Methods For Analysis Of Passenger Trip Performance In A Complex Networked Transportation System

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

By

Danyi Wang
Bachelor of Science
Wuhan University of Technology, 2000
Master of Science
George Mason University, 2002

Director: Dr. Lance Sherry, Associate Professor
Department of Systems Engineering and Operations Research

Summer Semester 2007
George Mason University
Fairfax, VA
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<td>ASQP</td>
<td>Airline Service Quality Performance</td>
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<td>ASM</td>
<td>Available Seat Mile</td>
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<td>ATNAT</td>
<td>Air Transportation Network Analysis Tool</td>
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<td>Air Transportation System</td>
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<td>GUI</td>
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<td>MCT</td>
<td>Minimal Connecting Time</td>
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<td>NAS</td>
<td>National Airspace System</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NEXTOR</td>
<td>The National Center of Excellence for Aviation Operations Research</td>
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<td>Transportation Research Board</td>
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Abstract

METHODS FOR ANALYSIS OF PASSENGER TRIP PERFORMANCE IN A COMPLEX NETWORKED TRANSPORTATION SYSTEM

Danyi Wang, PhD
George Mason University, 2007
Dissertation Director: Dr. Lance Sherry

The purpose of the Air Transportation System (ATS) is to provide safe and efficient transportation service of passengers and cargo. The on-time performance of a passenger’s trip is a critical performance measurement of the Quality of Service (QOS) provided by any Air Transportation System. QOS has been correlated with airline profitability, productivity, customer loyalty and customer satisfaction (Heskett et al. 1994).

Bratu and Barnhart have shown that official government and airline on-time performance metrics (i.e. flight-centric measures of air transportation) fail to accurately reflect the passenger experience (Bratu and Barnhart, 2005). Flight-based metrics do not include the trip delays accrued by passengers who were re-booked due to cancelled flights or missed connections. Also, flight-based metrics do not quantify the magnitude of the delay (only the likelihood) and thus fails to provide the consumer with a useful assessment of the impact of a delay. Passenger-centric metrics have not been developed because of the unavailability of airline proprietary data, which is also protected by anti-trust collusion concerns and civil liberty privacy restrictions.
Moveover, the growth of the ATS is trending out of the historical range.

The objectives of this research were to (1) estimate ATS-wide passenger trip delay using publicly accessible flight data, and (2) investigate passenger trip dynamics out of the range of historical data by building a passenger flow simulation model to predict impact on passenger trip time given anticipated changes in the future. The first objective enables researchers to conduct historical analysis on passenger on-time performance without proprietary itinerary data, and the second objective enables researchers to conduct experiments outside the range of historic data.

The estimated passenger trip delay was for 1,030 routes between the 35 busiest airports in the United States in 2006. The major findings of this research are listed as follows:

1. High passenger trip delays are disproportionately generated by cancelled flights and missed connections. Passengers scheduled on cancelled flights or missed connections represent 3 percent of total enplanements, but generated 45 percent of total passenger trip delay. On average, passengers scheduled on cancelled flights experienced 607 minutes delay, and passengers who missed the connections experienced 341 minutes delay in 2006. The heavily skewed distribution of passenger trip delay reveals the fact that a small proportion of passengers experience heavy delays, which can not be reflected by flight-based performance metrics.

2. Trend analysis for passenger trip delays from 2000 to 2006 shows the increase in flight operations slowed down and leveled off in 2006, while enplanements kept increasing. This is due to the continuous increase in load factor. Load factor has increased from 69% in 2003 to 80% in 2006. Passenger performance is very sensitive to changes in flight operations: annual total passenger trip delay was increased by 17% and 7% from 2004 to 2005, and from 2005 to 2006, while flight operations barely increased (0.5% from 2004 to 2005, and no increase from 2005 to 2006) during the same time period.
3. Passenger trip delay is shown to have an asymmetric performance of passenger trip delay in terms of routes. Seventeen percent of the 1030 routes generated 50 percent of total passenger trip delays. An interesting observation is that routes between the New York metropolitan area and the Washington D.C. metropolitan area have the highest average passenger trip delays in the system.

4. In terms of airports, there is also an asymmetric performance of passenger trip delay. Nine of the 35 busiest airports generated 50 percent of total passenger trip delays. Some airports, especially major hubs, impact the passenger trip delays significantly more than others. Recognition of this asymmetric performance can help reduce the total passenger trip delay propagation in the air transportation network by making changes primarily in major airports, such as Atlanta, GA (ATL), Chicago O’Hare (ORD) and Newark (EWR) airports.

5. Congestion Flight Delay, Load Factor, Flight Cancellation Time, and Airline Cooperation Policy are the most significant factors affecting total passenger trip delay in the system. A 15-minute reduction in flight delay is predicted to produce a 24 percent decrease in total passenger trip delays, and should save approximately $2.3 million in passenger value of time per day. An improved airline cooperation policy in re-booking disrupted passengers is predicted to produce a 12 percent decrease in total passenger trip delays, and flights cancelled earlier in the day is predicted to produce a 10 percent decrease in total passenger trip delay. The load factor has increased from 70 percent in 2000 to 80 percent in 2006. The systemically high load factors lead to a very brittle transportation system that has little resiliency or adaptability when confronted with either weather or congestion induced flight cancellations (Donohue and Shaver, 2008). Decreasing the load factor to 70 percent is predicted to produce an 8 percent reduce in total passenger trip delay. The combined effect of multiple factors should be investigated and used to support the decisions made by officials, policy makers and researchers, so that they can achieve their strategy goals with minimal costs or changes associated with the most significant factors.
This dissertation provides new system performance measurements from the passenger’s view. The results of this research provide decision makers with improved metrics for future investment decisions and better tools to manage the system. The passenger flow simulation model also provide the means to perform analysis for proposed changes to the system.
Chapter 1: Introduction

According to Air Transportation Association (ATA) statistics, U.S. passenger and cargo airlines recorded $163 billion operational revenue in 2006. Although flight schedule and ticket prices have proven to be the main drivers of airline profitability, studies show that ontime performance and service reliability are important to achieving long-term profitability (Bratu, 2003) Customer satisfaction is a key player in the service-profit chain, which drives airline profitability, productivity and customer loyalty and satisfaction (Heskett et al., 1994).

Except for slot constrained airports, airlines are able to schedule as many flights as they wish at all airports. Data recently released by the U.S. Air Transportation Association (ATA) show that passenger enplanements, revenue passenger miles (RPMs), available seat miles (ASMs), passenger load factor (LF) and cargo revenue ton miles (RTMs) for U.S. carriers reached new highs in 2006. U.S. airline operations grew to 11.3 million departures, with carriers transporting 745 million passengers and 797 billion RPMs systemwide. “Higher volumes of traffic, which are expected to continue to grow, strongly reinforce the need to modernize our antiquated air traffic control system,” said Air Transportation Association (ATA) Vice President and Chief Economist John Heimlich. “It is imperative that we implement technology upgrades and adopt procedures that will accommodate the growing demand being placed on the system by all users of ATC services and infrastructure. Without an effective transformation of the ATC system, the negative impact on our nation’s economy will be severe.” (ATA
news release May 1, 2006) Moreover, the disproportionate increase in flights relative to total airport capacity resulted in severe system congestion, and numerous flight delays and cancellations, adversely affecting the traveling public (Tam and Hansman, 2003), (Bratu, 2003).

1.1 Correlation between Traffic Growth and Flight On-Time Performance

The economic boom in the mid to late 1990s stimulated the growth in air travel demand. Traffic loads and profits for the airline industry during this period set new records. In the 2000, the U.S. airline industry operated in excess of 23,000 domestic and international flights per day, and enplaned more than 1.7 million daily passengers, more than 85 percent of whom have a choice of two or more airlines. The industry added nearly 300 billion dollars into our national economy in 2000 (ATA Report).

Between 1990 and 2000, the domestic revenue passenger miles at the major US carriers increased by 40 percent, while total aircraft seat capacity increased by only 23 percent. Load factors climbed to record levels: the average load factor in 1990 was 60 percent, but that had increased to 70 percent by 2000 (Tam and Hansman, 2003). In conjunction with the high load factor, airport runway capacity/flight demand imbalance drove flight on-time percentage from 82 percent in the early 90’s down to 73 percent in 2000. Detailed flight on-time performance in 2000 is described in Figure 1.1. The percentage of delayed flights and cancelled flights were as high as 30 percent in June 2000 and 6 percent in December 2000, respectively, while the values of these two metrics were only 19 percent and 1 percent in 1990.
Figure 1.1: Screen Shot of BTS On-Time Performance Statistics in 2000, Source:BTS
The Air Travel Consumer Report is a monthly product of the Department of Transportation’s Office of Aviation Enforcement and Proceedings (OAEP). The report is designed to assist consumers with information on the quality of services provided by the airlines. The report has a special section that deals with consumer complaints which is based on data compiled by the OAEP’s Aviation Consumer Protection Division (ACPD). Air travel consumers can call, write or e-mail the ACPD to report air travel service problems they experienced and register their concerns about airline service. According to the published Air Travel Consumer Report, annual consumer complaints peaked in 2000 at 20,564, which is more than three times the annual complaints in 1997. 2000 became a benchmark representing the impact of an economic boom on our current air transportation system: traffic volume reached record highs while quality of service bottomed out.

The internet bubble burst in 2001, compounded by the terrorist attacks of 9/11, dramatically decreased the demand for air travel. Passenger traffic plummeted in the days and weeks after 9/11. This decline of passenger traffic helped relieve the imbalance of airport runway capacity/flight demand.

The flight on-time percentage is inversely proportional to the change in passenger traffic (see both Figure 1.2 and Figure 1.3). Figure 1.2 depicts the changes in flight on-time percentage from 1990 to 2006. Figure 1.3 depicts enplanements and revenue passenger miles from 1978 to 2006.
Figure 1.2: Flight On-Time Percentage, 1990-2007, Data Source:BTS

Figure 1.3: Growth of Enplanements and Revenue Passenger Miles (RPMs), 1978-2006, Source:ATA
During the economic boom in 1990s, the passenger traffic rose steadily and reached the record high in 2000. Meanwhile the flight on-time performance slid down through the 90's until it declined to 73 percent in 2000. During the post-bubble economic recession, passenger traffic remained low and flight on-time percentage return to levels similar to those in the early 1990s. However, after a slow and gradual growth, passenger traffic exceeded 2000 records, reached a new peak in 2004, and continues to increase. In 2006, the system transported 745 million enplanements and flew 797 billion RPMs. As a consequence, flight on-time percentage in 2007 fell back to 2000 level.

Figure 1.4: Historical Load Factor from 1978 to 2006, Source:ATA

In the wake of the post-bubble economic recession, the airline industry had become
increasingly aware of declining revenues amidst persisting issues with service quality and flight delays. The decline in revenues and the increased exposure to low-cost competition had increased pressure on the major US airlines to cut costs. One of the major cost-cutting efforts was the accelerated retirement of older airplanes and the consolidation of aircraft fleets. Another area of cost-cutting was in the area of labor (Tam and Hansman, 2003). A side effect of all these changes in fleet, labor and operational strategy of legacy airlines was the high load factor. As shown in Figure 1.4, load factor climbed relatively slowly and steadily from 1978 to 2000. After 2001, the load factor grew at a rapid pace and reached 80 percent in 2006.

The systemically high load factors lead to a very brittle transportation system that has little resiliency or adaptability when confronted with either weather- or congestion-induced flight cancellations (Donohue and Shaver, 2008).

1.2 Correlation between Flight On-Time Performance and Passenger On-Time Performance

Along with the boost of traffic volume, the airport runway capacity/flight demand imbalance is clearly evident between 1978 and 2006. According to the newly published air travel consumer report (DOT), complaints on flight schedule disruptions have increased by 77 percent from 2003 to 2006. It is hard to explain the situation using flight-based metrics: flight on-time percentage only dropped by 4 percent from 2003 to 2006 (BTS). The divergence of flight on-time performance and passenger on-time performance has been identified.

The behavior of the ATS can be modeled as a two tiered flow model: the vehicle
tier and the passenger tier. As shown in Figure 1.5, inputs to the vehicle tier are flight schedule. Affected by weather, congestion and other matters, flights may not follow the schedules exactly, and disruptions such as delay and cancellation can occur. Flight-based metrics are defined and used to measure the vehicle performance in the vehicle tier.

![Figure 1.5: Vehicle Tier and Passenger Tier of Air Transportation System](image)

Researchers have proven flight-based metrics are not good proxy for passenger travel experience. More importantly, they underestimate the time penalties of missed connections and cancellations on passenger trip time (Bratu and Barnhart, 2005),

...
Inputs to the passenger tier include not only flight performance, but also passenger factors. Passenger factors describe passenger and seat information such as aircraft size, and number of passengers loaded on a flight. Load factor is the seat occupancy rate which equals number of passengers loaded divided by aircraft size. Passengers depart, arrive and connect between airports. Flight delay postpones passengers' arrival time at their destination airports. Connecting passengers could miss their connecting flights due to delay brought by the first-leg flight. Hundreds of passengers can get stuck at the same airport if a flight is cancelled. All these disruptions on passenger trip time happen for a variety of reasons.

A passenger-based metric, “Estimated Passenger Trip Delay (EPTD),” is developed in this research to measure the passenger-tier performance. Unlike the flight-based metrics, a passenger-based metric measures the system performance from the flying public’s viewpoint. Output of the passenger tier is the total and average estimated passenger trip delay in terms of airport, route and cause.

The next example illustrates the divergence between the vehicle-tier performance and the passenger-tier performance: a small aircraft with 20 passengers and a heavy aircraft with 200 passengers do not differ in the vehicle tier if they are delayed by the same amount of time. Metrics in the vehicle tier measure the quantity of delayed flights and the delayed time without taking passenger factors into account. However, in the passenger tier, the total passenger trip delay generated by the heavy aircraft is 10 times more than those generated by the small aircraft.

Flight cancellation is a more complicated disruption in a passenger trip metric than in a vehicle flight metric. Flight frequency, time of day, aircraft size, load factor
and distribution of cancelled flights all have strong impacts on passenger trip delay caused by cancelled flights. The example given in Table 1.1 compares passenger trip delay caused by cancelled flights from Chicago O’Hare airport to New York LaGuadia airport on March 28 and August 18, 2006.

Table 1.1: Passenger Trip Delay due to Cancelled Flights on Route ORD-LGA

<table>
<thead>
<tr>
<th>Date</th>
<th># of Cancelled FLs</th>
<th>Total PaxDelay</th>
<th>Avg. PaxDelay</th>
<th>Cancelled Time</th>
<th>Carrier</th>
<th>Load Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 28</td>
<td>5</td>
<td>2298 hrs</td>
<td>270 min</td>
<td>Morning &amp; Afternoon</td>
<td>UA &amp; AA</td>
<td>77%</td>
</tr>
<tr>
<td>August 18</td>
<td>5</td>
<td>6460 hrs</td>
<td>704 min</td>
<td>Afternoon</td>
<td>AA</td>
<td>81%</td>
</tr>
</tbody>
</table>

The comparison is made for the same route (ORD-LGA) on different days. Both days have five cancelled flights. But the five cancelled flights on August 18 generated 6,460 hours of passenger trip delay, which is 2.8 times more than the passenger trip delay generated by the five cancelled flights on March 28. More detailed analysis shows the five cancelled flights on March 28 were from two airlines, spread out throughout the day, and had lower average load factors. However, the five cancelled flights on August 18 were all afternoon cancellations, and all operated by American Airlines. They had a higher average load factor of 81 percent. Cancelled passengers on August 18 had to compete for very limited empty seats and available flights, which resulted in 70 percent of the cancelled passengers waiting overnight. Detailed calculation method for passenger trip delay is discussed in Chapter 3.
Table 1.2 lists the distinction between the vehicle tier and the passenger tier.

Table 1.2: Distinction Between The Vehicle Tier And The Passenger Tier

<table>
<thead>
<tr>
<th>Aspects</th>
<th>The Vehicle Tier</th>
<th>The Passenger Tier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Flight</td>
<td>Passenger</td>
</tr>
<tr>
<td>Input</td>
<td>Flight Schedule</td>
<td>Flight Performance &amp; Passenger Factors</td>
</tr>
<tr>
<td>Output</td>
<td>Flight Performance</td>
<td>Passenger Performance</td>
</tr>
<tr>
<td>View</td>
<td>Measure the system performance from operational viewpoint</td>
<td>Measure the system performance from flying public’s viewpoint</td>
</tr>
<tr>
<td>Level of Detail</td>
<td>Flights</td>
<td>Passengers (more complicated and detailed)</td>
</tr>
<tr>
<td>Correlation</td>
<td>Passenger Performance is a function of Flight Performance and Passenger Factors</td>
<td></td>
</tr>
</tbody>
</table>

In summary, a divergence exists between the vehicle-tier performance and passenger-tier performance. Flight-based metrics are a poor proxy for the passenger trip experience, since they do not take passenger factors into account. It is imperative to develop passenger-based performance metrics that accurately reflect passenger trip experience and measure the system performance from the flying public’s viewpoint.
1.3 Problem Statement

The air transportation of passengers and cargo is provided by a distributed network of agents including airlines, air traffic control, airports, and their supply chains (Donohue and Zellweger, 2001). These agents form layers of functional networks each providing services to the others (Holmes and Scott, 2004). To meet the obligations of stakeholders, each agent reports performance metrics based on their function. For example, air traffic control reports gate-to-gate block times and takeoff-to-landing block times to the FAA. These metrics reflect the performance of the system when the aircraft is in the jurisdiction of air traffic control. Likewise, airlines and the Department of Transportation report flight performance based on the scheduled departure and arrival times (ASPM) (DOT) (GOTP).

Different stakeholders of the system have their own views of evaluating system performance. The FAA and airlines use flight-based metrics because they manage air traffic and flights. Similarly, the metrics describing passengers’ travel experience shall be trip-based, or passenger-based. For a given flight, passenger trip time does not necessarily equal flight time. It is determined by flight times, connecting time, as well as the time accrued by passengers following missed connections and cancellations.

Passenger trip data is proprietary airline data and is not directly available to the public. Subject to civil liberty privacy restrictions and anti-trust collusion concerns, very little research has been conducted on passenger trip performance. Moreover, expansion of air transportation system is trending out of the historical operation range with record high load factor, operations and enplanements. This trend prohibits using historical data for analysis.
1.3.1 Research Objectives

Accurate and complete performance is very important, since it supports informed decisions by officials, operators, service providers, and system users. It helps them to assess progress in achieving its strategic goals and objectives.

Metrics reflecting passenger performance in the ATS shall be passenger-based. However, there are no clearly defined passenger-based metrics to describe passenger travel experience. Moreover, flight-based metrics are a poor proxy for passenger-based metrics, since they cannot accurately reflect the passenger travel experience. The missing feedback loop of passenger performance to FAA, airlines and passengers results in an incomplete and inaccurate system performance.

There are two major obstacles for developing passenger-based metrics and methods. First, the passenger itinerary data is not directly available to the public. Second, the current air transportation system is trending out of the historical operation range. A predictive passenger flow model for future option design evaluation is more valuable than a historical analysis on passenger performance.

The objectives of this research are to (1) analyze passenger trip delay using publicly available historical data, and to (2) develop a stochastic passenger flow simulation model for future option design evaluation. The first objective aims to avoid the proprietary passenger trip data problem, and the second objective aims to provide a better prediction of future options in light of the complexity brought by rapid growth of traffic.

1.3.2 Research Approach

To achieve the above two objectives, the following approach has been adopted:
1. Develop a set of unique Algorithms and generate a Stochastic Passenger and Vehicle Database to perform “historical analysis”:

(a) Convert vehicle flight data to passenger trip data;

(b) Facilitate statistical analysis of airports and routes, based on large quantity of historical segment flight data (from 2000 to 2006);

(c) Identify the unique behavior patterns of routes and airports that form the network properties to support the development of the passenger flow simulation (PFS).

2. Build a Passenger Flow Simulation (PFS) to perform “future option design evaluation”:

(a) Develop a Stochastic Hierarchical Timed Colored Petri Net to simulate passenger movements in the ATS,

(b) Conduct experiments outside the range of historical data,

(c) Investigate passenger flow in the air transportation system dealing with not only flight delays and cancellations, but also missed connections, and changes in policy, flight schedule and airline strategy,

(d) Identify and order rank significant factors affecting passenger trip time,

(e) Predict the impact on passenger trip time given anticipated changes in the future.

1.4 Contributions

There are two major contributions of this dissertation:
1. Very little research has been conducted on passenger on-time performance due to unattainable passenger trip data. Bratu and Barnhart were provided with one month of passenger booking data from a legacy airline. Their research on passenger on-time performance was the first to validate and measure the discrepancy between the vehicle-tier performance and the passenger-tier performance with actual airline data (Bratu, 2003), (Bratu and Barnhart, 2005). However, Bratu and Barnhart’s research relied on the proprietary airline data. This research designed a set of unique algorithms that can join multiple publicly available flight databases and convert the flight data into passenger trip data. It enables researchers to perform very detailed analysis on passenger trip delay without proprietary airline data.

2. The expansion of the ATS is trending out of historical range. According to the data recently released by the U.S. Bureau of Transportation Statistics, scheduled aircraft departures, passenger enplanements, revenue passenger miles (RPMs), available seat miles (ASMs), cargo revenue ton miles (RTMs) and load factor for U.S. carriers reached new highs in 2006. The Passenger Flow Simulation (PFS) model developed in this dissertation enables researchers to conduct experiments outside the range of historical data.

1.4.1 Industrial Applications of Research

This research should be of interest to Traffic Flow Management, FAA Strategy Planning, Airline Operation Centers, Airline Flight Reservation and Ticket Purchasing Department, and the Flying Public. At this moment, FAA Traffic Flow Management and FAA Strategy Planning Organizations have funded the industrial applications of
this research. Airline operation centers and flight reservation department are potential customers of this research.

In Fall 2006, Metron Aviation Inc. applied this research on the FAA’s new Traffic Flow Management tool called “Airspace Flow Program” to assess the benefits of the new program. More detailed information is available in Chapter 4.

In Spring 2007, FAA Strategy Planning Organization applied this research on system performance analysis and included it into the NAS Strategy Simulator (NSS), which is a dynamical system model developed by Ventana Systems in conjunction with the National Center of Excellence for Aviation Operations Research (NEXTOR) for the FAA. More detailed information is available in Chapter 4.

1.4.2 Papers

First-authored and co-authored papers and proposal are listed as follows:


Chapter 2: Literature Review

Related research to this dissertation is categorized into three areas:

1. Flight On-Time Performance Measurement;

2. Passenger On-Time Performance Measurement;

3. Petri Nets and Its Applications in Transportation Systems.

2.1 Flight On-Time Performance Measurement

The Department of Transportation (DOT) Aviation Consumer Protection Division operates a complaint-handling system for consumers who experience air travel service problems. The DOT monthly “Air Travel Consumer Report” is distributed to the industry and made available to the news media and the general public (DOT). It documents airline on-time performance based on number and percentage of disrupted activities, i.e. delayed flights, cancelled flights and diverted flights. The report has three sections explaining flight on-time performance and feedback from passengers: Flight Delays, Oversales and Consumer Complaints. The sections that deal with flight delays and oversales are based on data collected by the Department’s Bureau of Transportation Statistics. The section that deals with consumer complaints is based on data compiled by the OAEP’s Aviation Consumer Protection Division (ACPD). Each section of the report is preceded by a brief explanation of how to read and
understand the information provided. Reports from 1998 to 2007 are available on the Aviation Consumer Protection Division website.

Other sources of information on the on-time performance of air transportation, such as the DOT Bureau of Transportation Statistics (BTS) databases and the FAA Airline Service Quality Performance database, all consist of flight-based metrics. However, these “percentage” and “count” metrics do not reflect the degree of delay in excess of 15 minutes or the passenger travel experience.

With publicly accessible flight data and statistics, research on flight performance is well-developed, well-documented and accessible. The flight performance literature can be categorized into three areas: (1) Survey and report on flight performance, (2) Flight performance metrics and (3) Flight delay propagation in the network.

Publications in the category “survey and report on flight performance” describe the system evolution and changes in flight performance in past years. For example, the Federal Aviation Administration (FAA), the Department of Transportation (DOT) and Eurocontrol publish various performance reports, such as DOT’s Air Travel Consumer Report (DOT), Eurocontrol Annual Performance Review (Eurocontrol), and FAA’s Flight Plan Performance Report (FAA). Aside from these published reports, researchers also investigate the trends of system evolution and changes in flight performance. Tam and Hansman published their analysis of the dynamics of the U.S. commercial air transportation system (Tam and Hansman, 2003). They highlight key dynamics that govern the US domestic air transportation system from post-deregulation to re-construction after 9/11 terrorist attack. In their analysis, Tam and Hansman describe the system dynamics in each specific time period, such as
dramatic growth in domestic air travel in post-deregulation evolution, changes in operating strategy and passenger travel behavior during the economic boom of the late 1990s, and the structural shift of legacy airlines, worst flight performance and price competition during the post-bubble economic recession. More literature can be found on survey and report on flight performance (Ostrt and Strong, 2006), (FAA, 2004), (Bowen and Headley, 2006).

Publications in the category “flight performance metrics” evaluate existing performance metrics, propose new performance metrics and investigate potential problems caused by inappropriate performance metrics. For example, Bolczak et al (Bolczak and Hoffman, 1997) point out that delay metrics do not provide a complete picture of system performance, though they provide insights into some aspects of the system performance. Williams et al (Williams et al., 2004) proposed that common metrics should be designed to ensure the consistencies in assessing and monitoring system performance. Cherniavsky et al (Cherniavsky and Abrahamsen, 2000) developed airport utilization metrics for FAA’s Aviation System Performance Metrics (ASPM). More publications in flight metric category include (Breunig et al., 2003), (CNS/ATM Report, 1999), (Post, 2005) and others.

Publications in the category “flight delay propagation” describe the propagation process of flight delay in the air transportation network and investigate the underlying causes of the propagation. Aircraft, passengers and flight crew have different itineraries in the air transportation system. Flight delay propagates when an aircraft moves from one airport to another. Sometimes, flight delay created by the first leg can be absorbed if the airline schedules a large enough time buffer at the connecting airport. Beatty et al (Beatty et al., 1998) (Donohue and Zellweger, 2001) developed
the concept of a delay multiplier to estimate the true system impact of a delayed flight. Their results showed the delay multiplier grows nonlinearly with the size of the initial delay. Therefore, reducing a large initial delay by any amount has a significant effect on total delay for an airline. Another analysis of airport delay at key airports was reported by Welch et al (Welch and Lloyd, 2001). They demonstrated that each airport has a unique spectrum, which is a kind of delay “signature” for that airport. However, Welch’s results do not distinguish between operations in IMC (instrument meteorological conditions) and VMC (visual meteorological conditions). In 2003, Wang et al (Wang et al., 2003) developed an analytic model that explicitly separates the controllable factors that influence delays and propagation of delays from those factors that are random variables with distinguishable IMC and VMC. Xu et al (Xu et al., 2005) develop a stochastic model that uses Bayesian Networks (BNs) to model the relationships among different components of aircraft delay and the causal factors that affect delays. Xu’s Bayesian model allows investigation of the causal factors contributing to delay in each flight segment and the analysis of the contribution of each segment to the final arrival delay. More literature on flight delay propagation includes (Boswell and Evans, 1997), (Vigneau, 2003), (Xu et al., 2007), (Laskey et al., 2006) and others.

2.2 Passenger On-Time Performance Measurement

Despite a large literature on flight performance, little has been published on passenger performance. The key research papers on passenger trip delay estimation are published by the MIT Center of Transportation and Logistics and the University of Maryland.
In the summer of 2001, Professor Cynthia Barnhart from MIT presented her estimation (with student Stephane Bratu) on passenger trip delay for a single legacy airline in a congressional hearing. The results showed the average time penalty on passenger trip time due to missed connection and flight cancellation is 303 minutes, while average delay for non-disrupted passengers was only 16 minutes. It is the first study to measure the strong impact of flight schedule disruption on passenger trip time with real data. The MIT Center of Transportation and Logistics continued their research on passenger on-time performance measurement (Barnhart and Bratu), (Bratu and Barnhart, 2005), (Bratu and Barnhart, 2006), (Sarmadi, 2004). In 2003, Stephane Bratu, Professor Barnhart’s Ph.D student, published his Ph.D thesis on airline passenger on-time schedule reliability analysis (Bratu, 2003).

In his thesis, Bratu combined the operational flight data from the FAA’s Aviation System Performance Metrics (ASPM) database with the proprietary airline data to estimate passenger delays due to missed connections and cancelled flights. He established relationships between passenger delays and other statistical factors. Bratu found that flight-based metrics can not accurately reflect the delays on disrupted passengers. More importantly, simple flight-based statistics tend to underestimate passenger delays because, on average, disrupted passengers experience much longer delays than flights on average. For example, as listed in Figure 2.1, Bratu shows that 97 percent of passengers from a specific airline who were not disrupted by missed connections and cancellations experienced an average delay of 16 minutes for a 10-day period in August 2000. This is roughly equivalent to the average flight delay of 15.4 minutes for this period. In contrast, the 3 percent of passengers who were disrupted by missed connections or cancelled flights experienced an average delay of
303 minutes. Seventy-eight percent of the disrupted passengers were recovered the same day (SD) as their planned arrival day. But the other 22 percent of the disrupted passengers were stranded overnight (OV) at the airport and not recovered until the next day. Their average delay were 721 minutes compared to only 185 minutes for the disrupted passengers reaccommodated the same day.

<table>
<thead>
<tr>
<th>Passenger</th>
<th>Average delay</th>
<th>% disrupted passengers</th>
<th>% of disrupted passenger delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>185 minutes</td>
<td>78%</td>
<td>48%</td>
</tr>
<tr>
<td>OV</td>
<td>721 minutes</td>
<td>22%</td>
<td>52%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Passenger</th>
<th>Average delay</th>
<th>% Passengers</th>
<th>% Total passenger delays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disrupted</td>
<td>303 minutes</td>
<td>3.2%</td>
<td>39%</td>
</tr>
<tr>
<td>Non-disrupted</td>
<td>16 minutes</td>
<td>96.8%</td>
<td>61%</td>
</tr>
</tbody>
</table>

Figure 2.1: Passenger Trip Delay Statistics, Source: Stephane Bratu’s Thesis, 2003, MIT

The strength of MIT’s research is that it validated and measured the discrepancy between flight performance and passenger performance with real airline booking data. This is a breakthrough for research on passenger on-time performance. However, it is not possible to expand MIT’s research to the system level analysis, because all of its analysis is based on passenger reservation information and no-show rates provided by a U.S. legacy airline for the month of August 2000. The limitation of MIT’s research is that the results are totally depend on proprietary airline data, and this limitation restricts the development and prospect of the research.

Professor Michael Ball at the University of Maryland (UMD) expanded MIT’s
research on passenger trip delay estimation. He and his students developed a passenger delay analytical model for the NAS Strategy Simulator (NSS). The NAS Strategy Simulator (NSS) is a dynamical system model of the National Airspace System (NAS) designed to understand the interactions between passengers, airlines and system of airports and air traffic control. Maryland’s analytical model is based on a decision tree, which is designed to estimate the probabilities of passengers being delayed, and cancelled or missed connections (Figure 2.2). They derived flight information, such as flight cancellation rate, average flight delay, and individual flight schedule, from the FAA’s Aviation System Performance Metrics (ASPM) database. This information is fed into a regression model to estimate the probability of missing connections.

