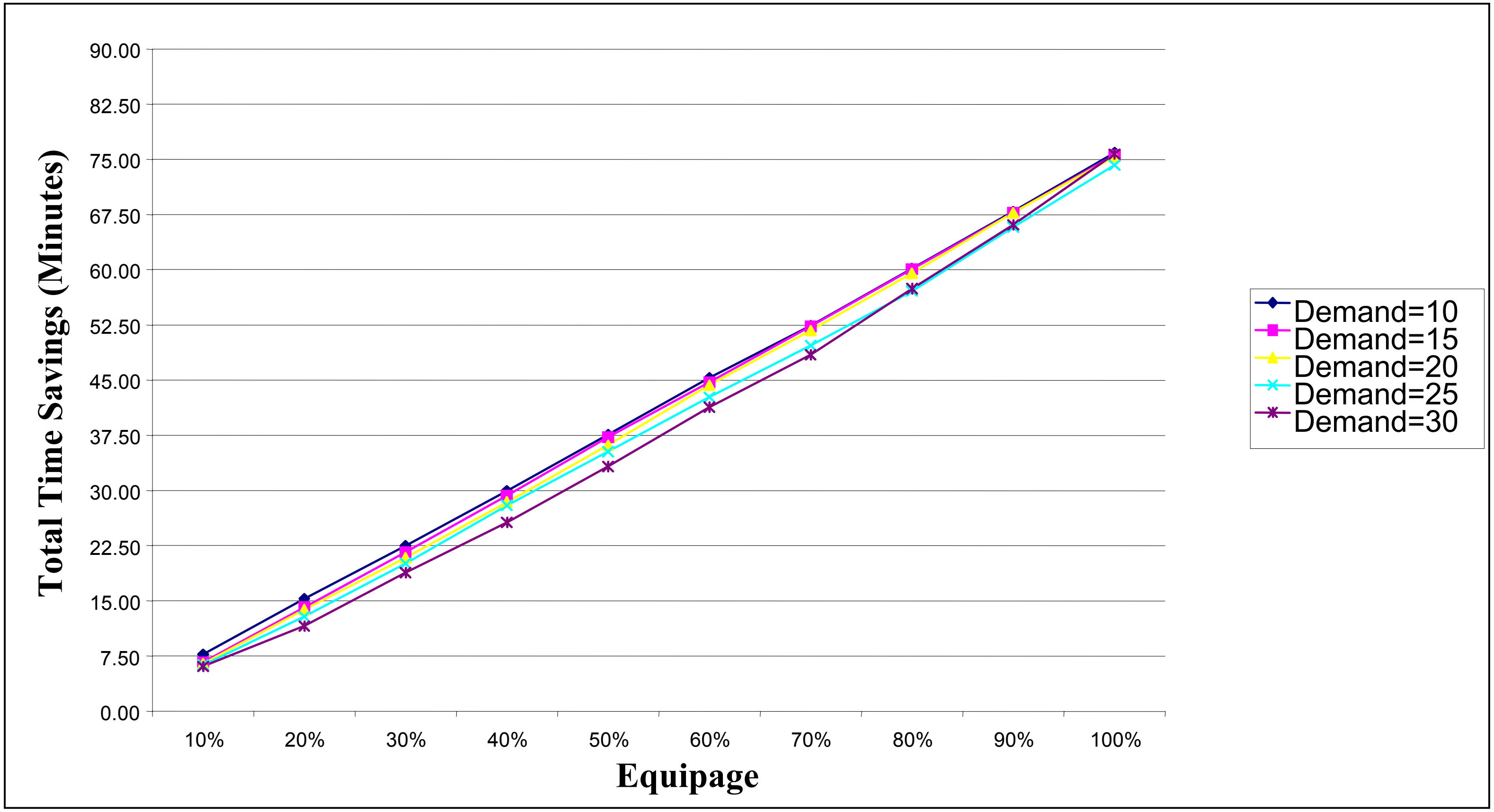
- Each scenario, savings estimated for 150 aircraft