Figure 2.2: Decision Tree to Determine Passenger Disruption Probability, Source: University of Maryland
Concerned about the limitation of Bratu’s research (only one airline, one-month data in August 2000), Ball and Bratu agreed on an average passenger trip delay of 420 minutes for all the disrupted passengers in the current air transportation system. The total passenger trip delay estimated by UMD’s analytical model equals the product of “estimated number of disrupted passengers” and “420 minute average passenger trip delay”.

Unlike Bratu and Barnhart’s research, Ball et al emphasize the estimation of disruption probability more than the estimation of passenger trip delay. The strength of UMD’s research is that it is trying to expand the passenger trip delay estimation to the system level. As part of the NAS Strategy Simulator, researchers can predict the impact on passenger trip time given anticipated changes in the system. A limitation of UMD’s research is that it depends heavily on Bratu and Barnhart’s results. UMD’s model characterizes passenger trip delay by a single number of 420 minutes, regardless of other factors. Passenger trip delay is not homogeneous in the system. It differs in terms of route, airport, time of day and carrier. This author remains skeptical about the results relied on the assumption of 420 minutes of delay for all disrupted passengers.

In this dissertation, unique algorithms are developed to manipulate and integrate publicly accessible flight databases for a macro-level, systemwide passenger trip on-time performance measurement. Major differences between Bratu et al (2005), Ball et al (2006) and this research are listed in Table 2.1.
Table 2.1: Differences Between Passenger Trip Delay Estimation Models

<table>
<thead>
<tr>
<th>Aspects</th>
<th># Bratu et. al (MIT)</th>
<th>Ball et al (UMD)</th>
<th>Wang et al (GMU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Passenger booking data for August 2000 from a single legacy airline, combined with FAA ASPM flight data</td>
<td>ASPM flight data and Bratu et al’s results</td>
<td>Publicly accessible flight data from Bureau of Transportation Statistics</td>
</tr>
<tr>
<td>Objectives</td>
<td>The model is designed to optimize the airline schedule recovery</td>
<td>The model is designed to estimate NAS-wide passenger trip delay</td>
<td>The model is designed to estimate flight-by-flight passenger trip delay</td>
</tr>
<tr>
<td>Perspective</td>
<td>Evaluate the performance from airline’s perspective</td>
<td>Evaluate the performance from passenger’s perspective</td>
<td>Evaluate the performance from passenger’s perspective</td>
</tr>
<tr>
<td>Level of Detail</td>
<td>Flight-by-flight level, detailed but with data limitation</td>
<td>System level, very rough estimation, but can be used NAS-wide</td>
<td>Flight-by-flight level, detailed and can be used NAS-wide</td>
</tr>
</tbody>
</table>
2.3 Petri Nets and Applications in Transportation Systems

2.3.1 Introduction of Petri Nets

A Petri Net is a graphical and mathematical modeling tool. The structure of Petri Nets is a bipartite directed graph describing the structure of a discrete event system, while the dynamics of the system are described by the execution of the Petri Net. In this research, the passenger flow is simulated using a hierarchical timed colored petri net. Definitions of Ordinary Petri Nets, Timed Petri Nets, Colored Petri Nets and Hierarchical Petri Nets are introduced in this section.

Ordinary Petri Nets (OPN)

Ordinary petri nets are bipartite directed graphs. In this type of graph there are two distinct types of nodes, and the directed edges must go between nodes of different types. In Petri Nets, the two types of nodes are called places and transitions. Places are depicted graphically by circles, and represent information or resource pools. The transitions are depicted graphically by bars or rectangles, and represent information processes or resource consumption.

The ordinary Petri Net is represented by a quadruple \((P, T, I, O)\) where:

- \(P = \{p_1, p_2, ..., p_n\}\) is a finite set of places
- \(T = \{t_1, t_2, ..., t_m\}\) is a finite set of transitions
- \(I\) is an input mapping \(P \times T \rightarrow \{0, 1\}\) corresponding to the set of directed arcs from \(P\) to \(T\). These arcs are referred as input arcs.
• $O$ is an output mapping $T \times P \rightarrow \{0, 1\}$ corresponding to the set of directed arcs from $T$ to $P$. These arcs are referred as output arcs.

The distribution of tokens in the places of a petri net is called the marking of the petri net. The marking, is a mapping, $M$, of each place to a non-negative integer that equals the number of tokens in each place. It characterizes the state of the Petri Net. The initial marking is denoted by $M_0$. Any change in the marking and, therefore, any change in the state, is controlled by transitions.

Figure 2.3 shows an example of the firing of a transition. Transition $t_1$ is enabled because there is at least one token in each of its input places, $p_1, p_2$ and $p_3$. When $t_1$ fires, one token is removed from each of the input places of $t_1$ and tokens are added to each of the output places, $p_4$ and $p_5$. The firing of transitions causes the marking of the net to change from $[1,1,1,0,0]$ to $[0,0,0,1,1]$, and therefore introduces a change in the state of the system.

Figure 2.3: Firing of a Transition, Source: (Perdu, 1997), (Wagenhals, 2000)
Colored Petri Nets (CPN)

The usefulness of ordinary Petri Nets is limited, in part, because the tokens are indistinguishable. Modeling a simple system using ordinary Petri Nets can result in a very complex structure. Colored Petri Nets are a full extension of ordinary Petri Nets that provides a very compact way of modeling complex systems. Tokens are no longer identical but own some attributes called colors. Distinguishability of tokens in colored Petri Nets allows more precise and detailed models of complex asynchronous processes.

By definition, a colored petri net is a bipartite directed graph represented by a five tuple: \( CPN = (P,T,C,I,O) \) where:

- \( P = \{p_1, p_2, ..., p_n\} \) is a finite set of places
- \( T = \{t_1, t_2, ..., t_m\} \) is a finite set of transitions
- \( C \) are the sets of color associated with the places and the transitions such that:
  - \( C(p_i) = \{a_{i1}, ..., a_{iu_i}\}, u_i = |C(p_i)|, i = 1, 2, ..., n \)
  - \( C(t_j) = \{b_{j1}, ..., b_{vj_j}\}, v_j = |C(t_j)|, j = 1, 2, ..., m \)
- \( I \) is an input mapping \( C(p) \times C(t) \rightarrow N(\text{non-negative integers}) \) corresponding to the set of colored directed arcs from \( P \) to \( T \). These arcs are referred as input arcs.
- \( O \) is an output mapping \( C(t) \times C(p) \rightarrow N(\text{non-negative integers}) \) corresponding to the set of colored directed arcs from \( T \) to \( P \). These arcs are referred as output arcs.
Timed Colored Petri Nets

Transition fires either in sequence or concurrently in Ordinary Petri Nets. An extension of Ordinary Petri Nets is Timed Petri Nets where time is introduced to model delays associated with processes. This extension of the basic theory allows for quantitative analysis of response time, resource utilization, throughput rate and effect failures (Perdu, 1997).

Kristensen, et al. (Kristensen et al., 1998) describes a global clock whose value represents model time. In addition to having values, tokens can carry a time value or time stamp designed by adding a suffix of the form \( @[t] \) where \( t \) is either an integer or real. The tokens carrying time stamps must belong to a color set defined as “timed”.

There are two distinct approaches: the place model and the transition model. This variation of the two models provides flexibility in the use of time in Colored Petri Nets. Sometimes it is more natural to associate a time delay with a process that is modeled by a transition, and other times a time delay associated with an arc that represents the transfer of the output of a process to another process is more appropriate. Both models can be used at the same time in a model.

Colored Petri Nets extended by time make it possible to evaluate how efficient a system performs its operations and it makes it possible to model and validate real-time systems, where the correctness of the system relies on the proper timing of the events. Figure 2.4 illustrates the firing of a timed colored petri net. The transition \( t1 \) models a process that needs to be triggered and that takes one input token and produces, after 10 units of time, two output tokens and one status token.
Hierarchical Colored Petri Nets

It is impractical to draw a CPN model of a large system as a single net, since it would become very large and cumbersome. Moreover, the human modeller needs abstractions that make it possible to concentrate on only a few details at a time. The notion of Hierarchical Colored Petri Nets has been introduced to deal with this problem. A set of transitions and their interconnecting places can be replaced by a substitution transition, which then refers to a subpage containing the subnet that this substitute transition replaces.

Hierarchical Colored Petri Nets allow different substitution transitions referring to the same subnet. The substitution transitions represent different instances of the subnet. The distinction between the different instances is made through the correspondence of socket nodes at the upper level and port nodes of the instance at the lower level.

Figure 2.4: Firing of a Transition in Timed Colored Petri Nets, Source: (Perdu, 1997)
In this dissertation, a passenger flow process is simulated as a hierarchical timed colored petri net model. Group of passengers transported between airports is defined as a Color called PaxGroup. Time stamps associated with each PaxGroup record the model time during the travel process. The passenger flow simulation (PFS) model contains 1030 routes, 34 airports, 17 major carriers, 8500 daily flights and roughly 900,000 daily enplanements. In order to simulate such a complex transportation system, the model is designed with three levels of hierarchy. The top level net contains 34 airport substitution transitions, one enroute substitution transition and their sockets connected to subnets. A detailed description on the passenger flow simulation model is available in Chapter 4.

### 2.3.2 Petri Net Application in Transportation Systems

Petri Nets are well suited to model public transport networks since they can easily model the asynchronous behavior of the different transport means and the synchronization between buses, trains, subways and passengers when a set of passengers gets on or off means of transport. Petri Nets have been applied to traffic control modeling of transportation systems, such as train system (Hielscher et al., 1998), (Jansen et al., 1998) and traffic light systems (Perkusich, 1999), (Wang et al., 1999).

The application of CPN in transportation systems is evolving from modeling “control” part to modeling more complicated behavior, such as traffic flow, passenger flow, and connections between transportation means. In 2003, Turki, Grunder, and Elmoudni used Stochastic Petri Net to model and analyze periodic event scheduling for hub-based bus network. Their focus was on the minimization of the connection
time, since the improvement of connection conditions is the main condition to pro-
vide a satisfactory level of quality of service. They concluded that the new modeling
tool, Stochastic Petri Nets, is “valid, flexible and powerful tool for evaluating pub-
lic transportation systems and then for improving the scheduling task (Turki et al.,
2003),(Turki et al., 2002).

A simple Petri Net is not well adapted for an accurate modeling of a large public
transportation system due to tremendous size and the complexity of the system. More
complicated PN, such as CPN, timed PN, stochastic PN, etc. are needed. Castelain
and Mesghouni used CPN to model passenger flow in public bus system (Castelain and
Mesghouni, 2002). They designed a model of the bus transportation network taking
into account the passenger flow in order to measure the consequences of the decision
of regulation to the passenger flow. In this model, both transportation modes and
passengers are included based on a high-level CPN. As shown in Figure 2.5, the left
figure illustrates the modeling idea of passenger flow. When a bus with passengers
arrives at a station, part of the passengers will get off the bus. These passengers
can leave definitively the station or can wait for other bus lines for connections.
Connecting passengers from other bus lines will get on the bus and join the passengers
stay in the bus until the bus leave this station for the next one.

Figure 2.5 gives an example of the exchange of passengers between two buses
crossing at the connection node. “The second bus of line 4 has just arrived at the
bus stop with 35 passengers. 55% of passengers (ie. 19 persons) stay in the bus, 30%
of passengers (ie. 11 persons) are leaving the bus stop and 15% of passenger (ie. 5
persons) want to get on a bus of line 41. Then the 3 passenger waiting for a bus of
line 4 will get on the bus” (Castelain and Mesghouni, 2002).
Air Transportation System (ATS) is a more complicated transportation system compared with others. Use of Petri Net in air transportation area is a fairly new application. Most of PN applications in ATS concentrate on safety aspect, especially on modeling flight movement on runway (Kovace et al., 2004), (Donohue and Zellweger, 2001), (Blom et al., 2000). In this research, a stochastic hierarchical timed CPN (SHT-CPN) model is developed to simulate passenger flow through the Air Transportation Network, and to predict impacts on passenger trip time given anticipated changes in the future. Detailed description on the SHT-CPN model is available in Chapter 4.
Chapter 3: EPTD Algorithms and Database
(Methods and Results)

Passenger trip time determines passengers' choice of transportation mode, and has been positively correlated with airline revenue growth and consumer satisfaction. For a given flight, passenger trip time is determined by flight time, connecting time, as well as the time accrued by passengers following missed connections and cancellations. In this chapter, a set of unique algorithms are developed to estimate passenger trip delay using publicly accessible flight data.

Figure 3.1 depicts the overview of methods and model. This chapter targets the “Historical Analysis” part above the dotted line. Different algorithms are designed to manipulate the data in different data processing phases. First, the flight data is collected from several publicly accessible databases emphasizing different aspects of the ATS. Then the data is processed in the “Data Processing Algorithm” to filter out errors and formalize the data format. In the “Data Joining Algorithm” these “processed” data from different databases join together to form a “mega-database.” “Estimating Passenger Trip Delay Algorithm” is then applied to the mega-database to calculate the passenger trip delays caused by delayed and cancelled flights, and generates the “stochastic passenger and vehicle database,” which contains both flight and passenger trip data. There are two outcomes from the stochastic passenger and vehicle database. One is a graphic user interface (GUI) tool called Air Transportation
Network Analysis Tool (ATNAT). It can provide users with stochastic flight experience statistics, passenger experience statistics and market statistics in terms of user’s choice of origin, destination airport and airline. A detailed description on ATNAT is available in Chapter 3.3. The other outcome is the historical analysis report on passenger trip delay in terms of airport, route, time and causes.

The “historical analysis” on passenger trip delay sets the stage for “future option design evaluation.” As shown in Figure 3.1, processed data, estimating passenger trip delay algorithm and the analysis report, are embedded into the passenger flow simulation (PFS) model as parameters, logical structure and initial tokens. A more detailed description is available in the next chapter.

For consistency purpose, metric name “passenger trip delay” is used in both historical analysis and PFS. The “estimated passenger trip delay” in the historical part is actually “estimated passenger segment delay”, because all the historical data used for the estimation are segment-based flight data, and missed connection process is not included in the historical analysis part. The “estimated passenger trip delay” in the PFS part is the correct definition, because PFS simulates passenger trip disruptions not only due to flight delays and cancellations, but also due to missed connections.

A flight segment is defined as a takeoff and a landing. A trip is a complete itinerary which may consist of a single segment or multiple segments.
Figure 3.1: Overview of Methods and Model
3.1 Flight DataBases

All the flight data used in this research are from the Bureau of Transportation and Statistics (BTS). They are publicly accessible on the BTS website (AOTP), (T100), (DB1B).

3.1.1 Airline On-Time Performance Database

The airline on-time performance (AOTP) database is monthly data reported by U.S. certified air carriers that account for at least one percent of domestic scheduled passenger revenues. It contains on-time arrival data for nonstop domestic flights by major air carriers, and provides such additional items as departure and arrival delays, origin and destination airports, flight numbers, scheduled and actual departure and arrival times, cancelled or diverted flights, taxi-out and taxi-in times, air time, and nonstop distance.

The airline on-time performance (AOTP) database provides more than 111 million flight records from year 1988 to the present. Table 3.1 lists the most recent major air carriers whose flight activities are recorded in the AOTP database. Figure 3.2 lists part of the descriptions and definitions for the AOTP database. The complete definitions and descriptions for all 57 fields are available in Appendix A.
Table 3.1: Airline On-Time Performance Release History

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<td>N/A</td>
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<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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</tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>OO</td>
<td>SkyWest Airlines</td>
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<td>✓</td>
<td>✓</td>
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<td>✓</td>
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<td>ATA Airlines</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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<td>United Airlines</td>
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<td>✓</td>
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<td>✓</td>
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<td>US Airways</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>Southwest Airlines</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>YV</td>
<td>Mesa Airlines</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The airline on-time performance (AOTP) database is a flight-by-flight operating database. Each row in the table represents an actual flight.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>On-Time Performance</td>
</tr>
<tr>
<td>Description</td>
<td>This table contains data reported by US certified air carriers that account for at least one percent of domestic scheduled passenger revenues so that information on air carriers’ quality of service can be made available to consumers of air transportation.</td>
</tr>
<tr>
<td>Records</td>
<td>111,508,785</td>
</tr>
<tr>
<td>Fields</td>
<td>57</td>
</tr>
<tr>
<td>First Year</td>
<td>1987</td>
</tr>
<tr>
<td>Last Year</td>
<td>2007</td>
</tr>
<tr>
<td>Frequency</td>
<td>Monthly</td>
</tr>
<tr>
<td>Latest Available Data</td>
<td>April, 2007</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Departure And Arrival Times</td>
<td>The time an aircraft becomes airborne upon departure or touches down upon arrival.</td>
</tr>
<tr>
<td>Arrival Delay</td>
<td>Arrival delay equals the difference of the actual arrival time minus the scheduled arrival time. A flight is considered on-time when it arrives less than 15 minutes after its published arrival time.</td>
</tr>
<tr>
<td>CRS</td>
<td>Computer Reservation System. CRS provide information on airline schedules, fares and seat availability to travel agencies and allow agents to book seats and issue tickets.</td>
</tr>
</tbody>
</table>

Figure 3.2: Airline On-Time Performance Database Description and Definitions

The 57 fields present flight information, such as origin airport, destination airport, actual departure time, arrival delay, carrier, air time, taxi-out time, etc., for a specific flight.
3.1.2 Air Carrier Statistics (T-100) Database

The Air Carrier Statistics (T-100) database contains domestic nonstop segment data reported by both U.S. and foreign air carriers, including carrier, origin, destination, aircraft type and service class for transported passengers, freight and mail, available capacity, scheduled departures, departures performed, aircraft hours, and load factor when both origin and destination airports are located within the boundaries of the United States and its territories.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>T-100 Domestic Segment (All Carriers)</td>
</tr>
<tr>
<td>Description</td>
<td>This table contains domestic non-stop segment data reported by both U.S. and foreign air carriers, including carrier, origin, destination, aircraft type and service class for transported passengers, freight and mail, available capacity, scheduled departures, departures performed, aircraft hours, and load factor when both origin and destination airports are located within the boundaries of the United States and its territories. Foreign carrier data is not available until 3 months after U.S. carrier data is released. 4,128,160</td>
</tr>
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<td>Records Fields</td>
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<tr>
<td>First Year</td>
<td>1990</td>
</tr>
<tr>
<td>Last Year</td>
<td>2007</td>
</tr>
<tr>
<td>Frequency</td>
<td>Monthly</td>
</tr>
<tr>
<td>Latest Available Data</td>
<td>March, 2007</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Freight</td>
<td>Property, other than express and passenger baggage transported by air.</td>
</tr>
<tr>
<td>Air Time</td>
<td>The airborne hours of aircraft computed from the moment an aircraft leaves the ground until it touches the ground at the end of a flight stage.</td>
</tr>
<tr>
<td>Aircraft Configuration</td>
<td>The type of payload an aircraft was designed to carry: passenger, cargo, or both.</td>
</tr>
<tr>
<td>Airline ID</td>
<td>An identification number assigned by US DOT to identify a unique airline (carrier). A unique airline (carrier) is defined as one holding and reporting under the same DOT certificate regardless of its Code, Name, or holding company/corporation. Use this field for analysis across a range of years.</td>
</tr>
</tbody>
</table>

Figure 3.3: Air Carrier Statistics (T-100) Database Description and Definitions
The Air Carrier Statistics (T-100) database provides more than 4 million flight records from 1990 to the present. Figure 3.3 shows part of the descriptions and definitions for the T-100 database. The complete definitions, field descriptions and release history are available in Appendix A.

Unlike the AOTP database, which has flight-by-flight performance data, the T-100 database contains aggregated passenger and seat information for 174 air carriers. Figure 3.4 gives an example of what T100 data looks like.

<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>origin</th>
<th>dest</th>
<th>carrier</th>
<th>departures</th>
<th>seats</th>
<th>passengers</th>
<th>region</th>
<th>ac_type</th>
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</thead>
<tbody>
<tr>
<td>2006</td>
<td>1</td>
<td>DFW</td>
<td>MSP</td>
<td>MQ</td>
<td>27.0</td>
<td>1890.0</td>
<td>1742.0</td>
<td>D</td>
<td>631</td>
</tr>
<tr>
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<td>MQ</td>
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<td>640</td>
</tr>
<tr>
<td>2006</td>
<td>1</td>
<td>DTW</td>
<td>LAS</td>
<td>NW</td>
<td>45.0</td>
<td>8210.0</td>
<td>7564.0</td>
<td>D</td>
<td>622</td>
</tr>
<tr>
<td>2006</td>
<td>1</td>
<td>DTW</td>
<td>LAS</td>
<td>NW</td>
<td>17.0</td>
<td>3808.0</td>
<td>3652.0</td>
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<tr>
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<td>LAS</td>
<td>NW</td>
<td>61.0</td>
<td>9028.0</td>
<td>8642.0</td>
<td>D</td>
<td>694</td>
</tr>
<tr>
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<td>LAX</td>
<td>NW</td>
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<td>13144.0</td>
<td>12450.0</td>
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<td>622</td>
</tr>
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<td>NW</td>
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<td>5376.0</td>
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<td>623</td>
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<tr>
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<td>LAX</td>
<td>NW</td>
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<td>7548.0</td>
<td>7082.0</td>
<td>D</td>
<td>694</td>
</tr>
<tr>
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<td>LGA</td>
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<td>14590.0</td>
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<td>640</td>
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<td>D</td>
<td>694</td>
</tr>
</tbody>
</table>

Figure 3.4: Sample: Air Carrier Statistics (T-100) database

The first record in the table shows that there were 1,742 passengers and 1,890 seats transported from Dallas Fort Worth International Airport to Minneapolis St. Paul International Airport by American Eagle Airlines using Canadair RJ-700 aircraft (“AC_Type” = 631) in January 2006.
3.1.3 Airline Origin and Destination Survey (DB1B) Market Database

The Airline Origin and Destination Survey (DB1B) Market Database is based on a 10 percent sample of airline tickets from reporting carriers. It contains directional market characteristics of each domestic itinerary of the Origin and Destination Survey, such as the reporting carrier, origin and destination airport, prorated market fare, number of market coupons, market miles flown, and carrier change indicators.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>DB1BMarket</td>
</tr>
<tr>
<td>Description</td>
<td>This table contains (directional) origin and destination markets from the Origin and Destination Survey (DB1B), which is a 10% sample of airline tickets from reporting carriers. It includes such items as passengers, fares, and distances for each directional market, as well as information about whether the market was domestic or international. The file also reports operating and ticketing carrier information for flight segments within the directional market. This table is related to both the O&amp;D Segment and Ticket files by the unique Market ID on each record.</td>
</tr>
<tr>
<td>Records</td>
<td>233,743,992</td>
</tr>
<tr>
<td>Fields</td>
<td>39</td>
</tr>
<tr>
<td>First Year</td>
<td>1993</td>
</tr>
<tr>
<td>Last Year</td>
<td>2006</td>
</tr>
<tr>
<td>Frequency</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Latest Available Data</td>
<td>December, 2006</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport Code</td>
<td>A three character alpha-numeric code issued by the U.S. Department of Transportation which is the official designation of the airport.</td>
</tr>
<tr>
<td>City Code</td>
<td>A three character alpha-numeric code issued by the U.S. Department of Transportation to designate the city where the origin or destination airport is located.</td>
</tr>
<tr>
<td>Coupon</td>
<td>A piece of paper or series of papers indicating the itinerary of a passenger. An airline ticket includes an auditor’s coupon, flight coupons, and a passenger receipt.</td>
</tr>
</tbody>
</table>

Figure 3.5: Airline Origin and Destination Survey (DB1B) Market Database Description and Definitions
The Airline Origin and Destination Survey (DB1B) Market Database provides more than 233 million records from 1993 to the present. Figure 3.5 lists part of the descriptions and definitions for the DB1B database. The complete definitions and descriptions for all 39 fields are available in Appendix A.

Like the T-100 database, Airline Origin and Destination Survey (DB1B) Market Database provides quarterly aggregated market data. It contains a 10 percent sample of ticket, passenger and itinerary information. The proportion of connecting passengers and nonstop passengers on each route or in each airport can be estimated in the DB1B database.

Figure 3.6 gives an example of what DB1B data looks like.

<table>
<thead>
<tr>
<th>ITIN_ID</th>
<th>MARKET_COUpons</th>
<th>ORIGIN</th>
<th>DEST</th>
<th>AIRPORT_GROUP</th>
<th>TICKET_CARRIER</th>
<th>PASSENGERS</th>
<th>MARKET_NONSTOP_FARE</th>
<th>MILES</th>
</tr>
</thead>
<tbody>
<tr>
<td>20063222</td>
<td>1</td>
<td>TPA</td>
<td>PHL</td>
<td>TPA:PHL</td>
<td>US</td>
<td>1.0</td>
<td>219.88</td>
<td>920.0</td>
</tr>
<tr>
<td>20063569</td>
<td>2</td>
<td>SAN</td>
<td>PHL</td>
<td>SAN:CLT:PHL</td>
<td>US</td>
<td>1.0</td>
<td>135.78</td>
<td>2369.0</td>
</tr>
<tr>
<td>200631187</td>
<td>1</td>
<td>ATL</td>
<td>CLT</td>
<td>ATL:CLT</td>
<td>UA</td>
<td>2.0</td>
<td>154.0</td>
<td>227.0</td>
</tr>
<tr>
<td>20063368</td>
<td>1</td>
<td>IAH</td>
<td>PHL</td>
<td>IAH:PHL</td>
<td>US</td>
<td>1.0</td>
<td>266.51</td>
<td>1324.0</td>
</tr>
<tr>
<td>20063401</td>
<td>1</td>
<td>ORD</td>
<td>CLT</td>
<td>ORD:CLT</td>
<td>US</td>
<td>1.0</td>
<td>114.53</td>
<td>509.0</td>
</tr>
<tr>
<td>200631362</td>
<td>2</td>
<td>ATL</td>
<td>BOS</td>
<td>ATL:CLT:BOS</td>
<td>UA</td>
<td>1.0</td>
<td>574.01</td>
<td>946.0</td>
</tr>
</tbody>
</table>

Figure 3.6: Sample: Airline Origin and Destination Survey (DB1B) Market Database

The first record in the table shows that itinerary 20063222 is a ticket purchase for a single passenger flying non-stop on US Airways from Tampa International Airport to Philadelphia International Airport in the third quarter of 2006. Similarly, the second record is an itinerary for a single passenger flying on US Airways from San Francisco International Airport to Philadelphia International Airport with one stop.
at Charlotte Douglas International Airport. The third record is a nonstop itinerary for two passengers flying from Atlanta Hartsfield-Jackson International Airport to Charlotte Douglas International Airport on United Airlines.

3.2 Algorithms

The BTS databases introduced in the Flight Database section provide flight data on different aspects: the ATOP database provides flight-by-flight operational data, the T-100 database provides monthly aggregated passenger and seat information, and the DB1B database provides quarterly aggregated itinerary information. A set of algorithms is applied to the data collected from the AOTP, T-100 and DB1B databases in proper order to calculate passenger trip delays.

3.2.1 Data Processing Algorithm

<table>
<thead>
<tr>
<th>Functions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selectively extract data</td>
<td>Extract flight data from January 2000 to December 2006 between OEP35 Airports (Year 2001 is excluded)</td>
</tr>
<tr>
<td>Detect errors or abnormal data</td>
<td>AOTP Data in August 2004 has 623,107 flight records 1222 records are incomplete and filtered out</td>
</tr>
<tr>
<td>Repair data</td>
<td>In January 2001, 96951 records have “NULL” year, month, dayofmonth values. Recovered by decompose “flightdate” value</td>
</tr>
<tr>
<td>Reformat data</td>
<td>Some data categories are varchar type in original data file. Convert data type to integer, real, etc. for calculations</td>
</tr>
</tbody>
</table>
Data processing algorithm is the first algorithm applied to the collected original data. As shown in Table 3.2, it is responsible for extracting data, detecting errors or abnormal data, repairing data or reformatting data if necessary. The AOTP, T-100 and DB1B databases are abbreviated as AOTP*, T-100* and DB1B* after being processed.

3.2.2 Data Joining Algorithm

AOTP*, T-100* and DB1B* describe the different aspects of the ATS. They are connected to each other by the shared common keys.

As shown in Figure 3.7, AOTP*, T-100* and DB1B* are connected to each other by the combination of year-month-origin-destination-carrier. Each row of AOTP* contains flight operational data of a single flight, while T-100* is aggregated monthly data. The common keys (or data fields) used to join these two databases are Year, Month, Origin, Destination, and Carrier. For example, the first row in AOTP* is a Delta flight that departed from ATL to LGA on August 30, 2004. So the common keys shared with T-100* are 2004, 8, ATL, LGA, DL. Searching the mapped record in T-100* with Year=2004, Month=8, Origin=ATL, Destination=LGA and Carrier=DL, average “passenger data”, such as an average aircraft size of 202 and average loaded passengers of 158, could be obtained (in the first row of T-100*). Similarly, “market data” of flights in AOTP*, such as market value and average tax and fees, can be obtained by searching corresponding records with same values of common keys in DB1B*.
Figure 3.7: Data Join Algorithm

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Origin</th>
<th>Dest</th>
<th>Carrier</th>
<th>Seats</th>
<th>Passengers</th>
<th>Dep</th>
<th>AvgFL</th>
<th>AvgAcsze</th>
<th>AvgPax</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>9</td>
<td>ATL</td>
<td>LGA</td>
<td>DL</td>
<td>98404</td>
<td>798091</td>
<td>485</td>
<td>73%</td>
<td>202</td>
<td>158</td>
</tr>
<tr>
<td>2004</td>
<td>0</td>
<td>ORD</td>
<td>LGA</td>
<td>AA</td>
<td>64108</td>
<td>51051</td>
<td>497</td>
<td>89%</td>
<td>129</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**T-100**

Common Keys to Relate AOTP* and T-100**: Year, Month, Origin, Dest, Carrier

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Origin</th>
<th>Dest</th>
<th>Carrier</th>
<th>DepTime</th>
<th>ArrTime</th>
<th>Cancelled</th>
<th>CRSDepTime</th>
<th>CRSArrTime</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>0</td>
<td>30</td>
<td>ATL</td>
<td>LGA</td>
<td>DL</td>
<td>1038</td>
<td>1537</td>
<td>0</td>
<td>1240</td>
<td>1030</td>
</tr>
<tr>
<td>2004</td>
<td>8</td>
<td>30</td>
<td>ATL</td>
<td>LGA</td>
<td>DL</td>
<td></td>
<td></td>
<td>1</td>
<td>1439</td>
<td>1230</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DB1B**

Common Keys to Relate AOTP* and DB1B*: Year, Qtr, Origin, Dest, Carrier

<table>
<thead>
<tr>
<th>Year</th>
<th>Qtr</th>
<th>Origin</th>
<th>Dest</th>
<th>Carrier</th>
<th>Passengers</th>
<th>MarketFee</th>
<th>Tax&amp;Fee</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>2</td>
<td>ATL</td>
<td>DCA</td>
<td>DL</td>
<td>11138</td>
<td>$140</td>
<td>$20</td>
</tr>
<tr>
<td>2004</td>
<td>3</td>
<td>ORD</td>
<td>LGA</td>
<td>UX</td>
<td>10377</td>
<td>$142</td>
<td>$20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DB1B* is generated by joining DB1B with Tax&Fee

<table>
<thead>
<tr>
<th>Airport</th>
<th>Ticket Tax Rate</th>
<th>Segment Tax</th>
<th>Passenger Facility Charge (PFC)</th>
<th>Federal Security Service Fee (FSSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL</td>
<td>7.5%</td>
<td>$3</td>
<td>$4.5</td>
<td>$2.5</td>
</tr>
<tr>
<td>EWR</td>
<td>7.5%</td>
<td>$3</td>
<td>$3</td>
<td>$2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DB1B**

Common Keys to Relate DB1B and Tax&Fee: Airport

<table>
<thead>
<tr>
<th>Year</th>
<th>Qtr</th>
<th>ITIN_ID</th>
<th>Origin</th>
<th>Dest</th>
<th>Carrier</th>
<th>Airport_Group</th>
<th>Passengers</th>
<th>MarketFee</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>2</td>
<td>20042664397</td>
<td>ATL</td>
<td>DCA</td>
<td>DL</td>
<td>ATL/DCA</td>
<td>1</td>
<td>$95</td>
</tr>
<tr>
<td>2004</td>
<td>3</td>
<td>20042664600</td>
<td>ATL</td>
<td>DCA</td>
<td>CO</td>
<td>ATL/EWR/DCA</td>
<td>1</td>
<td>$144</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Major functions of the Data Joining Algorithm are listed in Table 3.3.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restructure databases</td>
<td>New data columns that are not included in the original database need to</td>
</tr>
<tr>
<td></td>
<td>be generated for future calculations, e.g. the tax&amp;fee data column in</td>
</tr>
<tr>
<td></td>
<td>DB1B* database is not in the original DB1B</td>
</tr>
<tr>
<td>Link databases</td>
<td>Origin, Dest, FlightDate, etc. are primary keys linking AOTP*, DB1B*</td>
</tr>
<tr>
<td></td>
<td>and T100* databases. Market_ID and Itin_ID are primary keys linking DB1B</td>
</tr>
<tr>
<td>Join databases</td>
<td>Following these links or primary keys, values of different categories</td>
</tr>
<tr>
<td></td>
<td>can be joined to form new tables or databases</td>
</tr>
</tbody>
</table>

After the data has been filtered, reorganized and rejoined, the Estimating Passenger Trip Delay Algorithm is applied to the mega-database to estimate passenger trip delays (EPTD). The passenger-based metric, EPTD, indicates whether trips have been disrupted and how badly they were disrupted compared with the original flight schedule.

### 3.2.3 Estimating Passenger Trip Delay (EPTD) Algorithm

The algorithm described in this section is designed to compute the Estimated Total Passenger Trip Delay (ETPTD) for single-segments flights. The algorithm includes trip delays that are a result of delays caused by rebooking passengers on later flights due to cancelled flights and/or delays incurred by flight delays.
Estimated Passenger Trip Delay (EPTD) Due To Delayed Flights

“Passenger delay due to delayed flights” is computed by processing the data for each flight in the AOTP* database for a given route and specified period (e.g. 365 days) to compute the delay time for the flight. This time is then multiplied by the average number of passengers for this flight (from the T-100 database) to derive the passenger delay time for the flight. The total passenger delay due to delayed flights is computed by summarizing the passenger delays caused by all the delayed flights for the specified period. Note, flights with an arrival delay of more than 15 minutes are defined as “delayed flights.” In other words, flights arriving earlier than scheduled or with an arrival delay of less than or equal to 15 minutes are defined as “ontime.”

The equations for this process are listed below:

\[
EPTD_{PVDB}(i) = Pax_{T_{-100}}(i) \times (ActArrTime_{AOTP*}(i) - SchArrTime_{AOTP*}(i))
\]

where:

- \( EPTD \) = Passenger Trip Delay
- \( N \) is a finite non-negative integer set of flights sorted by departure time in a specified period (e.g. year 2006)
- \( D \subset N \) : is a finite set of flights with arrival delay more than 15 minutes (i.e. delayed flights)
- \( i \in D \), represents any delayed flights
- \( ActArrTime(i) = \) actual arrival time of delayed flight \( i \)
- \( SchArrTime(i) = \) scheduled arrival time of delayed flight \( i \)
- \( Pax(i) = \# \) of passengers loaded on delayed flight \( i \)
Subscript $PVDB$: this value comes from the Stochastic Passenger and Vehicle Database generated by algorithms

Subscript $T-100^*$: this value comes from T-100* database

Subscript $AOTP^*$: this value comes from AOTP* database

**Estimated Passenger Trip Delay (EPTD) Due To Cancelled Flights**

“Estimated passenger delay due to cancelled flights” is computed based on the assumption that a passenger displaced by a cancellation will be re-booked on a subsequent flight operated by the same carrier with the same origin/destination pair. The passenger will experience a trip time that now includes both the flight delay of the re-booked flight plus the additional time the passengers must wait for the re-booked flight. The ability to re-book passengers on subsequent flights is determined by the load-factor and aircraft size of the subsequent flights. In general, passengers from a cancelled flight will be relocated to two or three different flights due to limited empty seats on each available flight.

For each flight that is listed as cancelled, the algorithm checks the T-100 database for the average aircraft size and average passengers loaded for the cancelled flight as well as the aircraft size and load factor for the next available flights operated by the same carrier on the same route segment. Passengers for the cancelled flight are then re-booked on these subsequent available flights up to 15 hours from the scheduled departure time of the cancelled flight. The 15-hour upper-bound is derived from (Bratu, 2003) and reflects an estimate of the upper bound of passenger trip delays due to cancelled flights. Also, it should be noted that the algorithm described in this paper allows passengers to be re-booked on flights operated by subsidiary airlines.
(e.g. American Airlines (AA) and its subsidiary American Eagle (MQ)), but not on other airlines.

The delay time accrued by waiting for the re-booked flight is added to the delay time for the re-booked flight. The equation for this process is listed below:

$$EPTD_{PVDB}(i) = \sum_{j \in C} (Pax_{T-100}(k_j) \times \text{MAX} [15 \text{ hrs}, (\text{ActArrTime}_{AOTP}(k_j)-\text{SchArrTime}_{AOTP}(j))])$$

where:

- $EPTD$ = Estimated Passenger Trip Delay
- $N$ is a finite non-negative integer set of flights sorted by departure time in a specified period (e.g. year 2006)
- $C \subset N$ : is a finite set of flights being cancelled
- $j \in C$, represents any cancelled flights
- $NC \subset N$ : is a finite set of non-cancelled flights $\rightarrow C \cap NC = N$
- $k_j \in NC$: is a finite set of non-cancelled flights used to re-load passengers from cancelled flight $j$
- $Pax(k_j) = \text{number of cancelled passengers re-loaded from flight } j \text{ to flight } k_j$
- $\text{ActArrTime}(k_j) = \text{actual arrival time of flight } k_j$
- $\text{SchArrTime}(j) = \text{scheduled arrival time of cancelled flight } j$
- Subscript PVDB: this value comes from the Stochastic Passenger and Vehicle Database
• Subscript T-100*: this value comes from T-100* database

• Subscript AOTP*: this value comes from AOTP* database

An example of the estimation of average passenger delay time caused by a cancelled flight is provided in Figure 3.8.

Assume a flight with 100 passengers is cancelled. Its scheduled arrival time was 12:00 pm. The first available flight has 30 empty seats and is scheduled to arrives at 2:00 pm. The second available flight has 45 empty seats and it is scheduled to arrive at 3:00 pm. The third available flight has 40 empty seats and is scheduled to arrive at 4:00 pm. The passengers re-booked on the first available flight will experience a delay time of two hours each. The passengers re-booked on the second available flight will experience a delay time of three hours each. Those passengers re-booked to the third available flight will experience a delay time of four hours. The total Passenger Trip Delay due to the cancelled flight is $2\text{ (hr)} \times 30 + 3\text{ (hr)} \times 45 + 4\text{ (hr)} \times 25 = 295\text{ hours}$.
The overall algorithm for computation of Passenger Delay Time is provided in Figure 3.9. SQL code of the algorithm is available in Appendix C.

Figure 3.9: Estimating Passenger Trip Delay Algorithm

“Estimating Passenger Trip Delay Algorithm” has the following three assumptions:

1. The algorithm estimates passenger load factors based on publicly available
monthly average data for each flight on each route. When the algorithm re-books passengers from cancelled flights, it assumes the load factor for each flight is the average load factor for those flights for that particular combination of origin-dest-carrier-month. Analysis of a sample of cancelled flights indicates that the average load factor on cancelled flights is equal to the average load factor on noncancelled flights and that this assumption is statistically valid.

2. The algorithm only re-books passengers on single-segment flights. The algorithm does not re-book passengers with a connecting flight to their original destination. Accounting for alternative routing would be possible but adds significant complexity to the algorithm. This is a subject for further research.

3. The algorithm only re-books passengers on flights operated by the same airline or its subsidiaries. Accounting for re-booking on other airlines is possible within the constraints of the existing algorithm but is not consistently practiced. For example, it is understood that some low-cost carriers do not have the infrastructure to handle coupons from other airlines. At this time, the algorithm sets an upper bound for delays due to cancelled flights of 15 hours. This value was chosen based on previous work by Bratu and Barnhart and reflects the behavior that passengers with extensive delays would be re-booked on other airlines. This is an area for further research.
3.3 Analysis and Results

Individual passenger trip delay is the additional time (compared with original schedule) a passenger experiences due to flight delay or cancelled flight. Estimated Passenger Trip Delay for the ATS is the sum of each individual passenger trip delay over a specified period. In this way, total passenger trip time for the NAS is a function not only of the flight delays, but also of the number of passengers on a cancelled flight, the number of seats available and the load factor on noncancelled flights, and the frequency of service to the destination of a cancelled flight.

In this section, passenger trip delay is estimated for domestic flights through the Operational Evolution Plan (OEP) 35 airports over a time period (2000-2006). Operational Evolution Plan (OEP) 35 airports are the nation’s busiest airports that have the greatest number of operations and are heavily traveled. They account for 73 percent of total enplanements and 69 percent of total operations in the air transportation system (Bhadra and Texter, 2005). The complete OEP 35 airports are listed in Appendix B. The closed network formed by OEP35 airports generates 1030 directed routes in 2006. The results reflect the asymmetric performance of the system: passenger trip delays are not distributed evenly. This asymmetry occurs for passengers in terms of routes, airports, time of year, etc.

3.3.1 Disproportionately High EPTD Generated By Cancelled Flights

The disruption to passenger trip time caused by cancellations is underestimated. A simple metric, such as number of cancellations, does not demonstrate the complexity
of the passenger re-book process and the huge delays on passengers.

Flight cancellation is a complicated disruption to passengers, because it has a stronger impact on passenger trip delay than flight delay does. Figure 3.10 shows NAS-wide Total Estimated Passenger Trip Delay (EPTD) in 2006. Cancelled flights accounted for only 1.4 percent of total scheduled flights in 2006, but they generated 39 percent of total passenger trip delay.

![Figure 3.10: Total Estimated Passenger Trip Delay in Year 2006](image)

On average in 2006, passengers scheduled on cancelled flights experienced 607 minutes of delay, and passengers scheduled on the delayed flights experienced 56 minutes of delay.

To mitigate the effects of flight cancellation on passenger trip time, airlines could either provide redundant resources or reduce cancellation. The redundant resources include more empty seats, lower load factor, higher flight frequency, and backup
aircraft and flight crew. These redundant resources ensure the flexibility of the re-booking process when disruptions occur. On the other hand, they increase airline costs and reduce airline efficiency.

3.3.2 EPTD Trend Analysis (2000-2006)

Air Transportation System performance in 2000 is an interesting benchmark: Traffic volume reached record highs, while quality of service bottomed out. Affected by the economic recession after 9/11, air transportation demand dropped dramatically and slowly climbed back after four years. In 2006, the air transportation industry broke the 2000 record demonstrating the new highs.

A trend analysis for estimated annual total passenger trip delays for 2000, 2001, 2003, 2004, 2005 and 2006 is provided in this section. In this analysis, 2001 is excluded to avoid possible anomalous effects of 9/11 on the air transportation industry.

As shown in Figure 3.11, both total scheduled flights and total enplanements dropped by 14 percent and 11 percent respectively in 2002 and then in 2004, returned to the same level as in 2000. From 2004 to 2006, their increase gradually slowed and leveled off. Though there was only 0.5 percent increase in total scheduled flights from 2004 to 2005 and almost no increase from 2005 to 2006, total enplanements was increased by 4 percent and 2 percent during the same time periods. This can be explained with high load factors: according to the Bureau of Transportation, average load factors for these years were 71 percent in 2000, 69 percent in 2002 and 2003, 73 percent in 2004, 76 percent in 2005 and 80 percent in 2006.
Passenger performance is more sensitive to subtle changes in flight operations. Figure 3.12 illustrates the NAS-wide total EPTD from 2000 to 2006. The percentage changes of EPTD from 2004 to 2005 is 17 percent given only 0.5 percent change in scheduled flights and 4 percent change in total enplanements.

![Annual Scheduled Flights and Enplanements](image)

Figure 3.11: Annual Total Scheduled Flights and Enplanements from Year 2000 to Year 2006)

The strong impact of cancelled flights on total EPTD is clearly evident. Cancelled flights only account for approximately 1.4 percent (except for 2000) and generated
40 percent of total EPTD. In 2000, the cancellation rate was as high as 3.6 percent, which resulted in 60 percent (111 million hours) of total EPTD due to cancelled flights. From 2004 to 2006, the percentages of delayed flights and cancelled flights were fixed to 21 percent and 1.4 percent respectively. Thus the ratio of total EPTD due to delayed flights and total EPTD due to cancelled flights remained at the same level of 60%:40%. But the total EPTD increased slowly and steadily from 86 million hours in 2003 to 108 million hours in 2006.

Figure 3.12: Trend Analysis for Total Estimated Passenger Trip Delay (2000-2006)

The distribution of passenger trip delay is heavily skewed. 1.4 percent passengers shared 40 percent of total EPTD, and experienced an average delay of 607 minutes in 2006. Figure 3.13 depicts the average flight delay, average passenger trip delay due to delayed flights and average passenger trip delay due to cancelled flights.

Average flight delay is a widely used metric to reflect the degree of delay. But it
cannot fully explain the asymmetric distribution of passenger trip delay. Passengers scheduled on cancelled flights experienced an average delay of 607 minutes in 2006, whereas the average flight delay for 2006 was only 9 minutes. On average, the average EPTD due to delayed flights is 6 times more than the average flight delay, and the average EPTD due to cancelled flights is 60 times more than the average flight delay.

Figure 3.13: Trend Analysis for Average Estimated Passenger Trip Delay (2000–2006)

Overall, traffic demand has returned and exceeded the level in 2000. But the growth has decelerated since 2004 and leveled off in 2006. Though the demand maintains an even level in 2006, higher load factor leads to positive increments in both enplanements and EPTD.
3.3.3 Asymmetric Performance of EPTD

The asymmetric performance occurs in passengers in terms of routes, airports, and time of year.

EPTD By Month

Figure 3.14 shows the EPTD for each month in year 2006. The highest ranked five months, December, July, June, February and October, account for 51 percent of the EPTD: December accounts for 13 percent of the EPTD. July accounts for 11 percent, June accounts for 10 percent, February accounts for 9 percent and October accounts for 8 percent of the EPTD. The lowest ranked two months, April and January, account for only 6 percent of the EPTD each.

Figure 3.14: EPTD by Month: Five months of the year account for 51% of the EPTD in 2006
Within the 51 percent of the EPTD generated in the five highest ranked months, 56 percent ascribes to delayed flights and another 44 percent ascribes to cancelled flights, while the annual breakdown between EPTD for delayed and cancelled flights is 61%: 39%. This indicates the weights for cancelled flights in these five months is “above average.” The rank order of month is not always the same for every year. In general, months in high season (December, June, July and August) have higher ranks than others.

Figure 3.15 plots both the number of cancelled flights and the EPTD caused by these cancelled flights. The ranked histogram represents the monthly EPTD due to cancelled flights, and the curve plots the number of cancelled flights in each month.

![Figure 3.15: # of Cancellations by Month: Four months of the year account for 50% of EPTD due to cancelled flights in 2006](image)

The ranking of months by EPTD due to cancelled flights results in a different
sequence than the ranking of months by number of cancelled flights. In particular, January, despite being ranked 10th by EPTD is ranked 6th by the number of cancelled flights. This may be a reflection of time of day and the distribution of the cancellations (e.g. early morning cancellations, or more scattered distributed cancellation allows passengers to be re-booked more easily and accrue less EPTD). Cancelled passengers in January experienced a relatively lower average delay since total EPTD in January was “below expectation” and the number of cancelled flights was “above expectation.” On the contrary, passengers in March experienced a relatively higher average delay than others.

As mentioned before, number of cancellations is not a good surrogate for passenger delays due to cancellations. Passenger delays caused by cancelled flights can be affected by many factors, such as flight frequency, time of the day, load factor, aircraft size, etc. More cancelled flights do not necessarily mean more EPTD due to cancelled flights.

**EPTD By Route**

Figure 3.16 shows the 1030 routes between OEP-35 airports ranked by EPTD in 2006. Fifty percent of the annual EPTD can be attributed to EPTD on 17 percent of the routes. This illustrates the significantly higher number of trip delays absorbed by less than 1/5 of the routes.
Figure 3.16: EPTD by Route: Fifty Percent of the Annual EPTD is Generated by 17% of the 1030 Routes between OEP-35 airports

Total EPTD for each route is normalized by total number of disrupted (delayed and cancelled) passengers to estimate EPTD for disrupted passengers. Figure 3.17 illustrates the histogram of average EPTD for the 1030 routes in 2006.

One of the interesting findings is the high average EPTD for short-haul flights between the New York metropolitan area (JFK, LGA and EWR), the Washington D.C. metropolitan area (IAD, DCA, BWI) and the Philadelphia metropolitan area (PHL). This may be a reflection of a high cancellation rate on these routes. The top 10 routes with highest average EPTD are: EWR-PHL, PHL-EWR, BWI-JFK, JFK-BWI, JFK-CLE, EWR-IAD, PHL-IAD, BWI-EWR, IAD-CVG, and JFK-ORD.
EPTD By Airport

Figure 3.18 shows the OEP-35 airports ranked by EPTD in 2006. Fifty percent of the annual EPTD were generated by the top nine airports. The EPTD by airport is spread more evenly than the EPTD by routes, but still impacts some airports significantly more than others (e.g. ORD, ATL, DEN, EWR and LGA).

The total EPTD by airport is normalized by total number of disrupted passengers to estimate average EPTD for disrupted passengers. Figure 3.19 illustrates the histogram of average EPTD for OEP35 airports in 2006. The top six airports with average EPTD more than 100 minutes are ORD, CVG, IAD, DEN and LGA.
Figure 3.18: EPTD by Airport (Destination): Fifty Percent of the Annual EPTD is Generated by the Top 9 OEP-35 Airports

Rank of airports by average EPTD results in a different sequence than the rank of airports by total EPTD. In particular, Atlanta Hartsfield-Jackson (ATL) International Airport, despite being ranked second by total EPTD, is ranked 19th by average EPTD. That means the large amount of total EPTD at ATL is mainly caused by high passenger throughput instead of heavily delayed passengers. On the contrary, Washington-Dallas airport is ranked 19th by total EPTD, but ranked third by average EPTD. This indicates disrupted passengers at Washington-Dallas airport experienced a very high average delay, though the airport is relatively small with fewer total enplanements.
3.3.4 Heavily Skewed Distribution of EPTD

A statistical comparison of the distributions of on-time percentage and delay magnitude for flights and passenger trips is performed in this subsection (Wang et al., 2007 B). The underlying behavior of flight delays and passenger trip delays are represented by the right-tailed distribution in Figure 3.20. There are three pairs of parameters used to characterize the delays:

1. Percentage of flights (or passengers) that arrive within 15 minutes of scheduled arrival time \((-\infty, 15]\) (see (1) in Figure 3.20).

2. Average delay for flights (or passengers) that arrive within 15 minutes of scheduled arrival time. Here the author assumes all on-time flights (or passengers) have a zero-minute delay (see (2) in Figure 3.20).
3. Percentage of flights (or passengers) that arrive after 15 minutes of scheduled arrival time, but less than the time associated with 95th percentile delays (see (3) in Figure 3.20).

4. Average delay for flights (or passengers) that arrive after 15 minutes of scheduled arrival time, but less than the time associated with 95th percentile delays (see (4) in Figure 3.20).

5. Five percent of flights (or passengers) that arrive after the 95th percentile delays (see (5) in Figure 3.20).
6. Average delay for flights (or passengers) that arrive after the 95th percentile delays (see (6) in Figure 3.20).

Passenger trip delays include the delays experienced by passengers due to delayed flight, plus the delays accrued by waiting to be re-booked on a later flight when a flight is cancelled. As a consequence, the distribution for passenger trip delays exhibits a longer right tail. The question that is being resolved by this paper is: “Is the magnitude of the right tail for passenger trip delay statistically significant when compared to the right tail of flight delays?”

Calculating Flight Delay Parameters

- “15-OTP On-Time Flights Percentage”
  For each route, the number of on-time flights (with less than 15 minutes) is summed. This total is divided by the total number of scheduled flights on that route yielding the 15-OTP On-Time Percentage of Flights for the route.

- “Average Magnitude of Flight Delays”
  For each route, the flight delays for delayed flights (with flight delay more than 15 minutes) are summed. This total is divided by the total number of delayed flights on that route yielding the Average Magnitude of Flight Delays for the route.

- “Average Worst-Case Magnitude of Flight Delays”
  For each route, the top 5% flights with the largest flight delay are derived. Their flight delays are summed. This total is divided by the total number of these top 5% flights yielding the Average Magnitude of Flight Delays for the route.
Calculate Passenger Delay Parameters

- “15-POTP Passenger On-Time Percentage”
  For each route, the number of passengers that are schedule on on-time flights (with flight delay less than 15 minutes) is summed. This total is divided by the total number of passengers on that route yielding the 15-POTP On-Time Percentage for Passenger for the route.

- “Average Magnitude of Passenger Trip Delays”
  For each route, the TPTP is first calculated, and then divided by the total number of disrupted passengers (with PaxDelay more than 15 minutes) on that route yielding the Average Magnitude of Passenger Trip Delays for the route.

- “Average Worst-Case Magnitude of Passenger Trip Delays”
  For each route, the top 5 percent passengers with the largest passenger trip delay are derived. Their passenger trip delays are summed. This total is divided by the total number of the top 5 percent passengers yielding the Average Magnitude of Passenger Trip Delays for the route.

Figure 3.21 provides a sample of Flight Delay statistics and Passenger Trip Delay statistics generated by this analysis. By examination, 15-OTP and 15-POTP exhibit similarity, but the distinction between the two sets of Flight Avg. Magnitude and Passenger Average Magnitude are clearly evident.
First Pair of Parameters: 15-OTP v.s. 15-POTP

Figure 3.22 shows the histograms of Flight On-time Percentage and Passenger On-Time Percentage. The 15-OTP and 15-POTP distributions exhibit similarities. Among the 1030 routes, routes with the worst on-time percentages are EWR-PHL(47%), JFK-CLT(48%), JFK-ORD(50%), PHL-EWR(53%) and JFK-DFW(55%). Overall, the NAS has 77% of on-time flights with standard deviation equals to 7%.
Second Pair of Parameters: Average Magnitude of Flight Delay v.s. Average Magnitude of PaxDelay

Figure 3.23 shows the histograms of Average Magnitude of Flight Delays and the Average Magnitude of Passenger Trip Delays. In 2005, the average delay across all flights was 8 minutes. The average delay for those flights with delays in excess of 15 minutes on the OEP-35 routes ranged from 29 minutes (Salt Lake City - Washington National) to 122 minutes (Honolulu - Minneapolis) with an average of 55 minutes. The worst 5% delays ranged from 28 minutes (Portland - Chicago Midway) to 301 minutes (Honolulu - Minneapolis) with an average delay of 118 minutes.

The Average Magnitude for passenger trip delays exhibits a heavier right tail and larger mean than the Average Magnitude for flight delays ($\delta\sigma = 34$ min and $\delta\mu = 21$)
This divergence is caused by cancelled flights. The top 7 routes with largest Average Magnitude of Passenger Trip Delay are BWI-PIT (203min), CVG-MDW (258min), EWR-PHL (238min), JFK-PHL (253min), MDW-CVG (256min), PHL-EWR (298min), and PHL-JFK (209min). Many of these routes are short-haul routes serving shuttle flights with high frequency, small aircraft size, and high cancellation rate. The high cancellation rate results in large passenger trip delays.

Figure 3.23: Histograms of Average Magnitude of Flight Delays and Average Magnitude of Passenger Trip Delays
Third Pair of Parameters: Average Worst-Case Magnitude of Flight Delay v.s. Average Worst-Case Magnitude of PaxDelay

Figure 3.24 illustrates the distributions of the Average Worst-case Magnitude of Flight Delays and the Average Worst-case Magnitude of Passenger Trip Delays. The worst 5 percent of the delays are generally very large flight delays and delays caused by cancelled flights.

![Figure 3.24: Histograms of Average Worst-Case Magnitude of Flight Delays and Average Worst-Case Magnitude of Passenger Trip Delays](image)

The worst 5 percent of the flight delays have an average delay of 118 minutes with standard deviation equal to 32 minutes. When the impact of cancelled flights is counted, both mean and standard deviation of the passenger trip delays grow to 268 minutes and 136 minutes. Short-haul routes exhibited the worst passenger trip delays.
Statistical Comparison Between the Three Pairs of Parameters

Table 3.4 summarizes the statistics over all 1030 routes formed by OEP-35 airports. By inspection of the table, percentage of on-time flights is similar to the percentage on-time passengers. The mean of the average delay for flights delayed in excess of 15 minutes is 34 minutes lower than the mean of the average delay for passenger trips. The average worst-case flights delays in excess of the 95th percentile is 150 minutes lower than average worst-case passenger delays in excess of the 95th percentile.

Table 3.4: Comparison of Statistics for Distribution of Flight Delays and Distribution of Passenger Trip Delays

<table>
<thead>
<tr>
<th></th>
<th>Percentage On-Time</th>
<th>Mean Average Magnitude of Delays</th>
<th>Mean Average Worst-Case Magnitude of Delays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15-OTP</td>
<td>15-POTP</td>
<td>Flights</td>
</tr>
<tr>
<td>Average</td>
<td>0.7729</td>
<td>0.7726</td>
<td>53</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.072</td>
<td>0.073</td>
<td>9.1</td>
</tr>
<tr>
<td>The worst 5% (excess 95 percentile)</td>
<td>0.977</td>
<td>0.877</td>
<td>68</td>
</tr>
</tbody>
</table>

Paired t-tests and $\chi^2$ tests are performed on the above three sets of Flight Delay and Passenger Trip Delay metrics. A paired t-test of percentage on-time across all routes can not reject the null hypothesis that Passenger On-Time Percentage has the
same distribution mean as Flight On-Time Percentage (P-value 0.1858, 95% confidence interval -0.000015, 0.0008). The test cannot reject the null hypothesis that the Passenger On-Time Percentage and Flight On-Time Percentage have equal variance (P-value 0.5618). The scattered plot shows a highly linear relationship (R² = 0.99) between Passenger On-Time Percentage and Flight On-Time Percentage. Altogether, there is no significant evidence to claim the hypothesis that the distribution of Flight On-Time Percentage is different to the distribution as Passenger On-Time Percentage. A paired t-test cannot reject the null hypothesis that the distribution mean of the “Average Magnitude of Passenger Trip Delays” is 34 minutes in excess of the distribution mean of the “Average Magnitude of Flight Delays” (P-value 0.9985, 95% confidence interval -1.633, 1.6304). A paired t-test can not reject the null hypothesis that the distribution mean of “Average Worst-Case Magnitude of Passenger Trip Delays” is 150 minutes in excess of the distribution mean of “Average Worst-Case Magnitude of Flight Delays” (P-value 0.9704, 95% confidence interval -7.545, 7.2642). \( \chi^2 \) tests do reject the hypothesis that both of the above two distributions (Average Magnitude of Delays, and Average Worst-Case Magnitude of Delays) have equal variance. Both p-values are less than 0.001. The distributions of 15-POTP “Magnitude of Delay” metrics are significantly wider than the distributions of 15-OTP “Magnitude of Delay” metrics The results of the t-tests and \( \chi^2 \) tests quantify the non-negligible difference in the magnitude of delays experienced by passengers.

Overall, the statistical results above conclude that the Flight Delays do not represent a fair description of the performance of Passenger Trip Delays between OEP-35 airports. The passenger trip delays in excess of the flight delays are not negligible. With an average of 34 minutes difference between average delays across all routes and
2.5 hours difference between the average worst-case delays, the passenger trip delays affect passenger connections to other flights as well as other modes of transportation. These results have significant implications for the way passengers think about air transportation and flight choice, and the way consumer protection of airline travelers is provided.

**Integrating Probability of Delay with Magnitude of Delay**

Passenger choices of flights from and to large metropolitan areas have expanded over the past decade to include choice of departure and arrival airport. For example, Boston, New York, Washington D.C., San Francisco, Los Angeles, and South Florida are all serviced by multiple airports. The choice of airport pairs provides the passenger with an additional degree of freedom in selecting flights. 15-POTP for routes between the Washington, D.C. and Chicago are shown in Table 3.5. The most reliable routes are ranked by Passenger On-Time Percentage (i.e. 15-POTP). But the routes with the least passenger trip delay are ranked by average magnitude of passenger trip delay.

Figure 3.25 plots the statistics in Table 3.5 in two charts. The chart area is divided into four blocks. Routes in the upper-left block are the most reliable routes that have high passenger on-time percentage and low average magnitude of passenger trip delays. The highest reliability route is DCA to MDW with a 14 percent differential over routes departing IAD for either ORD or MDW, and 10 percent differential for flights on the BWI to MDW route. Risk-averse passengers with scheduled connecting time less than 1.5 hours might prefer the second reliable route BWI-MDW, since it has the lowest Magnitude of Passenger Trip Delays.
Table 3.5: Example of Using 15-POTP for Purchasing Airline Tickets

<table>
<thead>
<tr>
<th>Ranks</th>
<th>Origin</th>
<th>Dest</th>
<th><strong>15-POTP</strong></th>
<th>Avg. Magnitude of PaxDelay</th>
<th>Average Magnitude of PaxDelay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DCA</td>
<td>MDW</td>
<td>92%</td>
<td>120</td>
<td>171</td>
</tr>
<tr>
<td>2</td>
<td>BWI</td>
<td>MDW</td>
<td>82%</td>
<td>67</td>
<td>147</td>
</tr>
<tr>
<td>2</td>
<td>BWI</td>
<td>ORD</td>
<td>82%</td>
<td>102</td>
<td>295</td>
</tr>
<tr>
<td>4</td>
<td>DCA</td>
<td>ORD</td>
<td>80%</td>
<td>123</td>
<td>364</td>
</tr>
<tr>
<td>5</td>
<td>IAD</td>
<td>ORD</td>
<td>78%</td>
<td>103</td>
<td>342</td>
</tr>
<tr>
<td>6</td>
<td>IAD</td>
<td>MDW</td>
<td>76%</td>
<td>152</td>
<td>565</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ranks</th>
<th>Origin</th>
<th>Dest</th>
<th><strong>15-POTP</strong></th>
<th>Avg. Magnitude of PaxDelay</th>
<th>Average Worst-Case Magnitude of PaxDelay</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BWI</td>
<td>MDW</td>
<td>82%</td>
<td>67</td>
<td>147</td>
</tr>
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<td>BWI</td>
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<td>295</td>
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<tr>
<td>3</td>
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<td>ORD</td>
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<tr>
<td>6</td>
<td>IAD</td>
<td>MDW</td>
<td>76%</td>
<td>152</td>
<td>565</td>
</tr>
</tbody>
</table>

Figure 3.25: Plots of Reliability of Routes Between Washington D.C. and Chicago
3.3.5 ATNAT Tool

Transportation systems are commonly represented using networks as an analogy for their structure and flows. The Air Transportation Network physically consists of airports (nodes) and routes (arcs). These airports and routes are NOT homogeneous. They have specific behavior patterns that form the network properties. Moreover, EPTD has asymmetric performance for different airports and routes. Some simple strategies can be used by passengers to avoid high risk of delay, such as choosing a different departure time, airport or airline. An example is given in the previous section (Table 3.5 and Figure 3.25).