# Discrete Event Simulation (Cont'd)



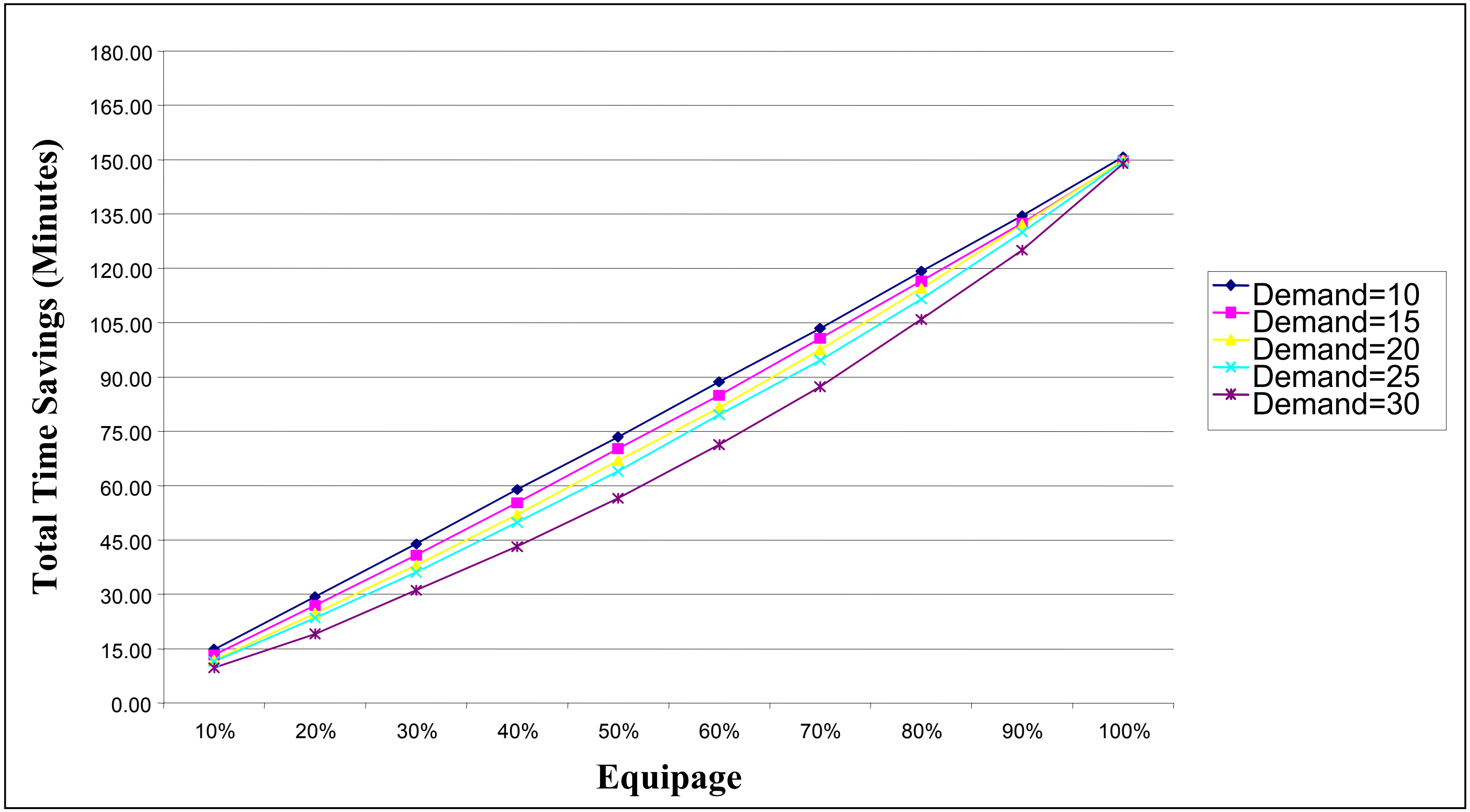

**.25 Minute Reduction**

# Discrete Event Simulation (Cont'd)




**.50 Minute Reduction**

# Discrete Event Simulation (Cont'd)




**1.00 Minute Reduction**

# Summary

- Departure delays can be reduced by improving pilots ability to navigate from the gate to the runway
  - At capacity constrained airports with departure queues
  - With less than 100% equipage