The Air Transportation Network Analysis Tool (ATNAT) is designed to provide a single source of statistical information about the performance of the routes, airports and airlines in the Air Transportation Network in 2004. It supports informed decisions of passengers by helping them better understand the historical performance of the route/airline combination.

Airports and Airlines Included

See Table 3.6.

Combinations of Information

By default, information is displayed as a daily average per O+D/airline combination (Figure 3.26). The number of days in the data set is displayed at the top-left corner of the table. This top-left designator will be referred to as the “subset identifier.”
Table 3.6: Airports and Airlines Included in the ATNAT Tool

<table>
<thead>
<tr>
<th>Airport</th>
<th>Airline</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATL</td>
<td>American (AA)</td>
</tr>
<tr>
<td>BOS</td>
<td>Alaska (AS)</td>
</tr>
<tr>
<td>BWI</td>
<td>JetBlue (B6)</td>
</tr>
<tr>
<td>CLE</td>
<td>Continental (CO)</td>
</tr>
<tr>
<td>CLT</td>
<td>Independence (DH)</td>
</tr>
<tr>
<td>CVG</td>
<td>Delta (DL)</td>
</tr>
<tr>
<td>DCA</td>
<td>Atlantic Southeast (EV)</td>
</tr>
<tr>
<td>DEN</td>
<td>Airtran (FL)</td>
</tr>
<tr>
<td>DFW</td>
<td>Hawaiian (HA)</td>
</tr>
<tr>
<td>DTW</td>
<td>America West (HP)</td>
</tr>
<tr>
<td>EWR</td>
<td>American Eagle (MQ)</td>
</tr>
<tr>
<td>FLL</td>
<td>Northwest (NW)</td>
</tr>
<tr>
<td>HNL</td>
<td>Comair (OH)</td>
</tr>
<tr>
<td>IAD</td>
<td>Skywest (OO)</td>
</tr>
<tr>
<td>IAH</td>
<td>Express Jet (RU)</td>
</tr>
<tr>
<td>JFK</td>
<td>ATA (TZ)</td>
</tr>
<tr>
<td>LAS</td>
<td>United (UA)</td>
</tr>
<tr>
<td>LAX</td>
<td>US Airways (US)</td>
</tr>
<tr>
<td>LGA</td>
<td>Southwest (WN)</td>
</tr>
</tbody>
</table>

Rank is based on the magnitude of the value (not the benefit/cost) for all O+D’s. In other words, the largest figure of on-time performance will be ranked first as well as the largest number of disrupted passengers per day. The subset identifier and rank profile changes based on the selections by the user. Figure 3.27 indicates the different selections and their respective impact.
Figure 3.26: The Air Transportation Network Analysis Tool (ATNAT)

Figure 3.27: Combinations of Inputs and Outputs for ATNAT
**Example**

Route DFW-ATL and Route MSP-ORD share many operational similarities. As shown in Figure 3.28, they both have four airlines operation on the routes. They operated on average 30 flights per day (2-1), eight of them were delayed (2-3). On both routes, 72 percent of passengers arrived on-time (1-1). However, route DFW-ATL had larger aircraft (3-1), higher load factors (3-2 and 3-3), and less cancellation (2-2) than the MSP-ORD route. These three factors are critical to determine the delays on passenger trip. Divergence between these two routes in the “passenger experience” category is clearly evident. More passengers were transferred and more passenger delays were generated on route DFW-ATL, because it has larger aircraft and higher load factors. But when passenger delay is normalized by enplanement, route MSP-ORD has higher “expected individual passenger delay” (26 minutes per enplanement) than route DFW-ATL (18 minutes per enplanement). Fourteen percent of passengers on route MSP-ORD experienced delays of more than one hour, while only 9 percent experienced delays on route DFW-ATL.
Figure 3.28: Statistic Parts of GUI for Routes DFW-ATL and MSP-ORD
Figure 3.29 shows the graphic illustration part of the ATNAT tool for both routes. The upper two graphs notify users of the likelihood that they would be delayed on each route. For example, on route DFW-ATL, 9.7 percent of passengers were delayed by 15-30 minutes, 8.8 percent of them were delayed by 30-60 minutes, and 5.8 percent of them were delayed by one to two hours. The yellow bar represents the passenger delay proportion caused by cancelled flights. Passengers on route DFW-ATL are more likely to encounter short delays while passengers on route MSP-ORD have higher risk of long delays. The two lower graphs illustrate the passenger risk of encountering long delays (more than one hour) in terms of scheduled departure time. According to the graphs, passengers on both routes should avoid booking flights scheduled to depart
between 4:00 p.m. and 8:00 p.m., since this time period has the highest delay risk. Particularly for connecting passengers, who depend more on on-time performance, it is suggested to choose flights scheduled to depart before noon (5:00 a.m. - 12:00 p.m.) on route DFW-ATL and flights scheduled to depart either early in the morning or at late night on route MSP-ORD.

The above example illustrates the statistics in “Passenger Experience”, “Flight On Route” and “Market Characteristics” categories in terms of route. The ATNAT tool can also be used to analyze the performance of airports or airlines. Possible combinations of inputs and corresponding outputs are listed in Figure 3.27.

### 3.4 Validation

Algorithms and database are validated with Bratu and Barnhart’s results based on actual airline proprietary data (Bratu, 2003). The same experimental environment in Bratu’s thesis is built for validation purpose:

1. Modify EPTD algorithm according to Bratu and Barnhart’s assumptions, such as discarding passengers with PaxDelay more than 15 hours.


3. Apply the modified EPTD algorithm on the collected flight data.

Average passenger trip delays estimated by EPTD algorithm is 290 minutes for both cancelled and miss-connection passengers. Compared with Bratu’s estimation of 303 minutes, results from EPTD algorithm are more conservative but with acceptable range.
Chapter 4: Passenger Flow Simulation (Methods and Results)

In the previous chapter, algorithms and databases were developed to achieve the “historical analysis” of the passenger trip experience, and to understand the correlations between the delay performance of the vehicle tier and the passenger tier of the ATS. The historical analysis cannot be used to predict the impact of future policy changes on passenger trip time. Also, the algorithms do not include the passenger trip delay caused by missed connections.

In this section, a stochastic passenger-based simulation model is built to capture the impact of missed connections on passenger trips and evaluate the system performance outside the range of historical data. The “historical analysis” provides unique route and airport properties (e.g. distributions of taxi-in time, taxi-out time and air time) for the passenger flow simulation (PFS). PFS simulates passenger flow through the network and predicts impacts on passenger performance given changes in system design, rules and performance. Experiments are performed to identify significant factors affecting passenger performance.
4.1 The Underlying Concept

Air transportation simulations of flight movement do not capture the passenger flow and connecting process. In the Air Transportation Network, passengers cluster together into groups to fly from one airport to another. After arriving at the destination airport, this group of passengers break up: nonstop passengers make connections to ground transportation, and connecting passengers continue their trips by re-clustering with other passengers. As illustrated in Figure 4.1, the re-clustered passenger group consists of both local passenger who just entered the system, and connecting passengers who came from other origin airports.

![Figure 4.1: Underlying Concepts for Passenger Flow Simulation Model](image)

The passenger flow simulation (PFS) model is built to simulate the dynamical clustering and scattering process of passenger flow in the ATS. Compared with the
flight-based simulation model, PFS:

- Converts flight unit to a passenger unit,

- Converts flight information, such as arrival time, departure time, Origin-Destination pair, etc., into attributes of passenger,

- Converts flight schedule into clustering and scattering rules followed by passengers.

In summary, this idea converts the “flight” concept into the “passenger” concept.

### 4.2 Petri Net Modeling Tool

A Petri Net is a graphical and mathematical modeling tool. It is well-suited to model a public transportation network because it is designed to model the asynchronous behavior of the different transport modes and the synchronization between buses, trains, subways and passengers when a set of passengers gets on or gets off a mode of transport (Castelain and Mesghouni, 2002). Petri Nets have been used to model the passenger connecting process in the public bus transportation system (Turki et al., 2002), (Turki et al., 2003), (Castelain and Mesghouni, 2002).

For an accurate modeling of a complex transportation system like the air transportation system, a more complicated extension of Petri Net is required. In this dissertation, a hierarchical, timed, colored petri net (CPN) is built in “CPN Tools” to simulate passenger flow and connecting process in the air transportation network. “CPN Tools” is a Graphic User Interface (GUI) tool for editing, simulating and analyzing Colored Petri Nets. Detailed information information of CPN Tools is available on [http://wiki.daimi.au.dk/cpntools/cpntools.wiki](http://wiki.daimi.au.dk/cpntools/cpntools.wiki)
CPN Tools can model the complex level of interactions in the ATS visually by creating nodes, transitions and arcs in the model environment. This visual modeling environment allows people to track and understand the behavior of each passenger easily. In addition, the object-oriented properties and the hierarchical structure that can be achieved in CPN Tools simplify the model structure. They allow the user to clone nets without re-building the whole net.

For the purpose of this research, there are three more reasons to choose colored petri nets:

1. It can present the idea of passenger clustering and scattering through the network by using “colored tokens” to represent different groups of passengers.

2. It can differentiate routes and passengers, and identify the distinct properties of each arc and node that compose the network by defining CPN attributes, guard function, arc expression, etc.

3. It can update policies, options and strategies fairly easily by changing arc functions and guard functions in the model.

More detailed introductions on Petri Nets, Colored Petri Nets, Hierarchical Petri Nets, and Timed Petri Nets are available in Chapter 2.3.1.

4.3 Structure of Passenger Flow Simulation (PFS)

The Operational Evolution Plan (OEP) 35 airports are the nation’s busiest airports defined by the FAA (FAA, 2004). They have the greatest number of operations and account for 73 percent of total enplanements and 69 percent of total operations
in the air transportation system (Bhadra and Texter, 2005). The Passenger Flow Simulation (PFS) is a closed network formed by 34 of the OEP-35 airports. Honolulu International Airport (HNL) is excluded due to its geographic location and negligible impact on the network.

4.3.1 PFS Overview

Table 4.1 lists overview statistics for the Passenger Flow Simulation (PFS) model:

<table>
<thead>
<tr>
<th>Airports</th>
<th>OEP-34 Airports (excluding HNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routes</td>
<td>1,030 routes formed by OEP34 airports</td>
</tr>
<tr>
<td>Major Carriers</td>
<td>17 major carriers</td>
</tr>
<tr>
<td>Daily Flights</td>
<td>8,500</td>
</tr>
<tr>
<td>Daily Enplanements</td>
<td>900,000</td>
</tr>
<tr>
<td>PFS Mode</td>
<td>Deterministic PFS and Stochastic PFS</td>
</tr>
<tr>
<td>Hierarchy</td>
<td>3-Level</td>
</tr>
<tr>
<td>Places</td>
<td>580</td>
</tr>
<tr>
<td>Transitions</td>
<td>343</td>
</tr>
<tr>
<td>Initial Tokens</td>
<td>20,000</td>
</tr>
<tr>
<td>Functions</td>
<td>42</td>
</tr>
</tbody>
</table>

4.3.2 PFS Color Definition

The concept of “color” distinguishes tokens (or resources) in the net. “PaxGroup” is defined as a color in PFS:
Color: \( PaxGroup = (Origin) \times (Dest) \times (# \text{ of Pax Loaded}) \times (AircraftSize) \times (SchDepTime) \times (SchArrTime) \times (Carrier) \times (FlightIndex) \times (# \text{ of Local Pax}) \) timed;

Figure 4.2 illustrates an example of the passenger boarding process. The PaxGroup (DCA, ORD, 185, 200, 730, 850, 13, 45, 165)@+ 750 means 185 passengers are loaded on an aircraft with 200 seats to fly from Washington-National (DCA) Airport to Chicago O’Hare (ORD) Airport. This flight was scheduled to depart on system time 730, and arrive on system time 850. But it actually departed on system time 750, 20 minutes later than scheduled. The flight is operated by United Airlines, with flight index 45. Within the 180 loaded passengers, 165 are local passengers whose itinerary destination is ORD.

Two groups of connecting passengers are supposed to be loaded on flight 45. The first group with 20 connecting passengers successfully boarded, because they arrived
at the boarding gate before the actual departure time of flight 45. But the second


group of 15 passengers arrive at the boarding gate at system time 770, which is 20

minutes later than the departure of flight at system time 750. This group of 15

passengers are “missed-connection passengers” in the system.

4.3.3 PFS Declaration

The PFS declaration includes definitions of functions, color, variables, values and

output files. All of these are listed in Appendix D.

4.3.4 PFS Hierarchy

The passenger flow simulation model has three levels as illustrated in Figure 4.3.

Airport and en route subnets are represented as substitute transitions in the top-level

page of PFS. Detailed explanation and zoom-in figures of top-level, second-level and

the third-level nets are available in the subsequent subsections.
4.3.5 PFS Top Level Net

The top-level page of PFS is illustrated in Figure 4.4. It depicts 34-airport substitute transitions, a single en route substitute transition, and the 68 ports connecting them. A zoom-in figure of Washington-National (DCA) airport shows an aggregated departure gate and an aggregated arrival gate for each airport. An airport substitution transition is directionally connected to/from route substitution transition through two ports: one represents arrival gate and the other represents departure gate.
The “air-side” gate-to-gate transportation of passengers is accomplished by flowing sequence departure gate → en route → arrival gate. Joining the process of connecting passengers happens within the airport substitution transition which belongs to level two and cannot be observed from the top-level page.

Figure 4.4: Top Level Page for 34-Airport PFS
4.3.6 PFS En route Subnet (2nd Level)

Figure 4.5 gives an example of a single route substitution transition (ATL-LGA). En route is an air-side gate-to-gate process. Four time points, out-of-the-gate, off-the-ground, on-the-ground and into-the-gate, referred to in the industry as “OOOI”, can be used to describe the en route process.

![Diagram of Enroute Subnet for a Single Route (ATL-LGA) for 4-Airport PFS](image)

Figure 4.5: Enroute Subnet for a Single Route (ATL-LGA) for 4-Airport PFS

The time difference spent on the taxiway between “out-of-the-gate” time point to “off-the-ground” time point is defined as taxi-out-time (or transition time for “Taxi-Out Process”). Similarly, the time difference spend on the taxiway between “on-the-ground” time point to “into-the-gate” time point is defined as taxi-in-time (or transition time for “Taxi-In Process”). “Air-time” is the time period after the departure from runway and before the arrival at runway, that is, the time difference between “off-the-ground” and “on-the-ground.” Passengers take off from the departure gate at time “out-of-the-gate,” and are ready to depart on the runway after taxi-out-time. After flying for some time period (air time), passengers arrive at the runway at time
point “on-the-ground,” and arrive at the gate after the taxi-in process. Transitions with “C” on the lower-right corner are transitions with code segments. All the codes written in Standard Meta Language (SML) are provided in Appendix E.

Figure 4.6 depicts the aggregated en route subnet for 1,030 routes formed by the 34 OEP airports in 2006. Instead of having a pair of departure and arrival ports for each route, the PFS has 34 departure ports and 34 arrival ports in total. PFS reads itinerary information from the passenger groups appearing at departing ports, and guides them to the right routes until arriving at the correct arrival ports.
Figure 4.6: Enroute Subnet for 34-Airport PFS
4.3.7 PFS Airport Subnet (2nd Level)

An airport substitution transition is much more complicated than a route substitution transaction. It contains passenger connecting, scattering and re-clustering processes within the boundary of one airport.

Figure 4.7 shows the airport subnet for ORD as an example. In this figure, all the arc expressions and code segments are in hidden status for a clear and clean presentation of the airport subnet structure. Passenger groups (PaxGroup) flow into the airport boundary from arrival gates on the top of Figure 4.7, and flow out of the airport boundary from departing gates on the left side of Figure 4.7. This flowing process is divided into three steps: (1) splitting PaxGroup, (2) re-clustering of PaxGroup and (2) loading PaxGroup. Figure 4.8, Figure 4.9 and Figure 4.10 illustrate the three steps of passenger flow respectively.
Figure 4.7: Airport Subnet (ORD) for 4-Airport PFS

**Step 1: Splitting PaxGroup**

As shown in Figure 4.8, PaxGroup flows into the airport boundary from arrival gates. In this specific example, arrival gates are: place “Arrivals ATL-ORD,” place “Arrivals LGA-ORD” and “Arrivals MEM-ORD.” After arriving at ATL airport, the PaxGroup
splits into two subgroups: “Local Arrivals” and “Connecting Arrivals”. Passengers belonging to “Local Arrivals” end their itineraries at ATL, while passengers belonging to “Connecting Arrivals” continue their itineraries for the second-leg flights from ATL.

“Local Passengers” are passengers whose itineraries end right after the flight arrives at the destination airport. They include not only non-stop passengers, but also connecting passengers whose itinerary destination is the destination airport of the segment flight. “Connecting passengers” are passengers who only stay at the airport for flight connection.

\[\text{Figure 4.8: Step 1: Splitting PaxGroup at ORD airport}\]

The ratio of connecting and local passengers in terms of route are obtained from the DB1B* database. For this specific example shown in Figure 4.8, passengers coming from ATL to ORD consist of 78 percent of the local passengers and 22 percent connecting passengers. This means 78 percent of passengers coming from ATL end their itineraries at ORD. The “airport groups” in DB1B table (see Figure ???) for this
78 percent passengers are either “ATL-ORD,” or “X-ATL-ORD.” Airport X could be any airports except for ATL or ORD. The other 22 percent of passengers are connecting passengers who come from ATL and connect at ORD (ATL-ORD-X).

**Step 2: Re-clustering PaxGroup**

A minimum amount of time, called Minimum Connecting Time (MCT), is required to guarantee a smooth connection of passengers and baggage delivery. Example in Figure 4.9 depicts the process of connecting and re-clustering at ORD.

The minimal connecting time is directly collected from airlines by the Official Airline Guide (OAG). This OAG-collected MCT is essential when constructing air transport schedules, because it is the time required for transferring not only passengers
and also baggage between flights. In general, airlines will schedule sufficient time for passenger and baggage connection. However, the actual time for passengers to walk from one gate to another could be much less than the given connecting time. Here the author assumes the MCT for passengers to walk from one gate to another is half of the MCT collected by the OAG. For example, MCT collected by the OAG for Chicago O’Hare airport (ORD) is 50 minutes, meaning the MCT for connecting passengers at Chicago O’Hare would be 25 minutes.

There are two functions involved in the code segment. One is the function “fun-MCT(airport),” which returns the minimal connecting time required for passengers between gates given connecting airport. The other function is an arc function, which divides a group of connecting passengers into several subgroups and sends them to different gates. For example, Continental Airlines only has connecting flights to Cleveland Hopkins (CLE) Airport, Newark (EWR) Airport and Houston (IAH) Airport connecting at Chicago O’Hare (ORD) Airport. If Continental Airlines has a connecting PaxGroup of 100 people arriving at ORD, 28 of the 100 passengers will go to CLE, 32 passengers will go to EWR airport and 40 passengers will go to IAH. The passenger flow ratio and airport connecting information is obtained from DB1B* data (see Figure ??). Let $P = \text{total number of passengers in format “X-ORD-Y,” and P1 = total number of passenger in format ‘X-ORD-IAH” (airport X and Y could be any airport except ORD). Then ratio P1/P is the proportion of connecting passengers flowing from ORD to IAH.}
Step 3: Loading PaxGroup

Passengers who showed up before the actual departure time will be successfully loaded, while passengers who failed to show up on time have to wait to be re-booked on the next available flight.

As shown in Figure 4.10, places “toATL,” “toLGA” and “toMEM” represent the boarding gates from ORD to ATL, LGA and MEM, respectively. Connection passengers reside in these “gate” places. Substitute transitions such as “Clustering
“Pax at ORD to ATL” are responsible to load connecting passengers on the right flights with local passengers. Flights stop loading passengers when either the departure time is on schedule, or no more seats are available. When the system time reaches the actual departure time of flight, it pushes back from the gate to the taxiway.

The subnet for substitute transition “Cluster Pax at ORD to ATL” will be explained in the next part: Passenger Loading Subnet(3rd Level)

4.3.8 PFS Passenger Loading Subnet(3rd Level)

Passengers coming from socket “toATL” are divided into two groups: (1) general connecting passengers flow to the upper branch, and (2) miss-connection passengers and cancelled passengers flow to the lower branch. The general connecting passengers (upper branch) have higher priority than cancelled or missed-connection passengers (lower branch). Passengers on both branches are sorted into first-come-first-serve airline queues to ensure only passengers belonging to this airline can be loaded on flights operated by this airline. Flights with loaded local passengers reside in place “Local Pax ORD-ATL.” When transition “Load Connecting Pax ORD-ATL” fires, it loads general connecting passengers, and generates a token in place “Ready PaxGroup” representing “ready to depart.” But before it actually departs, the flight checks the airline queue on the lower branch for missed connection or cancelled passengers. If there are missed connection or cancelled passengers waiting to be re-booked, and the flight still has empty seats, it begins loading the re-booked passengers until either no more empty seats are available, or no more re-booked passengers that are available to be re-booked before the departure time of the flights. Note, the underlying rule is, cancelled or missed connection passengers can only be re-booked to flights on the
same route and operated by the same airline as scheduled.

Figure 4.11 shows the third-level subnet of the PFS. It depicts the loading process at the departure gate.
Figure 4.11: Passenger Loading Subnet for Route ORD-ATL
There are three transitions with code segment in Figure 4.11:

- The code segment in the “Adjust” transition ensures that connecting passengers will go to the booked flights instead of jump on any available flight. This is the difference between air transportation and bus transportation. Passengers buy air tickets before the trip, and they have to follow the itinerary unless it is disrupted by overbooking, a cancelled flight, and missing a connection. Passengers in the bus transportation system do not buy tickets until they get on the bus. In other words, they have full control of the itinerary. Connecting passengers in the bus transportation system can get on the next bus going to the same destination. But connecting passengers in the air transportation system have to wait for the connecting flights they booked, even if they arrive at the gate early enough to catch an earlier flight to the same destination.

- the code segment in “Load Conn Pax ORD-ATL” exports connecting information to a txt file named “Connection_Results.” This is part of the PFS outputs.

- the code segment in “Load CancPax & MissConnPax ORD-ATL” exports re-booking information to a txt file named “Rebooking_Results.” This is part of the PFS outputs.

4.3.9 Passenger Missed Connection Algorithm in PFS

Each specially designed experiment has two PFS models: one is called “Base-Scenario,” and another is called “Experimental-Scenario.” “Base-Scenario” simulates passenger flow in an ideal ATS without any disruptions, such as flight delays or flight cancellations. All flights or PaxGroups depart and arrive at the scheduled time. The major
function of this “Base-Scenario” is to estimate passenger connecting information. In other words, the “Base-Scenario” simulates passenger booking process: when passengers purchase air tickets online, they choose connecting flights based on the scheduled flight information: that is, passengers assume an ideal ATS without delay and cancellation.

Figure 4.12 gives an example of purchasing an air ticket online. The itinerary IAD-LAS-SFO in the example is from Washington-Dallas (IAD) airport to San Francisco (SFO) airport, connecting in Las Vegas (LAS) airport.

The first-leg flight from IAD to LAS is scheduled to arrive at 7:13 pm. But there are two options for the second-leg flight. The only difference between option 1 and 2 is the scheduled connecting time. Option 1 has 50 minutes connecting time and option 2 has one hour and 29 minutes connecting time. This author assumes passengers will most likely choose the first option because it is more time-effective than waiting
an additional 39 minutes. Based on this assumption, the ideal scenario is executed, producing the estimated passenger connecting information for all connections in the 34-Airport PFS.

Figure 4.13 illustrates the process of estimating passenger trip delay in PFS. “Base-Scenario” is the ideal scenario of ATS with no disruptions. The passenger connecting information provided by Base-Scenario enables us to conduct research on miss-connection in the “Experimental-Scenario.” The simulation results of Experimental-Scenario estimate EPTD due to delayed flights, cancelled flights, and miss-connections.

Figure 4.13: Estimate Passenger Trip Delay in PFS
4.4 Deterministic Passenger Flow Simulation (PFS)

PFS for the closed network formed by OEP 34 airports has two modes: deterministic and stochastic. They share the same PFS structure, but with different functions and parameter values. The deterministic PFS purely converts the flight performance to passenger performance. The BTS database provides flight on-time performance data, which contains the historical flight performance information such as departure delay and arrival delay. In the deterministic PFS, each flight token departs and arrives at the actual departure and arrival time with actual departure and arrival delay. In the stochastic model, variables such as taxi-in, taxi-out and air-time, are given by normal random number generators with specific means and standard deviations for flights departing from/arriving at different airport, or on the different routes. Thus the flight arrival time (or arrival delay) is no longer deterministic.

Analysis on simulation results of deterministic PFS is described in the following sections.

4.4.1 Simulation Results and Validation: 34-Airport PFS on July 6 2005

July 6, 2005 is a randomly chosen weekday in summer 2005. This author chose summer 2005 over summer 2006 because traffic in summer 2005 was heavier than the traffic in summer 2006. Flight performance on July 6, 2005 is as follows:

- Scheduled Flights = 8,540 flights
- Delayed Flights = 1,764 flights = 21% of Scheduled Flights
- Cancelled Flights = 176 flights = 2% of Scheduled Flights
The “Experimental-Scenario” converts flight performance on July 6, 2005 into the corresponding passenger performance.

As shown in Figure 4.14, 2 percent of cancelled passengers generated 30 percent of total EPTD, 1 percent of missed connection passengers generated 15 percent of total EPTD, and 21 percent of delayed passengers generated 55 percent total EPTD. The 34-airport ATS generated 330,834 hours PaxDelay on July 6, 2005. On average, passengers scheduled on cancelled flights experienced 403 minutes of delay, missed connection passengers experienced 341 minutes of delay, and passengers scheduled
on delayed flights experienced 64 minutes of delay. The simulation results of 34-PFS validate the asymmetric behavior of EPTD once more. Cancelled and miss-connection passengers together only account for 3 percent of total enplanements, but generated 45 percent total EPTD with a high average delay of 382 minutes.

For validation purpose, the total EPTD and average EPTD estimated by EPTD algorithm for July 6, 2005 are compared with these estimated by deterministic PFS. Table 4.2 lists and compares the estimated total and average EPTD by EPTD algorithm and deterministic PFS.

<table>
<thead>
<tr>
<th></th>
<th>Deterministic PFS</th>
<th>EPTD Algorithm</th>
<th>Diff=</th>
<th>EPTD-PFS</th>
<th>/EPTD*100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>309,000 hrs</td>
<td>306,000 hrs</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>88 minutes</td>
<td>90 minutes</td>
<td>2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

“Diff” in Table 4.2 is calculated as: absolute value of (Algorithm - PFS) / Algorithm * 100. The percentages of difference for total and average EPTD between these two estimations are 1 percent and 2 percent respectively.

EPTD algorithm only estimates passenger trip delay due to delayed and cancelled flights. Consequently, the total and average statistics listed in Table 4.2 do not include EPTD due to missed connections. However, the estimated average EPTD due to missed connections can be compared to Bratu and Barnhart’s result of 303 minutes average delay for disrupted passengers. A subject of future work is to validate the EPTD due to missed connections with more airline proprietary itinerary data.
In PFS, total EPTD generated by a delayed flight is adjusted by subtracting the PaxDelay associated with missed-connection passengers who are supposed to be loaded in this flight by not. The 183,000 hours of total EPTD due to delayed flights shown in Figure 4.14 is adjusted by subtracting 28,000 hours of EPTD associated with missed-connection passengers. In Table 4.2, the 28,000 hours of EPTD is added back, because the validation excludes missed-connection passengers. This explains why the total EPTD of 309,000 hours in Table 4.2 is 28,000 hours more than the summation of EPTD due to delayed and cancelled flights in Figure 4.14.

4.4.2 Design of Experiment (DOE)

PFS analyzes the major trends in passenger flow dynamics to identify the critical factors that affect passenger trip time most (such as load factor, distribution of flights, etc.). In addition, specific scenarios can be generated to predict impacts on passenger trip time given anticipated changes in the future.

Purpose of DOE

Experiments are designed for deterministic PFS to:

- Identify and rank order the significant factors that have strong impacts on Passenger Trip Time
- Analyze the sensitivity of PaxDelay given changes in factors

Choice of Initial Significant Factors

Based on the literature (Bratu and Barnhart, 2005), six factors belonging to four categories are chosen as initial significant factors (in Table 4.3):
Table 4.3: Initial Significant Factors and Their Categories

<table>
<thead>
<tr>
<th>Categories</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Factors</td>
<td>(1) # of passengers loaded on a flight</td>
</tr>
<tr>
<td>Seat Factors</td>
<td>(2) Aircraft Size (# of total seats)</td>
</tr>
<tr>
<td>Flight Performance</td>
<td>(3) Flight Cancellation Time</td>
</tr>
<tr>
<td></td>
<td>(4) Flight Delay</td>
</tr>
<tr>
<td>Policy</td>
<td>(5) Airline Cooperation Policy</td>
</tr>
<tr>
<td></td>
<td>(6) Minimal Connecting Time (MCT)</td>
</tr>
</tbody>
</table>

Load factor equals “# of passengers loaded” divided by “aircraft size”. Flight cancellation time indicates the scheduled departure time of cancelled flights. This factor is used to measure the difference between early cancellations and late cancellations. Airline cooperation policy indicates airlines operating on the same route agree to help each other re-book cancelled and missed-connection passengers. In other words, cancelled or missed-connection passengers no longer need to stick with the same airline during the re-book process. Minimal connecting time indicates the average time for connecting passengers walking from one gate to another. This factor represents better terminal structure and more efficient allocation of gates related to EPTD.

**DOE Method**

A full factorial design for six factors assuming a linear response function, needs $2^6=64$ total runs, and each run (or experiment) requires two PFS models (Base Scenario and Experimental Scenario). In total, $64 \times 2 = 128$ PFS models need to be built and
executed for a full factorial design. A single run takes around four minutes of CPU
time on a CORE 2 DUO/2.40GHz/2.0GB RAM computer. But the logical check
time of deterministic PFS (before “ready to run” status of the model) depends on
the size and complexity of the model. In general, it takes 20 minutes for a one-day
PFS. Furthermore, a lot of time is needed to set up inputs and parameters for a PFS.
Concerned about time and computational hardware limitation, a fractional factorial
design is chosen:

- 6 factors
- 2 levels: high and low
- 1/8 fraction
- 8 total runs

The “high (H)” and “low (L)” levels for factors are listed in table 4.4. Note, the
percentage increase or decrease is based on the actual traffic statistics on July 6, 2005.

<table>
<thead>
<tr>
<th>Factors</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td># Passengers Loaded</td>
<td>↑ 5%</td>
<td>↓ 15%</td>
</tr>
<tr>
<td>Aircraft Size</td>
<td>↑ 15%</td>
<td>↓ 5%</td>
</tr>
<tr>
<td>Airline Cooperation Policy</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Flight Delay</td>
<td>+ 15 minutes</td>
<td>- 15 minutes</td>
</tr>
<tr>
<td>Cancellation Time</td>
<td>move cancellation time four hours earlier</td>
<td>maintain the same cancellation time on July 6, 2005</td>
</tr>
<tr>
<td>Minimal Connecting Time</td>
<td>+ 15 minutes</td>
<td>- 15 minutes</td>
</tr>
</tbody>
</table>
The high and low levels of “# of passengers” and “aircraft size” are designed to keep load factor in the range of [61%, 92%]. The highest value of load factor (92%) occurs in experiments with “# pax”=H and “aircraft size”=L, while the lowest value of load factor (61%) occurs in experiment with “# pax”=L and “aircraft size”=H.

The low level of “Flight Delay” is defined according to the flight-based metric OTP-15. OTP-15 defines on-time flights as flights with arrival delay no more than 15 minutes. The low level of flight delay is set to “zero-minute average flight delay.”

The high level of cancellation time is defined as “four hours earlier cancellations”. The time shift of four hours is determined by the earliest hour of day with scheduled flights and when the earliest time flight cancellation happened. The earliest hour with scheduled flights is 6:00 a.m. local time, and the earliest cancelled flight is scheduled to depart at 10:00 a.m. Therefore, a four-hour shift can represent “earlier cancellation” without shifting flights to an unrealistic time period with no flight scheduled.

### 4.4.3 Rank Order Significant Factors

The rank order of significant factors is based on the simulation results of deterministic PFS.

#### Rank Order Significant Factors for NAS-Wide EPTD

The NAS-wide EPTD is the summation of EPTD due to all causes: congestion delayed flights, cancelled flights and missed-connections. Figure 4.15 plots the rank order of factors in terms of the absolute value of coefficients for NAS-wide total EPTD. The relatively significant factors affecting NAS-wide total EPTD are:

- Congestion Flight Delay,
• # of Passengers (or load factor),

• Cancellation Time, and

• Airline Cooperation Policy.

Only one of the top four significant factors, airline cooperation policy, has a positive effect on passenger performance. The other three significant factors have negative effects on passenger performance. Note, positive coefficient indicates positive effect on total EPTD, i.e. negative effect on passenger performance: less total EPTD indicates better passenger performance.
Flight delay ranks first among all six factors, because more than half of the total EPTD are caused primarily by congestion related delayed flights (Wang et al., 2006), (Wang et al., 2007 A), (Wang et al., 2007 B). In addition, part of the EPTD due to missed-connections ascribes to late first-leg flights.

In summary, less flight delay, less passengers (or lower load factor), earlier flight cancellation time and airline cooperation policies can help reduce NAS-wide total EPTD.

**Rank Order Significant Factors for EPTD due to Cancelled Flights**

Detailed analysis in terms of the causes of EPTD shows different behavior of significant factors and their effects. Figure 4.16 plots coefficients for total EPTD due to cancelled flights. The relatively significant factors for total EPTD due to cancelled flights are:

- Airline Cooperation Policy,
- Aircraft Size and # of Passengers (or Load Factor),
- Flight Cancellation Time (i.e. time of day the flight is cancelled, earlier being better)

Airline cooperation policy ranks first among all the six factors. Cooperation between airlines to re-book disrupted passengers gives more flexibility to re-book passengers. Lower load factor benefits in both way: less affected passengers when a flight is cancelled, and more empty seats when rebooking passenger trips. Similarly, earlier flight cancellation has relatively more resource, such as flight frequency and empty
seats, to recover passenger trips.

Figure 4.16: Coefficient Plot for Total EPTD due to Cancelled Flights

\[
\text{Total EPTD} = 62651 - 13099\times \text{Airline Cooper} - 10755\times \text{Size} + 8176\times \text{FL Cancel Time} \\
+ 4929\times \text{Pax} + 1511\times \text{MCT} + 497\times \text{F Delay} - 247\times \text{Pax} \times \text{MCT}
\]

In summary, airline cooperation, lower load factor, and earlier cancellation time can help reduce the total EPTD due to cancelled flights.
Rank Order Significant Factors for EPTD due to Missed-Connections

Figure 4.17 plots coefficients for total EPTD due to missed-connections. The relatively significant factors for total EPTD due to missed-connections are:

- Flight Delay,
- Cancelled Time,
- Minimal Connecting Time

![Coefficient Plot for Total EPTD due to Missed-Connections](image)

Total EPTD = 46658 + 24161*FLDelay + 8780*FLCanciT + 7756*MCT
- 2231*Size - 1879*AirlineCooper - 1791*Pax - 1192*Pax*MCT

Figure 4.17: Coefficient Plot for Total EPTD due to Miss-Connections

Flight delay is a very important factor to determine EPTD due to missed-connections. Connecting passengers are not able to catch the next flights if the delayed time for
the previous flight is too long to be absorbed by connecting buffer. Both missed connection passengers and cancelled passengers are disrupted passengers and need to be re-booked. Cancellation time affects the EPTD due to missed-connections in a negative way: earlier cancellations (high level) relieve the competition of available resources between disrupted passengers, and decrease EPTD. Less required time for passengers walking from one gate to another gives a greater time buffer to absorb delay brought by the first-leg flight.

An interesting observation is that significant factors and rankings for average EPTD (min per passenger) are not necessary the same as those for total EPTD due to missed-connections. Figure 4.18 plots coefficients for average EPTD due to missed-connections. The relatively significant factors for average EPTD due to missed-connections are:

- Airline Cooperation,
- Flight Delay,
- Cancelled Time

Total EPTD is a combined result of the number of missed connection passengers and the average of EPTD due to missed connections. Different factors may have stronger impacts on average EPTD but not on number of passengers. The effect of this factor on total EPTD is then determined by the combined effect from both sides. A good example could be airline cooperation policy. Cooperation between airlines helps in reducing the average EPTD with no doubt. However, it has nothing to do with the number of missed connection passengers.
In summary, airline cooperation, less flight delay, earlier cancellation time and less MCT can help reduce both total EPTD and average EPTD due to missed-connections.

**Rank Order Significant Factors for EPTD due to Delayed Flights**

Figure 4.19 plots coefficients for total EPTD due to delayed flights. The relatively significant factors affecting total EPTD due to delayed flights are:

- Flight Delay,
- # Passengers

This is a straightforward result, since total EPTD due to delayed flights is only affected by flight delays and number of passengers loaded on the delayed flights.
4.4.4 Sensitivity of Factors

To better understand the magnitude of the impacts of factors on EPTD, total EPTD for the following experiments are calculated and compared with the total EPTD on July 6, 2005 (in Table 4.5). Using July 6 as the baseline for vehicle performance, this analysis determines the sensitivity of Total EPTD to changes in each of the factors.

The analysis gives a snapshot of the sensitivity of the factors. Flight delay has been proven to be the most significant factor affecting NAS-wide total EPTD. A 15 minute change in flight delay can decreased the total EPTD by 24 percent and save $2.3 million passenger value of time per day, which will contribute $840 million to annual save. Note, the listed experiments in Table 4.5 rely on changes in a single

\[
\text{Total EPTD} = 208927 + 86932*FL\text{Delay} + 20910*Pax + 8208*Size + \\
5868*\text{AirlineCooper} + 1983*FL\text{CancelTime} - 1622*MCT + \\
717*Pax*MCT
\]

Figure 4.19: Coefficient Plot for Average EPTD due to Delayed Flights
factor. Officials, operators and stakeholders of the ATS shall consider changes in a combination of factors to maximize benefits with relatively low costs for future option design.

Table 4.5: Sensitivity of the Total EPTD (Delay+Cancel+Missed-Connection) to Changes in Factors

<table>
<thead>
<tr>
<th>Changes in Factors</th>
<th>Compared with Total EPTD (320,000 hrs) on July 6, 2005 (with no change in factors)</th>
<th>↓ in Percentage</th>
<th>Total EPTD</th>
<th>Passenger Value of Time Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce flight delay by 15 minutes</td>
<td>↓ by 24%</td>
<td>243,000 hrs</td>
<td>$2.3 million</td>
<td></td>
</tr>
<tr>
<td>Allow airline cooperation</td>
<td>↓ by 12%</td>
<td>283,000 hrs</td>
<td>$1.1 million</td>
<td></td>
</tr>
<tr>
<td>Cancel flights four hours earlier</td>
<td>↓ by 10%</td>
<td>290,000 hrs</td>
<td>$0.9 million</td>
<td></td>
</tr>
<tr>
<td>Reduce load factor to 70%</td>
<td>↓ by 8%</td>
<td>296,000 hrs</td>
<td>$0.7 million</td>
<td></td>
</tr>
</tbody>
</table>

4.5 Stochastic Passenger Flow Simulation (PFS)

Deterministic PFS is introduced in the previous section. It is a pure conversion from vehicle performance to passenger performance, and has been proven to be an accurate conversion within 1% to 2% difference range.

A stochastic PFS is more suitable and valuable for prediction or future option
design evaluation purpose. Stochastic factors, such as air time, taxi-in time and taxi-out time, are set to normal random number generators with different means and standard deviations. Other significant factors, such as aircraft size, number of passengers loaded (or load factor), are represented as variables in the stochastic PFS. Officials, policy makers and researchers can easily change the values of stochastic factors or variables to represent anticipated changes in the future. The stochastic PFS provides a flexible simulation environment to conduct experiments outside the range of historical data.

Note, stochastic and deterministic PFS share the same model structure, but with different settings of functions and parameters.

4.5.1 Stochastic Factors and Variables

The stochastic factors and variables defined in stochastic PFS are listed as follows:

- **Taxi-Out Time:**
  
  **Category:** it is a stochastic factor whose value is given by a normal random number generator, Normal($\mu_i, \sigma_i$), where $i$ represents the deparing airport;
  
  **Example:** taxi-out time for flights departing from ATL fits Normal($\mu=20.7$ min, $\sigma=10.9$ min).
  
  **Potential Usage in Specific Scenario:** New runway, or more efficient service of ATC may decrease mean or standard deviation of taxi-out time.

- **Air Time:**
  
  **Category:** it is a stochastic factor whose value is given by a normal random number generator, Normal($\mu_j, \sigma_j$), where $j$ represents any route.
Example: air time for flights on route ATL to BOS fits Normal(μ=123.3 min, σ=5.6 min).

Potential Usage in Specific Scenario: Usage of new technology or aircrafts may decrease mean or standard deviation of air time.

• Taxi-In Time:

Category: it is a stochastic factor whose value is given by a normal random number generator, Normal(μ_i, σ_i), where i represents arriving airport.

Category: taxi-in time for flights arriving at ATL fits Normal(μ=10.3 min, σ=5.9 min).

Potential Usage in Specific Scenario: Better designed taxi-way may decrease mean or standard deviation of taxi-in time.

• Minimal Connecting Time (MCT):

Category: it is a variable whose value is given by function MCT(connecting airport).

Example: MCT for passengers connecting at BOS is set to be 20 minutes.

Potential Usage in Specific Scenario: More efficient gate and terminal design at an airport may decrease the MCT required for passengers connecting at this airport.

• # of Passengers:

Category: it is represented as variable “pax” in PaxGroup.

Example: PaxGroup 11(“TPA”, “PIT”, 96,137,750,888,14,41661,741,96)@+741 indicates there are 96 passengers loaded on a flight with 137 seats flying from Tampa to Pittsburgh.
Potential Usage in Specific Scenario: Increase the value of “pax” variable for all the PaxGroup coming to a city to represent the increase in passenger demand.

• Aircraft Size:
  
  **Category:** it is represented as variable “size” in PaxGroup.
  
  **Example:** PaxGroup 1′(“TPA”, “PIT”, 96, 137, 750, 888, 14, 41661, 741, 96)@+741 indicates there are 96 passengers loaded on a flight with 137 seats flying from Tampa to Pittsburgh.

  **Potential Usage in Specific Scenario:** Increase the value of “size” variable for all the PaxGroup to/from LGA to represent upgauging aircraft size at LGA.

• Scheduled Departure/Arrival Time:
  
  **Category:** they are represented as variable “schdeptime” and “scharrtime” in PaxGroup respectively.
  
  **Example:** PaxGroup 1′(“TPA”, “PIT”, 96, 137, 750, 888, 14, 41661, 741, 96)@+741 indicates Flight 41661 is scheduled to depart from Tampa at system time 750 and arrive at Pittsburgh at system time 888.

  **Potential Usage in Specific Scenario:** Changes in these two variables represents the time changes in airline schedule.

4.5.2 Simulation Results and Validation: 34-Airport PFS on July 6 2005

The stochastic PFS has been executed 10 times to obtain stochastic simulation results. Table 4.6 lists the estimated total and average EPTD for each run. The average and
standard deviation for “Total EPTD” on July 6, 2005 are 310,425 hours and 934 hours respectively. The average and standard deviation for “Average EPTD” on July 6, 2005 are 99 minutes and 0.8 minute respectively.

Table 4.6: Stochastic Simulation Results of the Stochastic PFS on July 6, 2005

<table>
<thead>
<tr>
<th>Run</th>
<th>Total EPTD (Delay+ Cancel+ MissedConn)</th>
<th>Avg. EPTD (Delay+ Cancel+ MissedConn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>310,013 hrs</td>
<td>100 min</td>
</tr>
<tr>
<td>R2</td>
<td>311,281 hrs</td>
<td>99 min</td>
</tr>
<tr>
<td>R3</td>
<td>310,141 hrs</td>
<td>99 min</td>
</tr>
<tr>
<td>R4</td>
<td>309,945 hrs</td>
<td>98 min</td>
</tr>
<tr>
<td>R5</td>
<td>311,169 hrs</td>
<td>98 min</td>
</tr>
<tr>
<td>R6</td>
<td>309,299 hrs</td>
<td>101 min</td>
</tr>
<tr>
<td>R7</td>
<td>312,310 hrs</td>
<td>98 min</td>
</tr>
<tr>
<td>R8</td>
<td>309,316 hrs</td>
<td>98 min</td>
</tr>
<tr>
<td>R9</td>
<td>310,516 hrs</td>
<td>99 min</td>
</tr>
<tr>
<td>R10</td>
<td>310,258 hrs</td>
<td>99 min</td>
</tr>
<tr>
<td>µ</td>
<td>310,425 hrs</td>
<td>99 min</td>
</tr>
<tr>
<td>σ</td>
<td>934 hrs</td>
<td>0.8 min</td>
</tr>
<tr>
<td>Deterministic PFS</td>
<td>330,834 hrs</td>
<td>103 min</td>
</tr>
<tr>
<td>Diff (Deterministic Stoch)</td>
<td>6%</td>
<td>4%</td>
</tr>
</tbody>
</table>

The average “Total EPTD” and the average “Avg. EPTD” of stochastic PFS are compared with the “Total EPTD” and “Avg. EPTD” of deterministic PFS. The difference between these two PFS modes are 6% and 4% for “Total EPTD” and “Avg. EPTD” respectively.

For validation purpose, the simulation results of the stochastic PFS are compared
with the baseline. Baseline is the EPTD for July 6 estimated by EPTD algorithm. As described in the validation section of deterministic PFS (Chapter 4.4.1), only EPTD due to delayed and cancelled flights are included in the validation process. Table 4.7 lists and compares the simulation results of both the stochastic and deterministic PFS with baseline.

Table 4.7: Validation of Stochastic PFS

<table>
<thead>
<tr>
<th></th>
<th>EPTD Algorithm</th>
<th>Deterministic PFS</th>
<th>Diff1 (Algorithm, DeterminPFS)</th>
<th>Stochastic PFS</th>
<th>Diff2 (Algorithm, StochaPFS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>306,000 hrs</td>
<td>309,000 hrs</td>
<td>1%</td>
<td>288,000 hrs</td>
<td>6%</td>
</tr>
<tr>
<td>Average</td>
<td>90 minutes</td>
<td>88 minutes</td>
<td>2%</td>
<td>84 minutes</td>
<td>7%</td>
</tr>
</tbody>
</table>

“Diff1” and “Diff2” in Table 4.2 are calculated as:

- **Diff1 (Algorithm, DeterminPFS)** = \(\frac{\text{absolute value of (Algorithm - DeterminPFS)}}{\text{Algorithm}} \times 100\),

- **Diff2 (Algorithm, StochaPFS)** = \(\frac{\text{absolute value of (Algorithm - StochaPFS)}}{\text{Algorithm}} \times 100\).

The difference between baseline and stochastic PFS is wider than the difference between baseline and deterministic PFS. This is mostly caused by the value settings of parameters, such as the mean and standard deviation of stochastic factors. Airtime for flights on a specific route is given by a normal random number generator with
historical mean and standard deviation. But in the real world, flights that are already late for departures intend to make up time by flying faster. As a consequence, flights with departure delay generally have a smaller air time than others. Better validation results can be achieved by more detailed definitions and settings, such as providing different normal random number generators for delayed and on-time departure flights.
Chapter 5: Industrial Applications of Research

The industrial applications and potential users of this research are listed as follows:


2. FAA Strategy Planning (Spring 2007):
   - Trend Analysis for Passenger Trip Delay,
   - Estimating Passenger Trip Delay in Year 2010,
   - Estimating Passenger Trip Delay for NAS Strategy Simulator

3. Airline Operation Centers

4. Flight Reservation and ticket purchasing

The third and fourth applications are potential users for an Air Transportation Network Analysis Tool (ATNAT) designed to provide a single source of statistical information about the performance of the routes, airports and airlines in the air transportation network. It suggests the most reliable and least-delay-risk route, airline, and departure time for passengers based on the passenger’s choice of origin and destination. Please refer to section 3.3.5 for a detailed introduction for the ATNAT tool.
5.1 Traffic Flow Management (Fall 2006)

Airspace Flow Programs (AFPs), introduced operationally by the FAA on June 5, 2006, were used operationally on 19 days in June through September as an alternative to Ground Delay Programs (GDPs) in support of Severe Weather Avoidance Procedures (SWAP). GDP was originally developed to address the need to efficiently meter airport arrival flows during periods of reduced airport arrival capacity. It delays inbound flights on the ground prior to departure. But when GDP is used in support of SWAP, it is “inefficient, ineffective and inequitable” (Libby et al., 2005):

1. Inefficient: most of the delay is applied to flights that are not part of the problem.

2. Ineffective: control only a fraction of the flights in the problem area.

3. Inequitable: only flights bound for large airports are ever affected.

Figure 5.1 illustrate an example of GDP in support of SWAP. A line of thunderstorms (shown as the FCA in the figure) moved across the eastern U.S. on July 7, 2004. Ten airports were issued GDP and 86,654 minutes of ground delay was imposed. However, (a) 60 percent of flights that entered Flow Constrained Area (FCA) were uncontrolled by SWAP GDPs, and (b) 80 percent of GDP-controlled flights did not traverse FCA.
The Collaborative Decision Making (CDM) community has recognized these limitations and is seeking a method to systematically manage demand at a constrained en route resource by identifying the flights that are expected to use that resource and holding them on the ground until the airborne capacity to deal with them is available. This is the precise function that the Airspace Flow Program (AFP) is designed to provide (Libby et al., 2005).

In the first operational analysis and performance assessment (Metron AFP Report I, 2006), Metron Aviation Inc. reported initial findings on AFP usage, compliance, equity, and initial estimates of savings realized in using AFPs instead of SWAP GDPs. This analysis focused on flight-based analysis. In the second AFP deliverable to the
FAA, Metron Aviation Inc. looked at the AFP benefits from the flying public’s view instead of a flight-based operational view. They continued to look at how AFP technology and procedures were used and what progress was made in meeting expectations of reduced delay and passenger disruption. The report to FAA is organized into four sections, and the passenger delay estimating algorithm is applied in the third section “Passenger Delay Analysis.”

1. Delay Comparison

2. Detailed look at AFP Usage (by Danyi Wang)

3. Passenger Delay Analysis (by Danyi Wang)

4. Recommendations

Estimated Passenger Trip Delay (EPTD) is calculated for the 19 AFP days in 2006 and the 16 GDPs in support of SWAP days in 2005. Results prove that using AFP has advantages over using GDP in support of SWAP. AFPs affected 24 percent less delayed flights and 78 percent less cancelled flights than GDPs in support of SWAP. It results in 50 percent less passenger trip delays and avoids millions of daily loss in passenger value of time. Detailed analysis and statistics are available in Metron’s reports, but will not be exposed in this thesis.

5.2 FAA NAS Strategy Simulator (Spring 2007)

The NAS Strategy Simulator (NSS) was developed by Ventana Systems in conjunction with NEXTOR (nextor.org) for the FAA. The simulator is a dynamical system model of the NAS designed to understand the interactions between three sectors: Passengers
and Shippers, Airlines, and system of airports and Air Traffic Control (Sherry et al., 2003). The Center of Air Transportation Systems Research conduct a study to estimate the passenger trip delays in 2010 and develop an NSS module to estimate passenger trip delays given anticipated changes in the future.

5.2.1 EPTD in 2010

In order to estimate passenger trip delays in 2010, we have

1. forecasted daily flight schedule in 2010 given by the FAA,

2. estimated load factor in 2010 (88%),

3. assumed increase in flight arrival delay in 2010,

4. estimated flight cancellation rate in 2010 (3.3%)

The 88% load factor is estimated by continuing the increase trend of load factor after 2006 (see Figure 5.2)

Similarly, percentage of delayed flights from January 2002 to May 2007 is depicted in Figure 5.3.

According to the trend, the percentage of delayed flights will reach 30 percent in 2010. The distribution of flight arrival delay on a specific route $i$ is a lognormal distribution with $\mu_i$ and $\sigma_i$. The arrival delay for each flight in the model is generated by the corresponding lognormal random number generator for that specific route. We assume both $\mu$ and $\sigma$ for each route will be increased by 20 percent until 2010 to achieve “30 percent delayed flights” in 2010.

Figure 5.4 illustrates the regression between the percentage of cancelled flights and the percentage of delayed flights from 2002 to 2007. Data before 9/11 is excluded,
Figure 5.2: Load Factor from 1978 to 2006, Data Source: ATA

Figure 5.3: Percentage of Delayed Flights from 2002 to 2007, Data Source: BTS
since position and shape of the regression curve has changed after 9/11 due to a structural shift of the system (Wang et al., 2006), (Tam and Hansman, 2003). The estimated flight cancellation rate in 2010 is 3.3 percent.

As shown in Figure 5.5, the EPTD estimation process consists of two “black boxes.” Given individual flight schedules, estimated changes in flight delay, estimated cancellation rates, and estimated load factors, flight performance is first estimated in black box 1. 3.3 percent of scheduled flights are randomly selected as cancelled flights, and the 96.7 percent of non-cancelled flights are updated with “arrival delay” generated by lognormal random number generators. Black box 2 is responsible for calculating passenger trip delays given flight performance data. The underlying
algorithm of black box 2 is the EPTD algorithm.

Comparing performance in 2005 with performance in 2010, the 22 percent increase in daily scheduled flights generated 175 percent increase in total EPTD. As shown in Table 5.1, the 22 percent increase in daily scheduled had a strong impact on both flight performance and passenger performance, but passenger performance is much more sensitive:

1. Flight Performance: 212 percent increase in daily scheduled flight resulted in
   - 75 percent more delayed flights, and
   - 127 percent more cancelled flights.

2. Passenger Performance: 21 percent increase in daily scheduled flight results in
- 195 percent more total EPTD,
- 140 percent more EPTD due to delayed flights,
- 278 percent more EPTD due to cancelled flights,
- 14.5 percent increase in average EPTD due to delayed flights,
- 25.1 percent increase in average EPTD due to cancelled flights.

The 21 percent increase in daily scheduled flights resulted in 75 percent and 127 percent increase in delayed and cancelled flights respectively. The 75 percent increase in delayed flights generated 140 percent increase in EPTD due to delayed flights. Similarly, the 127 percent increase in cancelled flights generated 278 percent increase in EPTD due to cancelled flights. Both increases in EPTD are almost twice the increase in flights.

Figure 3.12 shows that 2000 generated the highest annual total EPTD (180 million hours) so far. Table 5.2 lists and compares the average daily performance in 2000 and 2010.
Table 5.1: Comparison Between Average Daily Performance in 2005 and 2010

<table>
<thead>
<tr>
<th>Performance</th>
<th>Daily Metrics</th>
<th>2010</th>
<th>2005</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Perf.</td>
<td>Sch. FLs</td>
<td>9,750</td>
<td>8,060</td>
<td>+21%</td>
</tr>
<tr>
<td></td>
<td>Delayed FLs</td>
<td>3,065</td>
<td>1,753</td>
<td>+75%</td>
</tr>
<tr>
<td></td>
<td>Cancelled FLs</td>
<td>329</td>
<td>145</td>
<td>+127%</td>
</tr>
<tr>
<td>Passenger Perf.</td>
<td>Total PaxDelay (hrs)</td>
<td>815,794</td>
<td>276,156</td>
<td>+195%</td>
</tr>
<tr>
<td></td>
<td>Total PaxDelay due to Delayed FLs (hrs)</td>
<td>398,023</td>
<td>165,881</td>
<td>+140%</td>
</tr>
<tr>
<td></td>
<td>Total PaxDelay due to Cancelled FLs (hrs)</td>
<td>417,771</td>
<td>110,275</td>
<td>+278%</td>
</tr>
<tr>
<td></td>
<td>Avg. PaxDelay due to Delayed FLs (min)</td>
<td>63</td>
<td>55</td>
<td>+14.5%</td>
</tr>
<tr>
<td></td>
<td>Avg. PaxDelay due to Cancelled FLs (min)</td>
<td>687</td>
<td>549</td>
<td>+25.1%</td>
</tr>
</tbody>
</table>

Table 5.2: Comparison Between Average Daily Performance in 2000 and 2010

<table>
<thead>
<tr>
<th>Performance</th>
<th>Daily Metrics</th>
<th>2010</th>
<th>2000</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight Perf.</td>
<td>Sch. FLs</td>
<td>9,750</td>
<td>7,676</td>
<td>+27%</td>
</tr>
<tr>
<td></td>
<td>Delayed FLs</td>
<td>3,065</td>
<td>1,940</td>
<td>+58%</td>
</tr>
<tr>
<td></td>
<td>Cancelled FLs</td>
<td>329</td>
<td>276</td>
<td>+19%</td>
</tr>
<tr>
<td>Passenger Perf.</td>
<td>Total PaxDelay (hrs)</td>
<td>815,794</td>
<td>491,152</td>
<td>+66%</td>
</tr>
<tr>
<td></td>
<td>Total PaxDelay due to Delayed FLs (hrs)</td>
<td>398,023</td>
<td>187,425</td>
<td>+112%</td>
</tr>
<tr>
<td></td>
<td>Total PaxDelay due to Cancelled FLs (hrs)</td>
<td>417,771</td>
<td>303,728</td>
<td>+38%</td>
</tr>
<tr>
<td></td>
<td>Avg. PaxDelay due to Delayed FLs (min)</td>
<td>63</td>
<td>56</td>
<td>+12.5%</td>
</tr>
<tr>
<td></td>
<td>Avg. PaxDelay due to Cancelled FLs (min)</td>
<td>687</td>
<td>637</td>
<td>+7.8%</td>
</tr>
</tbody>
</table>
According to the prediction, both flight and passenger performance in 2010 will be worse than any historical year.

One of the assumption of this research is that the ATS capacity remains at the same level of 2005 in 2010.

The analysis confirms once again that (1) EPTD increases dramatically with the number of scheduled flights in the system, and (2) passenger performance is more sensitive to the changes than flight performance, especially when the demand is very close to or more than the system capacity.

5.2.2 EPTD Module for NSS

A system-level NSS module was developed to estimate passenger trip delays given anticipated changes. Figure 5.6 depicts the module structure in the NAS strategy simulator. In this module, year 2006 is used as a baseline in the module. M1: impact of load factor on passenger trip delay, and M2: impacts of flight frequency on passenger trip delay are the major factors affecting PaxDelay in the NAS. They are calculated and compared with those in the baseline. If M1 and M2 in year X enlarged the impact by x%, then the corresponding average passenger trip delay will be increased by x%.

Figure 5.7 lists all the equations used behind the module.
Figure 5.6: Estimating Passenger Trip Delay Module for NSS
Figure 5.7: Equations Used in the NSS Module

\[ \text{\# Delayed Flights} = (\text{Scheduled Flights}) \times (\% \text{ of Delayed Flights}) \]

\[ \text{\# Cancelled Flights} = (\text{Scheduled Flights}) \times (\% \text{ of Cancelled Flights}) \]

\[ \text{\# Cancelled Pax} = (\# \text{ Cancelled Flights}) \times (\text{Avg. Pax Loaded}) \]

\[ \text{\# Delayed Pax} = (\# \text{ Delayed Flights}) \times (\text{Avg. Pax Loaded}) \]

\[ \% \text{ Cancelled Flights} = 0.0097 \times \exp(0.0425 \times \text{Avg. ArrDelay}) \]

\[ \text{Avg. Empty Seats} = (1 - \text{Avg. Load Factor}) \times (\text{Avg. Aircraft Size}) \]

\[ \text{Avg. Pax Loaded} = (\text{Avg. Load Factor}) \times (\text{Avg. Aircraft Size}) \]

\[ \text{Avg. \# Operated Flights} = (\text{Scheduled Flights}) \times [1 - (\% \text{ of Cancelled Flights})] \]

\[ M_1: \text{Impact of Flight Freq. on PaxDelay} = \frac{\text{Avg. \# of Daily Operated Flights per Route per Carrier in year } X}{\text{Avg. \# of Daily Operated Flights per Route per Carrier in 2005}} \]

\[ M_2: \text{Impact of Load Factor on PaxDelay} = \frac{\sum_{i=1}^{x} i \times (1 - \frac{Y}{X})}{\sum_{i=1}^{x} i} \times M_1 \]

where \( X = \text{Avg. \# of Flights Needed for Single Cancelled Flight in year } X \)

\( Y = \text{Avg. \# of Flights Needed for Single Cancelled Flight in 2005} \)

\( P_1 = \# \text{ of Cancelled Pax in year } X \); \( P_2 = \# \text{ of Cancelled Pax in year 2005} \)

We assume flights are distributed evenly throughout the day, then

\[ T_1 = \text{Avg. PaxDelay of Cancelled Pax reloaded to 1st available flight in year } X \]

\[ T_2 = \text{Avg. PaxDelay of Cancelled Pax reloaded to 1st available flight in 2005} \]

\[ M_3 = \frac{\text{Avg. EPTD per Cancelled Pax in year } X}{\text{Avg. EPTD per Cancelled Pax in year 2005}} = \frac{\text{Total EPTD for a single Cancelled FL in year } X / P_1}{\text{Total EPTD for a single Cancelled FL in 2005 / } P_2} \]

\[ = \frac{(1 \times T_1^* + 2 \times T_1^* + \ldots + x \times T_1^*) / P_1}{(1 \times T_2^* + 2 \times T_2^* + \ldots + y \times T_2^*) / P_2} \]

\[ = \frac{\sum_{i=1}^{x} T_i / X \times 1}{\sum_{i=1}^{y} T_i / X \times M_1} \]
Chapter 6: Conclusions and Future Work

The goal of Air Transportation Services is to make a safe, affordable, and convenient transport service for passengers and cargo. As a consequence, the top level performance measures of the ATS should include the trip delays experienced by airline passengers. Passenger-based metrics, together with flight-based metrics can give a more accurate and complete description of the ATS performance.

The results reflect the asymmetric and unique passenger trip on-time performance and capture the complexity and significance of the impact of a small set of cancelled flights and missed connections on passenger trip delays. Note, all the statistics listed in this chapter are based on data in 2006.

6.1 Disproportionately High EPTD due to Cancelled Flights and Missed Connections

The results indicate that the distribution of passenger trip delays is a heavily skewed distribution with a long tail. Passenger trip delay does not distribute evenly through the passengers: passengers scheduled on cancelled flights or missed connections only account for 3 percent of the total enplanements, but they generated 45 percent of total EPTD and experienced a high average delay of 382 minutes (roughly 6 and half hours).
6.2 Asymmetric Behavior of EPTD in terms of Routes, Airports and Months

Seventeen percent of the 1030 routes between OEP 35 airports generated 50 percent of the total EPTD. This illustrates the significantly higher number of trip delays absorbed by less than 1/5 of the routes. An interesting finding is that routes between New York metropolis and Washington D.C. metropolis have the highest average passenger trip delays in the system.

Nine of the 35 OEP airports generated 50 percent of the EPTD. The EPTD by airport is spread more evenly than the EPTD by routes, but still impacts some airports significantly more than others (e.g. ORD, ATL, DEN, EWR and LGA).

For months, the highest-ranked five months: December, July, June, February and October, absorbed 51 percent of total EPTD. The rank order in terms of month is not always the same. For example, the highest-ranked four months which absorbed 50 percent of total EPTD in 2004 are: September, August, July and December.

6.3 Flight-Based and Passenger-Based Metrics

Flight-based metrics have been proven to be a poor proxy for passenger on-time experience (Bratu, 2003), (Bratu and Barnhart, 2005), (Ball et al., 2006). The asymmetric absorption of delays by different groups of passengers indicates that care must be used in the selection of system-wide metrics. This type of metric can unintentionally distort the actual performance of the system and effectively “hide” explanatory and diagnostic system behavior. The “percentage” and “count” flight-based metrics
do not reflect the degree of delay in excess of 15 minutes or the passenger travel experience. For example, a flight with 16 minutes delay and a flight with 60 minutes delay results in the same flight-based on-time performance when “percentage” or “count” metrics are used. Similarly, an evening cancelled flight with 300 passengers might generate a large number of passenger trip delays, but it is measured to be the same as an early cancelled flight with 50 passengers when flight-based metrics are used, since both account as “one cancelled flight”. One way to capture the passenger experience in a metric for the performance of the air transportation system is to compute the EPTD on a daily, monthly or annual basis. This metric, computed by running the algorithm described in this thesis, could serve as an indicator of passenger customer satisfaction of the performance of the system as a whole.

6.4 Accuracy of EPTD

Both flight operational data and passenger(seat) data are needed for the computation of Estimated Passenger Trip Delay (EPTD). Since the passenger data (such as passengers loaded, aircraft size, load factor) for a given flight is not publicly available, the algorithm used in this analysis, uses the average value for the passenger factors over the period of analysis. This estimate assumes that values of passenger factors (e.g. aircraft size, number of passengers and empty seats) are normally distributed around a mean that reflects the average value for all flights (Chapter 3.2). For the purpose of the analyzing of the system-level performance, this assumption is satisfactory. Based on the stochastic simulation runs, the model prediction is within approximately 10% of expected actual value.
6.5 Dealing with the Cancelled Flight Phenomenon

Contrary to popular belief, there are no federal requirements, and the airlines are not under any legal obligation, to guarantee their schedules (DOT, 2006). Furthermore, airlines are not required to compensate passengers whose flights are delayed or canceled. As a result regulation of airline cancellation practices is left to the market-based notion that consumers will “vote with their pocket-book” and not patronize airlines that tend to leave passengers stranded. This mechanism is not entirely efficient.

In general, the cancellation of a single flight is not an isolated event for the airline. Depending on the aircraft routing, a cancelled flight can result in a ripple of flight cancellations throughout the day, causing missed connections and disruptions at upstream and downstream airports. To minimize the impact to the overall airline schedule, airlines often choose to cancel several legs to avoid having to ferry aircraft to catch up to the aircraft routing. A cancellation cycle is a sequence of legs in a rotation in which the first leg departs from the same airport at which the last leg. These practices are not well understood and have been the widely reported in the research literature. In particular the impact of “traffic flow initiatives” on airline cancellation and delay practices has not been studied (Sherry et al., 2007).

Flight cancellation is a complicated disruption to passengers since it has a stronger impact on passenger trip delay than flight delay does. To mitigate the effects of flight cancellation on passenger trip time, airlines could either provide redundant resources or reduce cancellation. The redundant resources include more empty seats, lower load factor, higher flight frequency, backup aircraft and flight crew. These redundant resources ensure the flexibility of re-booking process when disruptions happen. But
on the other hand they increase airline costs and lower airline efficiency.

Due to the cost-cutting strategy used by most of today’s airlines, load factor is increasing rapidly. Over booking causes more disrupted passenger, and less empty seats make the re-booking of disrupted passengers even harder. Passenger trip delay increases exponentially with the increase of the load factor (Bratu, 2003). The complexity of impacts of cancelled flights on passenger trip time has changed with the changes in airline market strategy and recover policy. The significant factors control these strategies and policies need to be included in the simulation model for predictions in the future.

6.6 Passenger Perspective

Under this system passengers must treat trip time as a stochastic phenomenon that can be assigned a probability of occurrence, but cannot be avoided entirely in any systematic manner. As described in this paper, airports/routes are factors that determine the performance of the system. Simple strategies can be used by the passenger to reduce the probability of occurrence such as choice of departure airport and choice of route. For example, for trip from Washington, D.C. to Chicago, during the period analyzed in this paper, the flights from Washington Reagan International Airport (DCA) to Midway (MDW) had a 5 percent probability of more than one hour delay, whereas the flight from DCA to Chicago O’Hare had 12 percent of probability of more than one hour delay. Future work in this area involves the development of metrics useful to passengers such as time-of-day, day-of-week, monthly, and annual trends in airport and route performance. Also analysis of likelihood of cancellation or EPTD for specific flights could be provided as an aid to consumers (Wang et al., 2007 A).
6.7 Consumer Protection for Airline Travelers

The traditional view of consumer protection - the one adopted by the Department of Transportation - is to provide a comparison of flight-based services provided by the airlines to the passengers. This approach is based on the premise that the difference in service is derived only by the performance of the airlines. This view of consumer protection fails to recognize the effect of the integrated system, composed of airlines, airports, air traffic control, employment contracts, government funding systems, etc. This data illustrates the importance of consumer protection against the system (not just the enterprise).

Passenger based performance metrics are designed for airline travel consumer protection and capture the integrated performance of all the agents. These metrics will enable passengers to make choices regarding the air entire transportation system, not just the airlines.

It is recognized that these metrics represent “holistic” metrics of the performance of the “integrated” air transportation system. Improving these metrics is beyond the ability of individual enterprises in the supply chain (e.g. airlines, Air Traffic Control, airports, etc.). Improvement demands an integrated and cooperative solution. In addition, the data should be presented in a way to enable comparison of routes between markets.

6.8 Recommendations for Future Work

We identify the following potential ground for future work:
DOE with Non-linear Stochastic Runs

Trend analysis in Chapter 3.3.2 showed the growth of air transportation traffic has slowed down and leveled off in 2006. This trend indicates a non-linear relationship between significant factors affecting the system performance. Instead of having a linear (two-level) fractional factorial design for the deterministic PFS (in Chapter 4.4.2), a non-linear (three-level) fractional factorial experiment with interactions should be designed and applied on the stochastic PFS.

More Detailed Passenger and Seat Information

The EPTD algorithm is based on aggregated passenger and seat information from the T-100* database. The aggregated data limits the detail level of investigation, since it assumes that flights in peak hours have the same load factor as flights in non-peak hours. For the purpose of the analyzing air transportation system performance, this assumption is satisfactory. Future work is planned to investigate actual passenger enplanements and aircraft size from proprietary airline data.

More Detailed Parameter Setting in PFS

As explained in Chapter 4, more accurate simulation results can be achieved by providing more detailed definitions of parameters and distributions, such as using two random number generators to generate air time for flights with departure delay and flights without departure delay. The current stochastic passenger flow simulation model distinguishes passengers and flights in terms of airport, route and carrier. We recommend more meticulous differentiation of PaxGroup: not only in terms airport,
route and carrier, but also in terms of time of day, peak/non-peak hour, with depdelay/wo depdelay, etc.

Adding Ticket Price as a New Passenger-Based Metric Representing Costs

The Airline Origin and Destination Survey (DB1B) Market Database contains a 10 percent sample of airline tickets from reporting carriers. Market fare is one of the fields provided by the DB1B, which can be used as average ticket price paid by passengers. A new passenger-based metric could be developed from DB1B database presenting average market value (or cost to passengers) for a specific route operated by a specific airline. This metric, combined with EPTD metric, can tell the quality of service passengers received based on the price they paid for the service. In other words, the combination of EPTD metric and market value metric provides a cost/benefit analysis for passenger trips.

Build Java GUI for PFS

The passenger flow model is developed in CPN Tools, which is a GUI tool for editing, simulating and analyzing Colored Petri Nets. Dr. Abbas Zaidi and his students in Electronic and Computer Engineering Department of George Mason University are developing a java tool for CPN Tools. The java tool hides CPN model in a black box and allows general users to modify inputs and parameters without knowing petri nets. It also helps model developers protect the core model from unexpected modification, or even insulate the core model from irrelevant people.
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Bibliography

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Appendix A: BTS Databases

A.1 Airline On-Time Performance (AOTP) Database
## Figure A.1: Data Release History for AOTP

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*All Carriers Shown*
**Figure A.2: Database Description and Definitions for AOTP**

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**Terms and Definitions**

- **Actual Departure And Arrival Times**
  - **Actual Departure Time**: The time an aircraft becomes airborne upon departure or touches down upon arrival.
  - **Actual Arrival Time**: The time an aircraft touches down upon arrival.

- **Arrival Delay**
  - Arrival delay equals the difference of the actual arrival time minus the scheduled arrival time. A flight is considered on-time when it arrives less than 15 minutes after its published arrival time.

- **CRS**
  - Computer Reservation System. CRS provide information on airline schedules, fares and seat availability to travel agencies and allow agents to book seats and issue tickets.

- **Cancelled Flight**
  - A flight that was listed in a carrier’s computer reservation system during the seven calendar days prior to scheduled departure but was not operated.

- **Certificate of Public Convenience and Necessity**
  - A certificate issued to an air carrier under 49 U.S.C. 41102, by the Department of Transportation authorizing the carrier to engage in air transportation.

- **Certificated Air Carrier**
  - An air carrier holding a Certificate of Public Convenience and Necessity issued by DOT to conducts scheduled services interstate. Non-scheduled or charter operations may also be conducted by these carriers. (Same as Certified Air Carrier)

- **Certified Air Carrier**
  - An air carrier holding a Certificate of Public Convenience and Necessity issued by DOT to conduct scheduled services interstate. Non-scheduled or charter operations may also be conducted by these carriers. (Same as Certificated Air Carrier)

- **Departure Delay**
  - The difference between the scheduled departure time and the actual departure time from the origin airport gate.

- **Diverted Flight**
  - A flight that is required to land at a destination other than the original scheduled destination for reasons beyond the control of the pilot/company.

- **Domestic Operations**
  - All air carrier operations having destinations within the 50 United States, the District of Columbia, the Commonwealth of Puerto Rico, and the U.S. Virgin Islands.

- **Elapsed Time**
  - The time computed from the moment an aircraft first moves under its own power for purposes of flight, until it comes to rest at the next point of landing. (Same as Ramp to Ramp Time)

- **FIPS**
  - Federal Information Processing Standards, usually referring to a code assigned to any of a variety of geographic entities (e.g. counties, states, metropolitan areas, etc.). FIPS codes are intended to simplify the collection, processing, and dissemination of data and resources of the Federal Government.

- **Flight Number**
  - A one to four character alpha-numeric code for a particular flight.

- **In-Flight Time**
  - The total time an aircraft is in the air between an origin-destination airport pair, i.e. from wheels-off at the origin airport to wheels-down at the destination airport.

- **Late Flight**
  - A flight arriving or departing 15 minutes or more after the scheduled time.

- **Passenger Revenues**
  - Revenues from the air transportation of passengers.

- **Scheduled Departure Time**
  - The scheduled time that an aircraft should lift off from the origin airport.

- **Scheduled Time Of Arrival**
  - The scheduled time that an aircraft should cross a certain point (landing or metering fix).

- **Taxi-In Time**
  - The time elapsed between wheels down and arrival at the destination airport gate.

- **Taxi-Out Time**
  - The time elapsed between departure from the origin airport gate and wheels off.
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<td>Difference in minutes between scheduled and actual arrival time. Early</td>
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Figure A.3: Data Field Names and Descriptions for AOTP
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<td>Distance</td>
<td>Distance between airports (miles)</td>
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<tr>
<td>DistanceGroup</td>
<td>Distance Intervals, every 250 Miles, for Flight Segment</td>
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<td>TaxiIn</td>
<td>Taxi In Time, in Minutes</td>
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<td>TaxiOut</td>
<td>Taxi Out Time, in Minutes</td>
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<td>WheelsOff</td>
<td>Wheels Off Time (local time: hh:mm)</td>
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<td>WheelsOn</td>
<td>Wheels On Time (local time: hh:mm)</td>
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<td>Cancelled</td>
<td>Cancelled Flight Indicator (1=Yes)</td>
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<td>Diverted</td>
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<td>WeatherDelay</td>
<td>Weather Delay, in Minutes</td>
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<td>NASDelay</td>
<td>NAS Delay, in Minutes</td>
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<td>LateAircraftDelay</td>
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Figure A.4: Field Names and Descriptions for AOTP (Cont)
A.2 Air Carrier Statistics (T-100) Database
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Figure A.5: Data Release History for T-100 (first 32 of 174 carriers)
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<tr>
<th><strong>Property</strong></th>
<th><strong>Description</strong></th>
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</thead>
<tbody>
<tr>
<td>Name</td>
<td>T-100 Domestic Segment (All Carriers)</td>
</tr>
<tr>
<td>Description</td>
<td>This table contains domestic non-stop segment data reported by both U.S. and foreign air carriers, including carrier, origin, destination, aircraft type and service class for transported passengers, freight and mail, available capacity, scheduled departures, departures performed, aircraft hours, and load factor when both origin and destination airports are located within the boundaries of the United States and its territories. Foreign carrier data is not available until 3 months after U.S. carrier data is released.</td>
</tr>
<tr>
<td>Records</td>
<td>41,228,169</td>
</tr>
<tr>
<td>Flights</td>
<td>1990</td>
</tr>
<tr>
<td>First Year</td>
<td>2007</td>
</tr>
<tr>
<td>Last Year</td>
<td>Monthly</td>
</tr>
<tr>
<td>Frequency</td>
<td>Monthly</td>
</tr>
<tr>
<td>Latest Available Data</td>
<td>March, 2007</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Terms</strong></th>
<th><strong>Definitions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Freight</td>
<td>Property, other than express and passenger baggage transported by air.</td>
</tr>
<tr>
<td>Air Time</td>
<td>The airborne hours of aircraft computed from the moment an aircraft leaves the ground until it touches the ground at the end of a flight stage.</td>
</tr>
<tr>
<td>Aircraft Configuration</td>
<td>The type of payload an aircraft was designed to carry: passenger, cargo, or both.</td>
</tr>
<tr>
<td>Airlines ID</td>
<td>An identification number assigned by US DOT to identify a unique airline (carrier). A unique airline (carrier) is defined as one holding and reporting under the same DOT certificate regardless of its code, name, or holding company/corporation. Use this field for analysis across a range of years.</td>
</tr>
<tr>
<td>Airport Code</td>
<td>A three character alphanumeric code issued by the U.S. Department of Transportation which is the official designation of the airport.</td>
</tr>
<tr>
<td>Carrier Code</td>
<td>Codes assigned by IATA and commonly used to identify a carrier. As the same code may have been assigned to different carriers over time, the code is not always unique.</td>
</tr>
<tr>
<td>Departures Performed</td>
<td>Takeoffs made at an airport. (same as Completed Departures)</td>
</tr>
<tr>
<td>Departures Scheduled</td>
<td>Takeoffs scheduled at an airport, as set forth in published schedules. (same as Scheduled Departures)</td>
</tr>
<tr>
<td>Destination State FIPS</td>
<td>The FIPS code for the destination state. (see FIPS)</td>
</tr>
<tr>
<td>Source State FIPS</td>
<td>The FIPS code for the origin state. (see FIPS)</td>
</tr>
<tr>
<td>Mile</td>
<td>A statute mile (5,280 feet). All mileage computations are based on statute miles.</td>
</tr>
<tr>
<td>Passenger</td>
<td>Any person on board a flight who is not a member of the flight or cabin crew.</td>
</tr>
<tr>
<td>Payload</td>
<td>Equal to the certificated takeoff weight of an aircraft, less the empty weight, less all attributable aircraft equipment, and less the operating load (consisting of minimum fuel load, oil, flight crew, steward's supplies, etc.).</td>
</tr>
<tr>
<td>Ramp To Ramp Time</td>
<td>The time computed from the moment an aircraft first moves under its own power for purposes of flight, until it comes to rest at the next point of landing.</td>
</tr>
<tr>
<td>Revenue</td>
<td>Referring to activities for which remuneration is received by the carrier.</td>
</tr>
<tr>
<td>Seats Available</td>
<td>Installed seats in an aircraft (including seats in lounges) exclusive of any seats not offered for sale to the public by the carrier provided that in no instance shall any seat sold be excluded from the count of available seats.</td>
</tr>
<tr>
<td>Segment</td>
<td>A pair of points served or scheduled to be served by a single stage of at least one flight at any given time.</td>
</tr>
<tr>
<td>Unique Carrier Code</td>
<td>It is the Carrier Code most recently used by a carrier. A numeric suffix is used to distinguish duplicate codes, for example, PA, PA (1), PA (2). Use this field to perform analysis of data reported by one and only one carrier.</td>
</tr>
<tr>
<td>Unique Carrier Entity</td>
<td>Unique Carrier Entity. This field distinguishes entities used by two or more carriers with a numeric suffix, for example, 06036 and 06038 (1).</td>
</tr>
<tr>
<td>Unique Carrier Name</td>
<td>Unique Carrier Name. It is the name most recently used by a carrier. If two or more carriers have the same most recent name, a numeric suffix is used to distinguish them, for example, Air Caribbean, Air Caribbean (1).</td>
</tr>
<tr>
<td>World Area Code (WAC)</td>
<td>Numeric codes used to identify geopolitical areas such as countries, states (U.S.), provinces (Canada), and territories or possessions of certain countries. The codes are used within the various data banks maintained by the Office of Airlines Information (OAI) and are created by OAI.</td>
</tr>
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</table>

Figure A.6: Database Description and Definitions for T-100
<table>
<thead>
<tr>
<th>Field Name</th>
<th>Description</th>
<th>Support Table</th>
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</thead>
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<tr>
<td>Year</td>
<td>Year</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>Quarter</td>
<td>Quarter</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>Month</td>
<td>North</td>
<td>Get Lookup Table</td>
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<td>Origin</td>
<td>Origin Airport</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>OriginCityName</td>
<td>Origin City</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>OriginCityNum</td>
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<td>OriginState</td>
<td>Origin State Code</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>OriginStateFips</td>
<td>Origin State FIPS</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>OriginStateName</td>
<td>Origin Airport, State Name</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>OriginWac</td>
<td>Origin Airport, World Area Code</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>Dest</td>
<td>Destination Airport</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestCityName</td>
<td>Destination City</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestCityNum</td>
<td>Destination City Code</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestState</td>
<td>Destination State Code</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestStateFips</td>
<td>Destination State FIPS</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestStateName</td>
<td>Destination Airport, State Name</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>DestWac</td>
<td>Destination Airport, World Area Code</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>AirlineID</td>
<td>An identification number assigned by US DOT to identify a unique airline (carrier). A unique airline (carrier) is defined as one holding and reporting under the same DOT certificate regardless of its Code, Name, or holding company/corporation.</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>UniqueCarrier</td>
<td>Unique Carrier Code. When the same code has been used by multiple carriers, a numeric suffix is used for earlier users, for example, PA, PA(1), PA(2). Use this field for analysis across a range of years.</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>UniqueCarrierName</td>
<td>Unique Carrier Name. When the same name has been used by multiple carriers, a numeric suffix is used for earlier users, for example, Air Caribbean, Air Caribbean (1).</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>UniCarrierEntity</td>
<td>Unique Entity for a Carrier's Operation Region.</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>CarrierRegion</td>
<td>Carrier's Operation Region. Carriers Report Data by Operation Region</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>Carrier</td>
<td>Code assigned by IATA and commonly used to identify a carrier. As the same code may have been assigned to different carriers over time, the code is not always unique. For analysis, use the Unique Carrier Code.</td>
<td>Get Lookup Table</td>
</tr>
<tr>
<td>CarrierName</td>
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<td>CarrierGroup</td>
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</tr>
<tr>
<td>Distance</td>
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Figure A.7: Field Names and Descriptions for T-100
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<th>Field Name</th>
<th>Description</th>
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<td>DistanceGroup</td>
<td>Distance Intervals, every 500 Miles, for Flight Segment</td>
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<td>DepPerformed</td>
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<td>Payload</td>
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<td>Seats</td>
<td>Available Seats</td>
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<td>Passengers</td>
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<td>Freight</td>
<td>Non-Stop Segment Freight Transported (pounds)</td>
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<td>Mail</td>
<td>Non-Stop Segment Mail Transported (pounds)</td>
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<td>RampTime</td>
<td>Ramp to Ramp Time (minutes)</td>
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<td>AirTime</td>
<td>Airborne Time (minutes)</td>
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Figure A.8: Field Names and Descriptions for T-100 (Cont)
### A.3 Airline Origin and Destination Survey (DB1B) Market Database

**Origin and Destination Survey: DB1B Ticket Release History (by data)**

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Figure A.9: Data Release History for DB1B
Figure A.10: Data Release History for DB1B (Cont)
Figure A.11: Database Description and Definitions for DB1B

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<th>Property</th>
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<tr>
<td>Name</td>
<td>DB1STicket</td>
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<tr>
<td>Description</td>
<td>This table contains summary ticket-level data from the Origin and Destination Survey (DB1B), which is a 10% sample of airline tickets from reporting carriers. It includes such items as the reporting carrier, number of passengers, ticket fare, and total miles flown for each itinerary, as well as information about whether the itinerary was domestic or round-trip. This table is related to both the O&amp;D Segment and Market files by the unique itinerary ID on each record.</td>
</tr>
<tr>
<td>Records</td>
<td>126,324,370</td>
</tr>
<tr>
<td>Fields</td>
<td>24</td>
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<tr>
<td>First Year</td>
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<tr>
<td>Last Year</td>
<td>2006</td>
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<tr>
<td>Frequency</td>
<td>Quarterly</td>
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<tr>
<td>Latest Available Data</td>
<td>December, 2006</td>
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<table>
<thead>
<tr>
<th>Terms</th>
<th>Definitions</th>
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</thead>
<tbody>
<tr>
<td>Total Itinerary Yield</td>
<td>Itinerary fare per itinerary miles flown. The itinerary includes all segments of a journey from origin to destination.</td>
</tr>
<tr>
<td>Track</td>
<td>The actual flight path of an aircraft over the surface of the earth.</td>
</tr>
<tr>
<td>Field Name</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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<td>Itinerary ID</td>
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<tr>
<td>MtctID</td>
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<tr>
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<tr>
<td>MtctProduct</td>
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<tr>
<td>OriginCity</td>
<td>Origin Airport, City Code</td>
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<tr>
<td>OriginState</td>
<td>Origin Airport, Country Code</td>
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<tr>
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<tr>
<td>OriginWac</td>
<td>Origin Airport, World Area Code</td>
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<tr>
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<tr>
<td>DestAptInd</td>
<td>Destination Airport, Multiple Airtports Indicator</td>
</tr>
<tr>
<td>DestCity</td>
<td>Destination Airport, City Code</td>
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<td>DestCountry</td>
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<tr>
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<td>Ticketing Carrier Group</td>
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<td>OpCarrierChange</td>
<td>Operating Carrier Change Indicator (1=Yes)</td>
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<td>OpCarrierGroup</td>
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<td>TckCarrier</td>
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<tr>
<td>OpCarrier</td>
<td>Operating Carrier Code for On-line Itineraries (otherwise equals to 99)</td>
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<td>Bulk Fare Indicator (1=Yes)</td>
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<td>MtctFare</td>
<td>Market Fare (ItinYield*MtctMilesFlown)</td>
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<tr>
<td>MtctDistance</td>
<td>Market Distance (Including Ground Transport)</td>
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<tr>
<td>MtctDistanceGroup</td>
<td>Distance Group, in 500 Mile Intervals</td>
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<tr>
<td>MtctMilesFlown</td>
<td>Market Miles Flown (Track Miles)</td>
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<tr>
<td>NonStopMiles</td>
<td>Non-Stop Market Miles (Using Radial Measure)</td>
</tr>
<tr>
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<tr>
<td>MtctGeoType</td>
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Figure A.12: Field Names and Descriptions for DB1B
Appendix B: OEP 35 Airports
<table>
<thead>
<tr>
<th>City</th>
<th>Airport</th>
<th>Code</th>
</tr>
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<tbody>
<tr>
<td>Atlanta</td>
<td>Hartsfield-Jackson Atlanta International</td>
<td>ATL</td>
</tr>
<tr>
<td>Baltimore</td>
<td>Baltimore-Washington International</td>
<td>BW</td>
</tr>
<tr>
<td>Boston</td>
<td>Boston Logan International</td>
<td>BOS</td>
</tr>
<tr>
<td>Charlotte</td>
<td>Charlotte/Douglas International</td>
<td>CLT</td>
</tr>
<tr>
<td>Chicago</td>
<td>Chicago Midway International</td>
<td>MDW</td>
</tr>
<tr>
<td>Chicago</td>
<td>Chicago O'Hare International</td>
<td>ORD</td>
</tr>
<tr>
<td>Cincinnati</td>
<td>Cincinnati/Northern Kentucky International</td>
<td>CVG</td>
</tr>
<tr>
<td>Cleveland</td>
<td>Cleveland Hopkins International</td>
<td>CLE</td>
</tr>
<tr>
<td>Dallas - Fort Worth</td>
<td>Dallas/Fort Worth International</td>
<td>DFW</td>
</tr>
<tr>
<td>Denver</td>
<td>Denver International</td>
<td>DEN</td>
</tr>
<tr>
<td>Detroit</td>
<td>Detroit Metropolitan Wayne County</td>
<td>DTW</td>
</tr>
<tr>
<td>Fort Lauderdale - Hollywood</td>
<td>Fort Lauderdale-Hollywood International</td>
<td>FLL</td>
</tr>
<tr>
<td>Honolulu</td>
<td>Honolulu International</td>
<td>HNL</td>
</tr>
<tr>
<td>Houston</td>
<td>Houston George Bush Intercontinental</td>
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<td>Las Vegas McCarran International</td>
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<td>Minneapolis-St Paul</td>
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<td>MSP</td>
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<tr>
<td>New York</td>
<td>New York John F. Kennedy International</td>
<td>JFK</td>
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<td>New York</td>
<td>New York LaGuardia</td>
<td>LGA</td>
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<td>Newark</td>
<td>Newark Liberty International</td>
<td>EWR</td>
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<td>Philadelphia</td>
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<td>Phoenix Sky Harbor International</td>
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<td>Greater Pittsburgh International</td>
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<td>Portland</td>
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<td>Saint Louis</td>
<td>Lambert-St Louis International</td>
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<td>Salt Lake City</td>
<td>Salt Lake City International</td>
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<td>San Diego</td>
<td>San Diego International - Lindbergh Field</td>
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</tr>
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<td>San Francisco</td>
<td>San Francisco International</td>
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</tr>
<tr>
<td>Seattle-Tacoma</td>
<td>Seattle-Tacoma International</td>
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<tr>
<td>Tampa</td>
<td>Tampa International</td>
<td>TPA</td>
</tr>
<tr>
<td>Washington, DC</td>
<td>Ronald Reagan Washington National</td>
<td>DCA</td>
</tr>
<tr>
<td>Washington, DC</td>
<td>Washington Dulles International</td>
<td>IAD</td>
</tr>
</tbody>
</table>

**Figure B.1: Operational Evolution Plan (OEP) 35 Airports**
Appendix C: SQL Codes For Estimating Passenger Trip Delay

-- CREATE AOTP* TABLE

DECLARE @FIXED VARCHAR(30)

DECLARE @YEAR INT

DECLARE @MONTH INT

DECLARE @INFILE VARCHAR (40)

DECLARE @CORRECT VARCHAR (200)

DECLARE @CREATE VARCHAR(500)

DECLARE @INSERT VARCHAR (500)

SET @FIXED = 'On\_Time\_On\_Time\_Performance\_'

SET @YEAR = 2006

SET @MONTH=1

SET @INFILE = @FIXED + CAST(@YEAR AS VARCHAR(4)) + '\_' + CAST(@MONTH AS VARCHAR(2))

SET @CREATE = 'SELECT SEQ=IDENTITY(INT,1,1), YEAR, MONTH, DAYOFMONTH, DAYOFWEEK, ORIGIN, DEST, ARRDLY, ARRTIME, CRSARRTIME, DEPDELAY, DEPTIME, CRSDEPTIME, CARRIER, CANCELLED, CANCELLATIONCODE, FLIGHTDATE, FLIGHTNUM, TAILNUM, NASDELAY, CARRIERDELAY, LATEAIRCRAFTDELAY, SECURITYDELAY, WEATHERDELAY'
INTO ONTIME35\_2006 FROM ' + @INFILE + ' WHERE 1<>1 '
EXEC(@CREATE)}

-- INSERT IN DATA OF YEAR 2006
WHILE @MONTH<13
BEGIN
SET @INFILE = @FIXED + CAST(@YEAR AS VARCHAR(4)) + '_\_.' + CAST(@MONTH AS VARCHAR(2))

SET @INSERT = 'INSERT INTO ONTIME35\_2006 SELECT YEAR, MONTH, DAYOFMONTH, DAYOFWEEK, ORIGIN, DEST, ARRDLY, ARRTIME, CRSARRTIME, DEPDELAY, DEPTIME, CRSDEPTIME, CARRIER, CANCELLED, CANCELLATIONCODE, FLIGHTDATE, FLIGHTNUM, TAILNUM, NASDELAY, CARRIERDELAY, LATEAIRCRAFTDELAY, SECURITYDELAY, WEATHERDELAY FROM ' + @INFILE + '
WHERE ORIGIN IN (SELECT AIRPORT FROM BENCHMARK35)
AND DEST IN (SELECT AIRPORT FROM BENCHMARK35)
ORDER BY ORIGIN, DEST, CARRIER, MONTH, DAYOFMONTH, DEPTIME'

EXEC(@INSERT)
SET @MONTH = @MONTH + 1
END

------------------------------------------------------
-- CREATE T-100* TABLE
SELECT YEAR, MONTH, ORIGIN, DEST, CARRIER, SUM(SEATS)/SUM(DEPARTURES\_PERFORMED)
AS AVGSEAT, SUM(PASSENGERS)/SUM(DEPARTURES\_PERFORMED) AS AVGPAX,
SUM(SEATS)/SUM(DEPARTURES\_PERFORMED)-SUM(PASSENGERS)/SUM(DEPARTURES\_PERFORMED)
AS AVASEAT
INTO LF\_00
FROM T100\_2000
WHERE PASSENGERS>0 AND REGION='D' AND DEPARTURES\_PERFORMED>0
GROUP BY YEAR, MONTH, ORIGIN, DEST, CARRIER
ORDER BY YEAR, MONTH, ORIGIN, DEST, CARRIER

-- DATA PROCESSING AND JOINING
ALTER TABLE ONTIME35\_2006 ADD ARRDATETIME DATETIME NULL, DEPDATE DATETIME NULL,
AVGPAX INT NULL, AVASEAT INT NULL, PAXDELAY INT NULL, PAXDELAYEQ VARCHAR(50),
AVASEQ VARCHAR(50)
GO
DELETE FROM ONTIME35\_2006
WHERE (CANCELLED=0 AND (DEPTIME='NULL' OR ARRTIME='NULL'))

-- UPDATE AIRLINE INFO
UPDATE ONTIME35\_2006 SET CARRIER2=CARRIER
UPDATE ONTIME35\_2006 SET CARRIER='AA' WHERE CARRIER2='MQ'
UPDATE ONTIME35\_2006 SET CARRIER='DL' WHERE CARRIER2='OH' OR CARRIER2='EV'
UPDATE ONTIME35\_2006 SET CARRIER='CO' WHERE CARRIER2='RU'

-- CHANGE SOME VARCHAR(255) COLUMNS INTO INT IN
-- FIRST NEED TO TAKE CARE OF CHANGING VARCHAR VALUE 'NULL' INTO REAL NULL

UPDATE ONTIME35\_2006 SET ARRTIME = NULL WHERE ARRTIME='NULL'

UPDATE ONTIME35\_2006 SET DEPTIME = NULL WHERE DEPTIME='NULL'

UPDATE ONTIME35\_2006 SET CRSARRTIME = NULL WHERE CRSARRTIME='NULL'

UPDATE ONTIME35\_2006 SET CRSDEPTIME = NULL WHERE CRSDEPTIME='NULL'

UPDATE ONTIME35\_2006 SET FLIGHTNUM = NULL WHERE FLIGHTNUM='NULL'

UPDATE ONTIME35\_2006 SET TAILNUM = NULL WHERE TAILNUM='NULL'

-- THEN CHANGE TYPE

ALTER TABLE ONTIME35\_2006 ALTER COLUMN ARRTIME INT

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN DEPTIME INT

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN CRSARRTIME INT

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN CRSDEPTIME INT

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN ORIGIN VARCHAR(3)

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN DEST VARCHAR(3)

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN FLIGHTNUM INT

GO

ALTER TABLE ONTIME35\_2006 ALTER COLUMN TAILNUM VARCHAR(10)

GO
-- SET VALUE FOR COLUMN ARRDATE, DEPDATE FOR NON-CANCELLED FLIGHT

UPDATE ONTIME35\_2006 SET ARRDATE = DATEADD(MI,ARRTIME\%100,FLIGHTDATE),
DEPDATE = DATEADD(MI,DEPTIME\%100,FLIGHTDATE)
WHERE CANCELLED <>1

UPDATE ONTIME35\_2006

SET ARRDATE = DATEADD(HH,(ARRTIME-ARRTIME\%100)/100,ARRDATE),
DEPDATE = DATEADD(HH,(DEPTIME-DEPTIME\%100)/100,DEPDATE)
WHERE CANCELLED <>1

-- SET VALUE FOR COLUMN ARRDATE FOR CANCELLED FLIGHT

UPDATE ONTIME35\_2006 SET ARRDATE = DATEADD(MI,CRSARRTIME\%100,FLIGHTDATE),
DEPDATE = DATEADD(MI,CRSDEPTIME\%100,FLIGHTDATE)
WHERE CANCELLED = 1

UPDATE ONTIME35\_2006

SET ARRDATE = DATEADD(HH,(CRSARRTIME-CRSARRTIME\%100)/100,ARRDATE),
DEPDATE = DATEADD(HH,(CRSDEPTIME-CRSDEPTIME\%100)/100,DEPDATE)
WHERE CANCELLED = 1

-- SET PRIMARY KEY (SO THAT CODE RUNS MUCH MORE EFFICIENTLY)

ALTER TABLE ONTIME35\_2006

ADD CONSTRAINT PK\_ONTIME35\_2006 PRIMARY KEY (SEQ)

GO
-- SET VALUE FOR COLUMN AVASEAT FOR NON-CANCELLED FLIGHT

UPDATE ONTIME35\_2006 SET AVASEAT = (SELECT AVASEAT
FROM LF\_06
WHERE LF\_06.YEAR = ONTIME35\_2006.YEAR
AND LF\_06.MONTH = ONTIME35\_2006.MONTH
AND LF\_06.ORIGIN = ONTIME35\_2006.ORIGIN
AND LF\_06.DEST = ONTIME35\_2006.DEST
AND LF\_06.CARRIER = ONTIME35\_2006.CARRIER2)
WHERE CANCELLED <> 1

-- SOME NULL AVASEAT MIGHT BE CAUSED BY COMPANY AND SUBCOMPANY, SO

UPDATE ONTIME35\_2006 SET AVASEAT = (SELECT AVASEAT FROM LF\_06
WHERE LF\_06.YEAR = ONTIME35\_2006.YEAR
AND LF\_06.MONTH = ONTIME35\_2006.MONTH
AND LF\_06.ORIGIN = ONTIME35\_2006.ORIGIN
AND LF\_06.DEST = ONTIME35\_2006.DEST
AND LF\_06.CARRIER = ONTIME35\_2006.CARRIER)
WHERE CANCELLED <> 1 AND AVASEAT IS NULL

-- SOME CARRIER MIGHT NOT BE INCLUDED IN LF Table,

-- THEREFORE THEIR AVASEAT ARE SET TO BE THE AVG FOR ALL CARRIERS

UPDATE ONTIME35\_2006 SET AVASEAT = (SELECT AVG(AVASEAT) FROM LF\_06
WHERE LF\_06.YEAR = ONTIME35\_2006.YEAR
AND LF\_06\_MONTH = ONTIME35\_2006\_MONTH
AND LF\_06\_ORIGIN = ONTIME35\_2006\_ORIGIN
AND LF\_06\_DEST=ONTIME35\_2006\_DEST)
WHERE CANCELLED <> 1 AND AVASEAT IS NULL

-- CHECK WHETHER THERE IS NOT AVASEAT WITH NULL VALUE WITH CANCELLED<>1
SELECT * FROM ONTIME35\_2006 WHERE AVASEAT IS NULL AND CANCELLED<>1

-- SET VALUE FOR COLUMN AVASEAT FOR CANCELLED FLIGHT
UPDATE ONTIME35\_2006 SET AVASEAT = 0 WHERE CANCELLED = 1

-- SET VALUE TO 0 FOR BOTH NON-CANCELLED AND CANCELLED FLIGHT
UPDATE ONTIME35\_2006 SET PAXDELAY = 0

-- SET VALUE FOR COLUMN AVGPAX
-- GET THE PAX INFO FROM LOADING FACT TABLE
UPDATE ONTIME35\_2006 SET AVGPAX = (SELECT AVGPAX FROM LF\_06
WHERE LF\_06\_YEAR = ONTIME35\_2006\_YEAR
AND LF\_06\_MONTH = ONTIME35\_2006\_MONTH
AND LF\_06\_ORIGIN = ONTIME35\_2006\_ORIGIN
AND LF\_06\_DEST = ONTIME35\_2006\_DEST
AND LF\_06\_CARRIER=ONTIME35\_2006\_CARRIER2)

-- FOR THOSE WITH NULL AVGPAX, THEY MIGHT CAUSED BY COMPANY AND SUBCOMPANY
UPDATE ONTIME35\_2006 SET AVGPAX = (SELECT AVGPAX FROM LF\_06
WHERE LF\_06.YEAR = ONTIME35\_2006.YEAR
AND LF\_06.MONTH = ONTIME35\_2006.MONTH
AND LF\_06.ORIGIN = ONTIME35\_2006.ORIGIN
AND LF\_06.DEST = ONTIME35\_2006.DEST
AND LF\_06.CARRIER=ONTIME35\_2006.CARRIER)
WHERE AVGPAX IS NULL

-- FOR CARRIER NOT INCLUDED IN LF TABLE, WE USE AVG VALUE OF ALL CARRIERS
UPDATE ONTIME35\_2006 SET AVGPAX = (SELECT AVG(AVGPAX) FROM LF\_06
WHERE LF\_06.YEAR = ONTIME35\_2006.YEAR
AND LF\_06.MONTH = ONTIME35\_2006.MONTH
AND LF\_06.ORIGIN = ONTIME35\_2006.ORIGIN
AND LF\_06.DEST = ONTIME35\_2006.DEST)
WHERE ONTIME35\_2006.AVGPAX IS NULL

-- CHECK WHETHER EVERY RECORD HAS AVGPAX VALUE
SELECT * FROM ONTIME35\_2006 WHERE AVGPAX IS NULL

------------------------------------------------------
-- ESTIMATE PASSENGER TRIP DELAY
-- DECLARE ALL FETCH VARs (START WITH @)
DECLARE @SEQ INT, @YEAR INT, @MONTH INT, @DAYOFMONTH INT, @CANCELLED INT
DECLARE @PAXDELAY INT, @CANCELPAINT, @AVGPAX INT, @SINGLEPAXDELAY INT
DECLARE @NEWSEQ INT, @NEAVASEAT INT, @NEWDAYOFMONTH INT, @MINSEQ INT
@MAXSEQ INT, @CRSDEPTIME INT

DECLARE @NEWARRDATE DATETIME, @ARRDATE DATETIME, @DEPDATE DATETIME,
@TEMPDATE DATETIME

DECLARE @CARRIER VARCHAR(5), @ORIGIN VARCHAR(5), @DEST VARCHAR(5),
@AVASEQ VARCHAR(50), @PAXDELAYEQ VARCHAR(50)

-- DEFINE A CURSOR FOR LOOP

DECLARE CUR\_CANC\_FLIGHT CURSOR FAST\_FORWARD FOR

SELECT SEQ, YEAR, MONTH, DAYOFMONTH, ORIGIN, DEST, CARRIER, CRSDEPTIME,
CANCELLED, PAXDELAY, ARRDATE, DEPDATE, AVGPAX

FROM ONTIME35\_2006

WHERE CANCELLED = 1 AND SEQ<=(SELECT MAX(SEQ) FROM ONTIME35\_2006)

ORDER BY SEQ

OPEN CUR\_CANC\_FLIGHT

-- READ EACH COLUMN VALUE OF THIS CANCELLED FLIGHT AND GIVE THEIR VALUES
-- TO THOSE CORRESPONDING PARAMETERS

-- @ + COLUMN NAME IS FOR CANCELLED FLIGHTS
-- @ + NEW + COLUMN NAME IS FOR AVAILABLE FLIGHTS
-- NOTE: "AVG" ARE FOR LF TABLE, AVASEAT IS IN MAIN TABLE,
-- @CANCELPAX IS NOT A COLUMN IN ANY TABLE
FETCH NEXT FROM CUR\_CANC\_FLIGHT INTO @SEQ, @YEAR, @MONTH, @DAYOFMONTH, 
@ORIGIN, @DEST, @CARRIER, @CRSDEPTIME, @CANCELLED, @PAXDELAY, @ARRDATE, 
@DEPDATE,@AVGPAX

WHILE (@@FETCH\_STATUS = 0)
BEGIN
-- INITIALIZATION
SET @PAXDELAY = 0

-- GET THE PAX INFO FROM LOADING FACT TABLE
SELECT @CANCELPAX= @AVGPAX

-- INITIAL @AVASEQ, @PAXDELAYEQ
SET @PAXDELAYEQ = ' ',
SET @AVASEQ=' ',
SET @NEWSEQ=' ',

-- GET MIN MAX NUM FOR ALL FLIGHTS IN O-D/CARRIER COMBINATION
SET @MINSEQ = (SELECT MINSEQ FROM RANGE00 
WHERE ORIGIN=@ORIGIN AND DEST=@DEST AND CARRIER=@CARRIER AND MONTH=@MONTH AND DAYOFMONTH=@DAYOFMONTH)
SET @MAXSEQ = (SELECT MAXSEQ FROM RANGE00 
WHERE ORIGIN=@ORIGIN AND DEST=@DEST AND CARRIER=@CARRIER AND MONTH=@MONTH AND DAYOFMONTH=@DAYOFMONTH+1)
WHILE (@CANCELPAX > 0)
BEGIN
-- GET THE NEAREST AVAILABLE FLIGHT INFO - SEQ, ARRDATE AND AVGSEAT
SELECT @NEWSEQ = (SELECT MIN(SEQ) FROM ONTIME35\_2006
WHERE SEQ>=@MINSEQ AND SEQ<=@MAXSEQ AND DEPDATE>@DEPDATE AND
ORIGIN=@ORIGIN AND DEST=@DEST AND CARRIER=@CARRIER
AND CANCELLED=0 AND AVASEAT>0)

IF @NEWSEQ IS NULL
BEGIN
SET @PAXDELAY=900*@AVGPAX
SET @CANCELPAX=0
END
ELSE -- NOW GENERAL CALCULATION BEGINS
BEGIN
SET @NEWARRDATE = (SELECT ARRDATE FROM ONTIME35\_2006 WHERE SEQ=@NEWSEQ)

SET @NEWAVASEAT= (SELECT AVASEAT FROM ONTIME35\_2006 WHERE SEQ = @NEWSEQ)

SET @SINGLEPAXDELAY = DATEDIFF(MI,@ARRDATE, @NEWARRDATE)
IF @SINGLEPAXDELAY < 0 -- IF ACTUAL ARRTIME IS THE NEXT EARLY MORNING
SET @SINGLEPAXDELAY = DATEDIFF(MI,@ARRDATE, @NEWARRDATE) + 1440
-- CALCULATE PAXDELAY

IF @CANCELPA > @NEWAVASEAT -- NO MORE AVAILABLE SEAT
BEGIN

IF @SINGLEPAXDELAY<=900
BEGIN
  SET @PAXDELAY = @PAXDELAY + @NEWAVASEAT * @SINGLEPAXDELAY

  -- UPDATE \'# OF PAX LEFT FOR RELOCATION
  SET @CANCELPA = @CANCELPA - @NEWAVASEAT
  SET @PAXDELAYEQ = @PAXDELAYEQ + CAST(@SINGLEPAXDELAY AS VARCHAR(4))
  + 'X' + CAST(@NEWAVASEAT AS VARCHAR(3)) + ','
  SET @AVASEQ = @AVASEQ + CAST(@NEWSEQ AS VARCHAR(10)) + ','
END

ELSE -- THAT IS OUT OF UPPER BOUND, PAXDELAY=15 HOURS
BEGIN
  SET @SINGLEPAXDELAY = 900
  SET @PAXDELAY = @PAXDELAY + @CANCELPA * 900
  SET @PAXDELAYEQ = @PAXDELAYEQ + CAST(@SINGLEPAXDELAY AS VARCHAR(4))
  + 'X' + CAST(@CANCELPA AS VARCHAR(3)) + ','
  SET @CANCELPA = 0
  SET @AVASEQ = @AVASEQ + CAST(@NEWSEQ AS VARCHAR(10))
END
-- UPDATE AVASEAT FOR AVAFLIGHT

UPDATE ONTIME35\_2006 SET AVASEAT = 0 WHERE SEQ = @NEWSEQ

END

ELSE -- THERE ARE MORE SEATS THAN RELOCATED PAX

BEGIN

IF @SINGLEPAXDELAY<=900

SET @PAXDELAY = @PAXDELAY + @CANCELPAX * @SINGLEPAXDELAY

ELSE -- THAT IS OUT OF UPPER BOUND OR HAS NEGATIVE PAXDELAY

BEGIN

SET @SINGLEPAXDELAY = 900

SET @PAXDELAY = @PAXDELAY + @CANCELPAX * 900

END

-- UPDATE AVASEAT

UPDATE ONTIME35\_2006

SET AVASEAT = @NEWAVASEAT - @CANCELPAX WHERE SEQ = @NEWSEQ

SET @AVASEQ = @AVASEQ + CAST(@NEWSEQ AS VARCHAR(10))

SET @PAXDELAYEQ = @PAXDELAYEQ + CAST(@SINGLEPAXDELAY AS VARCHAR(4))
+ 'X' + CAST(@CANCELPAX AS VARCHAR(3))

SET @CANCELPAX = 0
-- UPDATE FOR @PAXDELAY

UPDATE ONTIME35\_2006

SET PAXDELAY = @PAXDELAY, AVASEQ = @AVASEQ, PAXDELAYEQ = @PAXDELAYEQ

WHERE SEQ = @SEQ

FETCH NEXT FROM CUR\_CANC\_FLIGHT INTO @SEQ, @YEAR, @MONTH, @DAYOFMONTH,
@ORIGIN, @DEST, @CARRIER, @CRSDEPTIME, @CANCELLED, @PAXDELAY, @ARRDATE,
@DEPDATE, @AVGPAX

END

CLOSE CUR\_CANC\_FLIGHT

DEALLOCATE CUR\_CANC\_FLIGHT

-- DOUBLE CHECK

SELECT * FROM ONTIME35\_2006 WHERE CANCELLED=1}
Appendix D: Declarations in PFS

globref outfile = TextIO.stdOut;

val rp=85;
val rs=95;
val rmct=100;
val mctgap=15;
val delaygap=15;
val idenindex=0;

colset Origin = string;
colset Dest = string;
colset Pax = int;
colset Size = int;
colset SchDep = int;
colset SchArr = int;
colset IndexofCarrier = int;
colset FlightIndex = int;
colset TimeStamp = int;
colset PaxGroup= product Origin*Dest*Pax*Size*SchDep
*SchArr*IndexofCarrier*FlightIndex*TimeStamp*Pax timed;
colset Plist = list PaxGroup;
colset Q = product IndexofCarrier*Dest;

colset CaPList = product Q*PList;

var r,r’,o’,o0,o00,o01,o2 : Origin;
var d,d’,d0,d00,d01,d1,d2,d3: Dest;
var p,p’,p0,p00,p01, p02,p03,p1,p2,p: Pax;
var s0,s’,s00,s01,s02,s03,s,s1,s2,s3: Size;
var sd,sd’,sd0,sd00,sd01,sd02,sd03,sd1,sd2,sd3:SchDep;
var sa,sa’,sa0,sa00,sa01,sa02,sa03,sa1,sa2,sa3: SchArr;
var i,i’,i0,i00,i01,i02,i03,i1,i2,i3:IndexofCarrier;
var f,f’,f0,f00,f01,f02,f03,f1,f2,f3:FlightIndex;
var ts,t,ts’,ts0,ts00,ts01,ts02,ts03,ts1,ts2,ts3: TimeStamp;
var list1,list2:PList;

fun max(x:int,y:int)=
if x>y then x
else if x=y then x+1
else y;
fun Mtime() =IntInf.toInt (time());

fun lognormal(x:real, y:real)=
let
val m=Math.ln(x)-0.5*Math.ln((y*y)/(x*x)+1.0);
val s=Math.sqrt(Math.ln((y*y)/(x*x)+1.0));

in

floor(Math.exp(normal(m,s)))

end;

fun taxiout(r)=

case (r) of

("ATL")=>lognormal(21.8 ,12.9 )|
("BOS")=>lognormal(20.5 ,14.0 )|
("BWI")=>lognormal(14.6 ,11.3 )|
("CLE")=>lognormal(17.3 ,12.2 )|
("CLT")=>lognormal(18.8 ,15.7 )|
("CVG")=>lognormal(16.5 ,9.1 )|
("DCA")=>lognormal(18.8 ,17.8 )|
("DEN")=>lognormal(15.0 ,8.9 )|
("DFW")=>lognormal(20.2 ,18.3 )|
("DTW")=>lognormal(19.2 ,14.0 )|
("EWR")=>lognormal(30.6 ,23.7 )|
("FLL")=>lognormal(17.3 ,10.9 )|
("IAD")=>lognormal(22.7 ,18.5 )|
("IAH")=>lognormal(24.9 ,18.0 )|
("JFK")=>lognormal(35.1 ,22.8 )|
("LAS")=>lognormal(17.4 ,8.6 )|
("LAX")=>lognormal(15.9 ,8.0 )|
("LGA")=>lognormal(27.3 ,21.9 )|
("MCO")=>lognormal(14.3 ,9.1 )|
("MDW")=>lognormal(16.0 ,15.1 )|
("MEM")=>lognormal(16.2 ,9.7 )|
("MIA")=>lognormal(18.7 ,14.7 )|
("MSP")=>lognormal(20.5 ,11.8 )|
("ORD")=>lognormal(24.3 ,23.0 )|
("PDX")=>lognormal(12.1 ,5.0 )|
("PHL")=>lognormal(30.5 ,25.2 )|
("PHX")=>lognormal(15.8 ,8.6 )|
("PIT")=>lognormal(14.5 ,11.5 )|
("SAN")=>lognormal(15.5 ,10.3 )|
("SEA")=>lognormal(14.5 ,5.9 )|
("SFO")=>lognormal(17.1 ,8.1 )|
("SLC")=>lognormal(17.6 ,7.3 )|
("STL")=>lognormal(13.3 ,8.0 )|
("TPA")=>lognormal(13.8 ,10.2 )|
_=>0;

fun airtime(r,d)=
case (r,d) of
("ATL","BOS")=>lognormal(123.6 ,6.9 )|
("ATL","BWI")=>lognormal(81.5 ,5.8 )|
("ATL","CLE")=>lognormal(75.3 ,80.5 )|
("ATL","CLT")=>lognormal(43.5,5.5)
("ATL","CVG")=>lognormal(59.2,5.8)
("ATL","DCA")=>lognormal(78.3,5.6)
("ATL","DEN")=>lognormal(157.1,7.5)
("ATL","DFW")=>lognormal(103.7,6.5)
("ATL","DTW")=>lognormal(87.1,6.8)
("ATL","EWR")=>lognormal(107.7,11.6)
("ATL","FLL")=>lognormal(84.0,6.6)
("ATL","IAD")=>lognormal(79.0,6.3)
("ATL","IAH")=>lognormal(98.3,8.8)
("ATL","JFK")=>lognormal(108.0,8.8)
("ATL","LAS")=>lognormal(218.0,7.8)
("ATL","LAX")=>lognormal(236.5,8.5)
("ATL","LGA")=>lognormal(106.8,9.4)
("ATL","MCO")=>lognormal(62.1,7.5)
("ATL","MDW")=>lognormal(83.7,8.2)
("ATL","MEM")=>lognormal(52.5,8.4)
("ATL","MIA")=>lognormal(85.1,6.7)
("ATL","MSP")=>lognormal(127.8,9.6)
("ATL","ORD")=>lognormal(91.5,12.2)
("ATL","PDX")=>lognormal(272.6,7.1)
("ATL","PHL")=>lognormal(96.2,7.6)
("ATL","PHX")=>lognormal(204.6,7.9)
("ATL","PIT")=>lognormal(42.3,206.9)
("ATL","SAN")=>lognormal(231.7 ,7.1 )
("ATL","SEA")=>lognormal(277.3 ,8.4 )
("ATL","SFO")=>lognormal(264.7 ,9.2 )
("ATL","SLC")=>lognormal(202.9 ,7.7 )
("ATL","STL")=>lognormal(73.0 ,6.5 )
("ATL","TPA")=>lognormal(60.9 ,5.5 )
("BOS","ATL")=>lognormal(137.0 ,11.2 )
("BOS","BWI")=>lognormal(63.0 ,5.3 )
("BOS","CLE")=>lognormal(90.5 ,4.9 )
("BOS","CLT")=>lognormal(108.4 ,12.6 )
("BOS","CVG")=>lognormal(113.4 ,7.3 )
("BOS","DCA")=>lognormal(70.5 ,7.6 )
("BOS","DEN")=>lognormal(213.3 ,47.8 )
("BOS","DFW")=>lognormal(209.1 ,9.5 )
("BOS","DTW")=>lognormal(97.4 ,8.1 )
("BOS","EWR")=>lognormal(51.5 ,8.2 )
("BOS","FLL")=>lognormal(164.5 ,7.9 )
("BOS","IAD")=>lognormal(73.5 ,8.4 )
("BOS","IAH")=>lognormal(217.9 ,11.7 )
("BOS","JFK")=>lognormal(44.2 ,7.6 )
("BOS","LAS")=>lognormal(269.6 ,72.1 )
("BOS","LAX")=>lognormal(330.1 ,13.0 )
("BOS","LGA")=>lognormal(43.6 ,6.9 )
("BOS","MCO")=>lognormal(151.5 ,8.8 )
("BOS","MDW")=>lognormal(128.2 ,7.8 )
("BOS","MIA")=>lognormal(166.3 ,9.2 )
("BOS","MSP")=>lognormal(161.0 ,10.0 )
("BOS","ORD")=>lognormal(129.6 ,9.7 )
("BOS","PHL")=>lognormal(60.3 ,7.4 )
("BOS","PHX")=>lognormal(295.1 ,14.7 )
("BOS","PIT")=>lognormal(77.1 ,6.1 )
("BOS","SAN")=>lognormal(327.5 ,10.0 )
("BOS","SEA")=>lognormal(333.0 ,12.4 )
("BOS","SFO")=>lognormal(345.3 ,13.0 )
("BOS","SLC")=>lognormal(279.7 ,11.1 )
("BOS","STL")=>lognormal(150.2 ,7.3 )
("BOS","TPA")=>lognormal(162.1 ,8.4 )
("BWI","ATL")=>lognormal(86.0 ,61.7 )
("BWI","BOS")=>lognormal(60.5 ,5.5 )
("BWI","CLE")=>lognormal(53.2 ,5.0 )
("BWI","CLT")=>lognormal(59.3 ,8.8 )
("BWI","CVG")=>lognormal(71.9 ,5.6 )
("BWI","DEN")=>lognormal(198.8 ,9.9 )
("BWI","DFW")=>lognormal(162.0 ,9.9 )
("BWI","DTW")=>lognormal(65.8 ,5.0 )
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("BWI","FLL")=>lognormal(129.8 ,8.5 )
("BWI","IAH")=>lognormal(168.5 ,9.9 )
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("BWI","LAS")=>lognormal(269.5, 11.7)
("BWI","LAX")=>lognormal(292.5, 11.4)
("BWI","MCO")=>lognormal(108.6, 5.9)
("BWI","MDW")=>lognormal(94.6, 7.0)
("BWI","MEM")=>lognormal(112.5, 4.4)
("BWI","MIA")=>lognormal(125.9, 7.2)
("BWI","MSP")=>lognormal(133.3, 8.9)
("BWI","ORD")=>lognormal(97.1, 9.4)
("BWI","PHL")=>lognormal(28.2, 4.9)
("BWI","PHX")=>lognormal(256.7, 11.9)
("BWI","PIT")=>lognormal(37.5, 6.0)
("BWI","SAN")=>lognormal(289.2, 12.7)
("BWI","SFO")=>lognormal(308.9, 11.2)
("BWI","SLC")=>lognormal(250.2, 8.8)
("BWI","STL")=>lognormal(107.5, 4.9)
("BWI","TPA")=>lognormal(118.2, 8.5)
("CLE","ATL")=>lognormal(75.2, 133.8)
("CLE","BOS")=>lognormal(81.2, 8.3)
("CLE","BWI")=>lognormal(55.6, 5.1)
("CLE","CLT")=>lognormal(69.1, 5.8)
("CLE","CVG")=>lognormal(44.4, 4.9)
("CLE","DCA")=>lognormal(54.0, 8.8)
("CLE","DEN")=>lognormal(160.3, 8.8)
("CLE","DFW")=>lognormal(140.3,10.8)
("CLE","DTW")=>lognormal(26.6,3.9)
("CLE","EWR")=>lognormal(66.5,7.9)
("CLE","FLL")=>lognormal(147.7,6.5)
("CLE","IAD")=>lognormal(52.8,5.3)
("CLE","IAH")=>lognormal(148.8,10.2)
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("CLE","LAS")=>lognormal(230.7,10.6)
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("CLE","LGA")=>lognormal(69.6,7.0)
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("CLE","MDW")=>lognormal(52.7,4.9)
("CLE","MEM")=>lognormal(91.4,3.7)
("CLE","MIA")=>lognormal(150.6,7.3)
("CLE","MSP")=>lognormal(97.6,8.5)
("CLE","ORD")=>lognormal(55.4,5.4)
("CLE","PHL")=>lognormal(61.7,7.0)
("CLE","PHX")=>lognormal(222.7,10.3)
("CLE","SAN")=>lognormal(250.9,8.0)
("CLE","SEA")=>lognormal(264.8,11.6)
("CLE","SFO")=>lognormal(272.6,10.3)
("CLE","STL")=>lognormal(75.4,4.5)
("CLE","TPA")=>lognormal(129.6,6.9)
("CLT","ATL")=>lognormal(46.1,8.2)
("CLT","BOS") => lognormal(100.6 ,6.6 ) |
("CLT","BWI") => lognormal(57.8 ,6.4 ) |
("CLT","CLE") => lognormal(68.4 ,6.6 ) |
("CLT","CVG") => lognormal(55.1 ,96.2 ) |
("CLT","DCA") => lognormal(54.6 ,5.2 ) |
("CLT","DEN") => lognormal(178.7 ,8.5 ) |
("CLT","DFW") => lognormal(129.3 ,7.5 ) |
("CLT","DTW") => lognormal(80.2 ,6.6 ) |
("CLT","EWR") => lognormal(84.2 ,10.0 ) |
("CLT","FLL") => lognormal(90.7 ,6.3 ) |
("CLT","IAD") => lognormal(58.9 ,6.9 ) |
("CLT","IAH") => lognormal(130.1 ,7.3 ) |
("CLT","JFK") => lognormal(88.2 ,12.3 ) |
("CLT","LAS") => lognormal(239.7 ,8.3 ) |
("CLT","LAX") => lognormal(263.0 ,9.3 ) |
("CLT","LGA") => lognormal(82.8 ,9.3 ) |
("CLT","MCO") => lognormal(66.4 ,6.6 ) |
("CLT","MEM") => lognormal(74.5 ,3.2 ) |
("CLT","MIA") => lognormal(93.0 ,5.9 ) |
("CLT","MSP") => lognormal(137.4 ,8.6 ) |
("CLT","ORD") => lognormal(93.9 ,12.5 ) |
("CLT","PHL") => lognormal(71.8 ,6.8 ) |
("CLT","PHX") => lognormal(228.1 ,8.4 ) |
("CLT","PIT") => lognormal(57.7 ,5.6 ) |
("CLT","SAN")=>lognormal(258.6 ,10.5 )
("CLT","SEA")=>lognormal(299.8 ,7.4 )
("CLT","SFO")=>lognormal(288.4 ,9.8 )
("CLT","STL")=>lognormal(88.0 ,3.8 )
("CLT","TPA")=>lognormal(72.7 ,7.9 )
("CVG","ATL")=>lognormal(69.3 ,8.5 )
("CVG","BOS")=>lognormal(104.4 ,8.6 )
("CVG","BWI")=>lognormal(65.6 ,6.9 )
("CVG","CLE")=>lognormal(40.4 ,3.7 )
("CVG","CLT")=>lognormal(57.2 ,8.5 )
("CVG","DCA")=>lognormal(63.5 ,7.2 )
("CVG","DEN")=>lognormal(142.1 ,8.2 )
("CVG","DFW")=>lognormal(115.2 ,8.9 )
("CVG","DTW")=>lognormal(44.3 ,6.5 )
("CVG","EWR")=>lognormal(92.1 ,9.4 )
("CVG","FLL")=>lognormal(134.2 ,7.6 )
("CVG","IAD")=>lognormal(63.3 ,6.0 )
("CVG","IAH")=>lognormal(127.3 ,11.9 )
("CVG","JFK")=>lognormal(95.0 ,9.2 )
("CVG","LAS")=>lognormal(213.9 ,9.6 )
("CVG","LAX")=>lognormal(234.9 ,9.2 )
("CVG","LGA")=>lognormal(90.4 ,8.6 )
("CVG","MCO")=>lognormal(103.9 ,6.4 )
("CVG","MEM")=>lognormal(62.1 ,5.2 )
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("DCA","JFK")=>lognormal(46.1,6.8)
("DCA","LAS")=>lognormal(266.4,12.4)
("DCA","LAX")=>lognormal(288.9,12.9)
("DCA","LGA")=>lognormal(44.2,6.3)
("DCA","MCO")=>lognormal(109.6,5.7)
("DCA","MDW")=>lognormal(90.6,6.2)
("DCA","MEM")=>lognormal(107.0,6.0)
("DCA","MIA")=>lognormal(125.0,6.8)
("DCA","MSP")=>lognormal(132.7,8.6)
("DCA","ORD")=>lognormal(94.4,10.0)
("DCA","PHL")=>lognormal(30.8,4.3)
("DCA","PHX")=>lognormal(253.8,11.1)
("DCA","PIT")=>lognormal(37.2,5.7)
("DCA","SEA")=>lognormal(311.9,11.5)
("DCA","SLC")=>lognormal(247.2,9.0)
("DCA","STL")=>lognormal(104.7,4.4)
("DCA","TPA")=>lognormal(116.2,8.1)
("DEN","ATL")=>lognormal(154.6,12.1)
("DEN","BOS")=>lognormal(225.1,41.4)
("DEN","BWI")=>lognormal(183.2,11.0)
("DEN","CLE")=>lognormal(148.5,8.7)
("DEN","CLT")=>lognormal(166.0,9.0)
("DEN","CVG")=>lognormal(135.9,9.0)
("DEN","DCA")=>lognormal(182.6,11.9)

("DEN", "DFW")=>lognormal(87.5 , 5.3 ) | 
("DEN", "DTW")=>lognormal(142.1 , 8.2 ) | 
("DEN", "EWR")=>lognormal(202.0 , 13.8 ) | 
("DEN", "FLL")=>lognormal(213.2 , 8.7 ) | 
("DEN", "IAD")=>lognormal(176.9 , 9.2 ) | 
("DEN", "IAH")=>lognormal(117.8 , 8.2 ) | 
("DEN", "JFK")=>lognormal(322.5 , 13.6 ) | 
("DEN", "LAS")=>lognormal(87.1 , 4.1 ) | 
("DEN", "LAX")=>lognormal(113.6 , 4.9 ) | 
("DEN", "LGA")=>lognormal(200.7 , 12.9 ) | 
("DEN", "MCO")=>lognormal(191.9 , 7.3 ) | 
("DEN", "MDW")=>lognormal(115.7 , 6.9 ) | 
("DEN", "MEM")=>lognormal(114.5 , 7.2 ) | 
("DEN", "MIA")=>lognormal(210.9 , 8.1 ) | 
("DEN", "MSP")=>lognormal(93.2 , 6.7 ) | 
("DEN", "ORD")=>lognormal(116.6 , 7.3 ) | 
("DEN", "PDX")=>lognormal(137.7 , 5.2 ) | 
("DEN", "PHL")=>lognormal(194.6 , 12.2 ) | 
("DEN", "PHX")=>lognormal(86.1 , 4.7 ) | 
("DEN", "PIT")=>lognormal(158.2 , 6.5 ) | 
("DEN", "SAN")=>lognormal(113.6 , 5.5 ) | 
("DEN", "SEA")=>lognormal(144.2 , 6.1 ) | 
("DEN", "SFO")=>lognormal(127.6 , 6.4 ) | 
("DEN", "SLC")=>lognormal(63.3 , 4.4 ) |
("DEN","STL")=>lognormal(100.9 ,4.7 )|
("DEN","TPA")=>lognormal(186.1 ,7.0 )|
("DFW","ATL")=>lognormal(105.2 ,10.2 )|
("DFW","BOS")=>lognormal(194.1 ,9.5 )|
("DFW","BWI")=>lognormal(153.7 ,9.1 )|
("DFW","CLE")=>lognormal(130.0 ,8.2 )|
("DFW","CLT")=>lognormal(125.2 ,6.1 )|
("DFW","CVG")=>lognormal(110.4 ,5.0 )|
("DFW","DCA")=>lognormal(150.9 ,7.9 )|
("DFW","DEN")=>lognormal(92.6 ,7.0 )|
("DFW","DTW")=>lognormal(131.2 ,9.1 )|
("DFW","EWR")=>lognormal(182.5 ,14.7 )|
("DFW","FLL")=>lognormal(147.1 ,9.3 )|
("DFW","IAD")=>lognormal(149.4 ,8.1 )|
("DFW","IAH")=>lognormal(42.9 ,5.3 )|
("DFW","JFK")=>lognormal(183.3 ,11.5 )|
("DFW","LAS")=>lognormal(138.4 ,5.6 )|
("DFW","LAX")=>lognormal(156.4 ,5.6 )|
("DFW","LGA")=>lognormal(182.9 ,12.0 )|
("DFW","MCO")=>lognormal(131.3 ,8.3 )|
("DFW","MDW")=>lognormal(108.6 ,12.0 )|
("DFW","MEM")=>lognormal(65.1 ,5.0 )|
("DFW","MIA")=>lognormal(142.6 ,6.6 )|
("DFW","MSP")=>lognormal(118.6 ,7.8 )|
("DTW","JFK")=>lognormal(77.8 ,7.1 )|
("DTW","LAS")=>lognormal(223.4 ,10.1 )|
("DTW","LAX")=>lognormal(247.7 ,10.7 )|
("DTW","LGA")=>lognormal(76.9 ,7.9 )|
("DTW","MCO")=>lognormal(128.4 ,7.3 )|
("DTW","MDW")=>lognormal(44.6 ,4.4 )|
("DTW","MEM")=>lognormal(88.6 ,4.9 )|
("DTW","MIA")=>lognormal(151.7 ,6.9 )|
("DTW","MSP")=>lognormal(87.2 ,7.4 )|
("DTW","ORD")=>lognormal(45.2 ,5.7 )|
("DTW","PDX")=>lognormal(257.0 ,9.3 )|
("DTW","PHL")=>lognormal(71.8 ,6.6 )|
("DTW","PHX")=>lognormal(215.2 ,10.5 )|
("DTW","PIT")=>lognormal(36.6 ,3.0 )|
("DTW","SAN")=>lognormal(245.9 ,10.5 )|
("DTW","SEA")=>lognormal(258.9 ,9.4 )|
("DTW","SFO")=>lognormal(264.4 ,11.5 )|
("DTW","SLC")=>lognormal(201.7 ,8.8 )|
("DTW","STL")=>lognormal(70.7 ,5.3 )|
("DTW","TPA")=>lognormal(128.9 ,5.1 )|
("EWR","ATL")=>lognormal(109.3 ,10.1 )|
("EWR","BOS")=>lognormal(39.9 ,4.5 )|
("EWR","BWI")=>lognormal(36.3 ,4.4 )|
("EWR","CLE")=>lognormal(65.1 ,7.6 )|
("EWR","CLT")=>lognormal(81.1 ,9.6 )
("EWR","CVG")=>lognormal(90.3 ,5.6 )
("EWR","DCA")=>lognormal(39.8 ,5.6 )
("EWR","DEN")=>lognormal(213.3 ,10.1 )
("EWR","DFW")=>lognormal(184.3 ,9.8 )
("EWR","DTW")=>lognormal(81.7 ,8.2 )
("EWR","FLL")=>lognormal(145.5 ,9.9 )
("EWR","IAD")=>lognormal(45.7 ,6.5 )
("EWR","IAH")=>lognormal(185.8 ,11.6 )
("EWR","LAS")=>lognormal(280.5 ,12.3 )
("EWR","LAX")=>lognormal(305.5 ,11.6 )
("EWR","MCO")=>lognormal(128.2 ,9.4 )
("EWR","MDW")=>lognormal(104.6 ,6.8 )
("EWR","MEM")=>lognormal(135.2 ,7.4 )
("EWR","MIA")=>lognormal(146.2 ,8.1 )
("EWR","MSP")=>lognormal(146.7 ,8.8 )
("EWR","ORD")=>lognormal(110.2 ,7.7 )
("EWR","PDX")=>lognormal(318.9 ,11.7 )
("EWR","PHL")=>lognormal(29.7 ,5.1 )
("EWR","PHX")=>lognormal(271.6 ,11.2 )
("EWR","PIT")=>lognormal(54.3 ,5.3 )
("EWR","SAN")=>lognormal(303.1 ,10.6 )
("EWR","SEA")=>lognormal(318.1 ,12.4 )
("EWR","SFO")=>lognormal(325.9 ,11.6 )
("EWR","SLC")=>lognormal(262.5 ,11.2 )
("EWR","STL")=>lognormal(127.6 ,5.7 )
("EWR","TPA")=>lognormal(139.1 ,11.0 )
("FLL","ATL")=>lognormal(86.7 ,10.6 )
("FLL","BOS")=>lognormal(161.2 ,6.4 )
("FLL","BWI")=>lognormal(126.9 ,7.0 )
("FLL","CLE")=>lognormal(141.0 ,6.1 )
("FLL","CLT")=>lognormal(95.4 ,6.3 )
("FLL","CVG")=>lognormal(125.5 ,6.9 )
("FLL","DCA")=>lognormal(121.0 ,6.3 )
("FLL","DEN")=>lognormal(218.1 ,10.1 )
("FLL","DFW")=>lognormal(150.4 ,8.1 )
("FLL","DTW")=>lognormal(151.1 ,9.5 )
("FLL","EWR")=>lognormal(150.7 ,10.3 )
("FLL","IAD")=>lognormal(119.9 ,4.6 )
("FLL","IAH")=>lognormal(127.8 ,7.9 )
("FLL","JFK")=>lognormal(146.1 ,66.1 )
("FLL","LAS")=>lognormal(268.4 ,11.1 )
("FLL","LAX")=>lognormal(285.4 ,6.7 )
("FLL","LGA")=>lognormal(147.2 ,10.7 )
("FLL","MCO")=>lognormal(35.4 ,3.3 )
("FLL","MDW")=>lognormal(154.0 ,8.4 )
("FLL","MEM")=>lognormal(114.6 ,5.9 )
("FLL","MSP")=>lognormal(195.2 ,7.8 )
("FLL","ORD")=>lognormal(160.5,9.0)
("FLL","PHL")=>lognormal(139.7,9.5)
("FLL","PHX")=>lognormal(253.2,9.1)
("FLL","PIT")=>lognormal(132.2,5.8)
("FLL","SLC")=>lognormal(264.3,7.7)
("FLL","STL")=>lognormal(137.9,7.0)
("FLL","TPA")=>lognormal(38.1,3.8)
("IAD","ATL")=>lognormal(82.9,10.1)
("IAD","BOS")=>lognormal(65.6,5.7)
("IAD","CLE")=>lognormal(52.3,6.4)
("IAD","CLT")=>lognormal(54.0,9.2)
("IAD","CVG")=>lognormal(67.3,6.3)
("IAD","DEN")=>lognormal(192.9,11.5)
("IAD","DFW")=>lognormal(155.6,9.1)
("IAD","DTW")=>lognormal(65.5,7.4)
("IAD","EWR")=>lognormal(46.5,6.5)
("IAD","FLL")=>lognormal(128.2,7.5)
("IAD","IAH")=>lognormal(163.0,9.2)
("IAD","JFK")=>lognormal(49.0,7.0)
("IAD","LAS")=>lognormal(263.1,10.3)
("IAD","LAX")=>lognormal(283.5,10.4)
("IAD","LGA")=>lognormal(46.1,7.7)
("IAD","MCO")=>lognormal(105.1,6.6)
("IAD","MDW")=>lognormal(88.9,6.4)
("IAD","MIA")=>lognormal(130.2 ,6.7 )
("IAD","MSP")=>lognormal(132.8 ,7.6 )
("IAD","ORD")=>lognormal(92.0 ,12.3 )
("IAD","PDX")=>lognormal(304.7 ,9.4 )
("IAD","PHX")=>lognormal(252.5 ,11.4 )
("IAD","PIT")=>lognormal(33.7 ,5.0 )
("IAD","SAN")=>lognormal(245.4 ,73.9 )
("IAD","SEA")=>lognormal(304.3 ,10.1 )
("IAD","SFO")=>lognormal(304.4 ,11.3 )
("IAD","SLC")=>lognormal(242.2 ,9.2 )
("IAD","TPA")=>lognormal(110.9 ,7.0 )
("IAH","ATL")=>lognormal(101.5 ,9.9 )
("IAH","BOS")=>lognormal(202.4 ,9.2 )
("IAH","BWI")=>lognormal(160.6 ,8.1 )
("IAH","CLE")=>lognormal(136.9 ,7.4 )
("IAH","CLT")=>lognormal(125.7 ,6.3 )
("IAH","CVG")=>lognormal(119.0 ,7.5 )
("IAH","DCA")=>lognormal(158.1 ,8.6 )
("IAH","DEN")=>lognormal(117.5 ,8.3 )
("IAH","DFW")=>lognormal(43.3 ,6.1 )
("IAH","DTW")=>lognormal(140.7 ,12.3 )
("IAH","EWR")=>lognormal(184.6 ,14.0 )
("IAH","FLL")=>lognormal(125.9 ,8.2 )
("IAH","IAD")=>lognormal(160.6 ,8.2 )
("IAH", "JFK") => lognormal(192.3, 6.3)
("IAH", "LAS") => lognormal(156.8, 5.1)
("IAH", "LAX") => lognormal(170.8, 6.1)
("IAH", "LGA") => lognormal(186.4, 12.6)
("IAH", "MCO") => lognormal(115.8, 5.8)
("IAH", "MEM") => lognormal(70.8, 5.3)
("IAH", "MIA") => lognormal(126.6, 8.6)
("IAH", "MSP") => lognormal(139.0, 7.1)
("IAH", "ORD") => lognormal(125.1, 10.5)
("IAH", "PDX") => lognormal(230.7, 8.4)
("IAH", "PHL") => lognormal(173.9, 9.6)
("IAH", "PHX") => lognormal(133.9, 5.6)
("IAH", "PIT") => lognormal(146.3, 7.5)
("IAH", "SAN") => lognormal(162.4, 6.5)
("IAH", "SEA") => lognormal(239.7, 8.5)
("IAH", "SFO") => lognormal(210.5, 9.4)
("IAH", "SLC") => lognormal(160.3, 6.7)
("IAH", "STL") => lognormal(98.3, 4.6)
("IAH", "TPA") => lognormal(106.4, 7.2)
("JFK", "ATL") => lognormal(112.7, 12.1)
("JFK", "BOS") => lognormal(39.1, 10.0)
("JFK", "BWI") => lognormal(36.8, 6.6)
("JFK", "CLE") => lognormal(71.2, 6.7)
("JFK", "CLT") => lognormal(89.9, 26.0)
("JFK","CVG")=lognormal(92.0,7.3)
("JFK","DCA")=lognormal(47.6,5.0)
("JFK","DEN")=lognormal(94.6,11.8)
("JFK","DFW")=lognormal(181.8,11.7)
("JFK","DTW")=lognormal(85.3,13.6)
("JFK","FLL")=lognormal(143.6,8.2)
("JFK","IAD")=lognormal(50.0,7.6)
("JFK","IAH")=lognormal(190.5,10.5)
("JFK","LAS")=lognormal(185.8,89.4)
("JFK","LAX")=lognormal(309.8,11.7)
("JFK","MCO")=lognormal(128.4,7.6)
("JFK","MIA")=lognormal(142.0,7.5)
("JFK","MSP")=lognormal(151.9,9.0)
("JFK","ORD")=lognormal(122.4,33.7)
("JFK","PDX")=lognormal(144.2,11.6)
("JFK","PHL")=lognormal(31.0,5.9)
("JFK","PHX")=lognormal(230.5,78.4)
("JFK","PIT")=lognormal(64.4,10.4)
("JFK","SAN")=lognormal(198.1,89.0)
("JFK","SEA")=lognormal(270.7,81.5)
("JFK","SFO")=lognormal(329.6,13.1)
("JFK","SLC")=lognormal(233.6,55.2)
("JFK","STL")=lognormal(127.2,8.6)
("JFK","TPA")=lognormal(138.1,8.4)
("LAS","ATL")=>lognormal(214.5,11.1)
("LAS","BOS")=>lognormal(314.9,72.3)
("LAS","BWI")=>lognormal(250.1,12.5)
("LAS","CLE")=>lognormal(214.7,8.3)
("LAS","CLT")=>lognormal(228.2,7.7)
("LAS","CVG")=>lognormal(203.5,8.7)
("LAS","DCA")=>lognormal(248.5,8.5)
("LAS","DEN")=>lognormal(86.9,4.8)
("LAS","DFW")=>lognormal(133.5,6.1)
("LAS","DTW")=>lognormal(212.3,9.6)
("LAS","EWR")=>lognormal(267.7,13.4)
("LAS","FLL")=>lognormal(258.5,6.8)
("LAS","IAD")=>lognormal(251.1,11.2)
("LAS","IAH")=>lognormal(157.1,10.1)
("LAS","JFK")=>lognormal(375.8,123.1)
("LAS","LAX")=>lognormal(40.4,3.3)
("LAS","MCO")=>lognormal(242.0,5.9)
("LAS","MDW")=>lognormal(186.2,7.2)
("LAS","MEM")=>lognormal(176.9,6.8)
("LAS","MIA")=>lognormal(261.7,7.2)
("LAS","MSP")=>lognormal(161.4,7.0)
("LAS","ORD")=>lognormal(187.6,8.3)
("LAS","PDX")=>lognormal(108.6,4.8)
("LAS","PHL")=>lognormal(262.4,13.6)
("LAS","PHX")$\Rightarrow$lognormal(46.6, 4.7)

("LAS","PIT")$\Rightarrow$lognormal(225.1, 8.4)

("LAS","SAN")$\Rightarrow$lognormal(44.2, 4.7)

("LAS","SEA")$\Rightarrow$lognormal(123.3, 5.6)

("LAS","SFO")$\Rightarrow$lognormal(64.6, 4.2)

("LAS","SLC")$\Rightarrow$lognormal(58.6, 3.8)

("LAS","STL")$\Rightarrow$lognormal(167.6, 5.4)

("LAS","TPA")$\Rightarrow$lognormal(237.3, 5.2)

("LAX","ATL")$\Rightarrow$lognormal(238.9, 13.3)

("LAX","BOS")$\Rightarrow$lognormal(308.0, 11.3)

("LAX","BWI")$\Rightarrow$lognormal(281.9, 11.3)

("LAX","CLE")$\Rightarrow$lognormal(245.2, 11.0)

("LAX","CLT")$\Rightarrow$lognormal(259.5, 9.8)

("LAX","CVG")$\Rightarrow$lognormal(228.9, 9.3)

("LAX","DCA")$\Rightarrow$lognormal(279.9, 10.6)

("LAX","DEN")$\Rightarrow$lognormal(113.9, 6.0)

("LAX","DFW")$\Rightarrow$lognormal(157.9, 7.2)

("LAX","DTW")$\Rightarrow$lognormal(240.1, 11.3)

("LAX","EWR")$\Rightarrow$lognormal(296.3, 14.8)

("LAX","FLL")$\Rightarrow$lognormal(278.9, 9.5)

("LAX","IAD")$\Rightarrow$lognormal(275.7, 11.1)

("LAX","IAH")$\Rightarrow$lognormal(174.8, 9.4)

("LAX","JFK")$\Rightarrow$lognormal(300.5, 14.2)

("LAX","LAS")$\Rightarrow$lognormal(45.2, 4.8)
('LAX', 'MCO') = lognormal(269.3, 8.7)
('LAX', 'MDW') = lognormal(217.0, 8.5)
('LAX', 'MEM') = lognormal(200.9, 8.3)
('LAX', 'MIA') = lognormal(275.8, 8.1)
('LAX', 'MSP') = lognormal(188.9, 8.8)
('LAX', 'ORD') = lognormal(215.0, 9.0)
('LAX', 'PDX') = lognormal(112.5, 4.1)
('LAX', 'PHL') = lognormal(292.4, 13.4)
('LAX', 'PHX') = lognormal(59.5, 3.8)
('LAX', 'PIT') = lognormal(257.7, 9.5)
('LAX', 'SAN') = lognormal(33.7, 3.9)
('LAX', 'SEA') = lognormal(128.0, 5.5)
('LAX', 'SFO') = lognormal(51.8, 4.8)
('LAX', 'SLC') = lognormal(85.0, 5.1)
('LAX', 'STL') = lognormal(197.2, 8.0)
('LAX', 'TPA') = lognormal(257.8, 7.2)
('LGA', 'ATL') = lognormal(111.7, 9.5)
('LGA', 'BOS') = lognormal(37.0, 4.7)
('LGA', 'CLE') = lognormal(68.3, 6.4)
('LGA', 'CLT') = lognormal(83.1, 8.5)
('LGA', 'CVG') = lognormal(92.2, 6.3)
('LGA', 'DCA') = lognormal(42.6, 5.9)
('LGA', 'DEN') = lognormal(215.2, 10.3)
('LGA', 'DFW') = lognormal(184.4, 8.2)
("LGA","DTW")=\text{lognormal}(81.1 ,7.4 )}
("LGA","FLL")=\text{lognormal}(144.8 ,9.2 )}
("LGA","IAD")=\text{lognormal}(45.7 ,3.8 )}
("LGA","IAH")=\text{lognormal}(189.1 ,10.3 )}
("LGA","MCO")=\text{lognormal}(128.0 ,7.2 )}
("LGA","MDW")=\text{lognormal}(105.7 ,6.4 )}
("LGA","MEM")=\text{lognormal}(134.0 ,6.9 )}
("LGA","MIA")=\text{lognormal}(144.8 ,8.4 )}
("LGA","MSP")=\text{lognormal}(144.6 ,8.5 )}
("LGA","ORD")=\text{lognormal}(111.5 ,8.3 )}
("LGA","PHL")=\text{lognormal}(33.8 ,6.9 )}
("LGA","PIT")=\text{lognormal}(57.3 ,4.7 )}
("LGA","STL")=\text{lognormal}(125.4 ,7.2 )}
("LGA","TPA")=\text{lognormal}(139.9 ,8.5 )}
("MCO","ATL")=\text{lognormal}(66.8 ,10.0 )}
("MCO","BOS")=\text{lognormal}(153.9 ,91.2 )}
("MCO","BWI")=\text{lognormal}(108.7 ,5.7 )}
("MCO","CLE")=\text{lognormal}(120.9 ,4.8 )}
("MCO","CLT")=\text{lognormal}(75.5 ,5.3 )}
("MCO","CVG")=\text{lognormal}(107.9 ,7.8 )}
("MCO","DCA")=\text{lognormal}(105.6 ,5.9 )}
("MCO","DEN")=\text{lognormal}(199.6 ,7.2 )}
("MCO","DFW")=\text{lognormal}(133.4 ,8.0 )}
("MCO","DTW")=\text{lognormal}(132.2 ,9.6 )
("MCO","EWR")=>lognormal(134.5 ,12.6 )
("MCO","FLL")=>lognormal(39.6 ,4.8 )
("MCO","IAD")=>lognormal(104.5 ,4.9 )
("MCO","IAH")=>lognormal(116.1 ,8.3 )
("MCO","JFK")=>lognormal(135.7 ,89.7 )
("MCO","LAS")=>lognormal(254.2 ,9.3 )
("MCO","LAX")=>lognormal(273.1 ,6.6 )
("MCO","LGA")=>lognormal(130.5 ,9.2 )
("MCO","MDW")=>lognormal(131.9 ,7.1 )
("MCO","MEM")=>lognormal(94.5 ,5.0 )
("MCO","MIA")=>lognormal(39.9 ,4.7 )
("MCO","MSP")=>lognormal(175.3 ,8.9 )
("MCO","ORD")=>lognormal(141.7 ,10.1 )
("MCO","PHL")=>lognormal(123.1 ,8.8 )
("MCO","PHX")=>lognormal(236.8 ,8.9 )
("MCO","PIT")=>lognormal(112.3 ,7.3 )
("MCO","SEA")=>lognormal(324.2 ,9.2 )
("MCO","SFO")=>lognormal(303.8 ,9.3 )
("MCO","SLC")=>lognormal(245.2 ,8.2 )
("MCO","STL")=>lognormal(121.0 ,6.5 )
("MDW","ATL")=>lognormal(91.3 ,10.7 )
("MDW","BOS")=>lognormal(111.1 ,7.8 )
("MDW","BWI")=>lognormal(87.0 ,6.8 )
("MDW","CLE")=>lognormal(49.2 ,7.5 )
\begin{verbatim}
("MEM","CLE")=>lognormal(86.5,5.3) |
("MEM","CLT")=>lognormal(75.9,5.5) |
("MEM","CVG")=>lognormal(65.1,5.3) |
("MEM","DCA")=>lognormal(102.6,11.7) |
("MEM","DEN")=>lognormal(119.9,8.1) |
("MEM","DFW")=>lognormal(65.2,5.9) |
("MEM","DTW")=>lognormal(86.7,8.0) |
("MEM","EWR")=>lognormal(134.3,11.5) |
("MEM","FLL")=>lognormal(115.4,6.7) |
("MEM","IAH")=>lognormal(77.0,9.2) |
("MEM","LAS")=>lognormal(181.8,7.4) |
("MEM","LAX")=>lognormal(200.8,7.2) |
("MEM","LGA")=>lognormal(130.0,10.3) |
("MEM","MCO")=>lognormal(96.3,6.2) |
("MEM","MIA")=>lognormal(119.5,8.0) |
("MEM","MSP")=>lognormal(102.1,8.8) |
("MEM","ORD")=>lognormal(78.0,7.3) |
("MEM","PHL")=>lognormal(122.4,8.6) |
("MEM","PHX")=>lognormal(164.0,7.5) |
("MEM","SEA")=>lognormal(246.5,9.9) |
("MEM","SFO")=>lognormal(224.7,9.0) |
("MEM","STL")=>lognormal(44.7,4.3) |
("MEM","TPA")=>lognormal(92.1,5.3) |
("MIA","ATL")=>lognormal(89.6,11.1) |
\end{verbatim}
("MIA","BOS")=>lognormal(162.5 ,7.7 )
("MIA","BWI")=>lognormal(125.6 ,6.5 )
("MIA","CLE")=>lognormal(145.7 ,6.3 )
("MIA","CLT")=>lognormal(98.0 ,5.8 )
("MIA","CVG")=>lognormal(130.8 ,6.2 )
("MIA","DCA")=>lognormal(121.7 ,5.8 )
("MIA","DEN")=>lognormal(217.9 ,8.2 )
("MIA","DFW")=>lognormal(146.5 ,7.3 )
("MIA","DTW")=>lognormal(152.2 ,8.8 )
("MIA","EWR")=>lognormal(155.1 ,11.6 )
("MIA","IAD")=>lognormal(125.6 ,6.8 )
("MIA","IAH")=>lognormal(129.7 ,9.6 )
("MIA","JFK")=>lognormal(144.4 ,10.6 )
("MIA","LAS")=>lognormal(271.8 ,8.8 )
("MIA","LAX")=>lognormal(282.3 ,5.7 )
("MIA","LGA")=>lognormal(150.3 ,10.5 )
("MIA","MCO")=>lognormal(38.2 ,5.5 )
("MIA","MEM")=>lognormal(117.5 ,4.9 )
("MIA","MSP")=>lognormal(192.8 ,8.1 )
("MIA","ORD")=>lognormal(162.6 ,12.2 )
("MIA","PHL")=>lognormal(139.7 ,9.0 )
("MIA","PHX")=>lognormal(251.9 ,6.5 )
("MIA","PIT")=>lognormal(135.9 ,4.1 )
("MIA","SEA")=>lognormal(367.7 ,15.9 )
("MIA", "SFO") => lognormal(317.9, 7.9)
("MIA", "STL") => lognormal(136.9, 4.9)
("MIA", "TPA") => lognormal(38.3, 4.5)
("MSP", "ATL") => lognormal(127.5, 11.0)
("MSP", "BOS") => lognormal(141.3, 9.3)
("MSP", "BWI") => lognormal(122.8, 7.3)
("MSP", "CLE") => lognormal(88.7, 10.2)
("MSP", "CLT") => lognormal(122.5, 7.7)
("MSP", "CVG") => lognormal(87.2, 8.8)
("MSP", "DCA") => lognormal(119.6, 9.7)
("MSP", "DEN") => lognormal(95.8, 7.0)
("MSP", "DFW") => lognormal(117.6, 6.9)
("MSP", "DTW") => lognormal(75.9, 8.1)
("MSP", "EWR") => lognormal(135.0, 11.0)
("MSP", "FLL") => lognormal(193.5, 9.0)
("MSP", "IAD") => lognormal(121.9, 8.3)
("MSP", "IAH") => lognormal(145.3, 9.0)
("MSP", "JFK") => lognormal(137.9, 7.1)
("MSP", "LAS") => lognormal(169.2, 7.4)
("MSP", "LAX") => lognormal(194.0, 7.7)
("MSP", "LGA") => lognormal(134.8, 10.4)
("MSP", "MCO") => lognormal(196.5, 8.5)
("MSP", "MDW") => lognormal(65.0, 6.4)
("MSP", "MEM") => lognormal(98.1, 8.9)
("MSP","MIA")=>lognormal(190.0,9.7)
("MSP","ORD")=>lognormal(54.2,6.2)
("MSP","PDX")=>lognormal(191.6,6.1)
("MSP","PHL")=>lognormal(130.4,9.5)
("MSP","PHX")=>lognormal(165.1,7.8)
("MSP","PIT")=>lognormal(96.5,5.1)
("MSP","SAN")=>lognormal(193.3,8.1)
("MSP","SEA")=>lognormal(191.5,5.9)
("MSP","SFO")=>lognormal(206.1,8.1)
("MSP","SLC")=>lognormal(142.3,7.0)
("MSP","STL")=>lognormal(66.2,5.4)
("MSP","TPA")=>lognormal(166.8,8.2)
("ORD","ATL")=>lognormal(92.6,11.1)
("ORD","BOS")=>lognormal(111.8,8.2)
("ORD","BWI")=>lognormal(87.5,7.5)
("ORD","CLE")=>lognormal(48.5,5.1)
("ORD","CLT")=>lognormal(87.3,8.2)
("ORD","CVG")=>lognormal(49.8,8.3)
("ORD","DCA")=>lognormal(84.4,7.2)
("ORD","DEN")=>lognormal(120.4,7.9)
("ORD","DFW")=>lognormal(111.7,8.7)
("ORD","DTW")=>lognormal(49.3,6.8)
("ORD","EWR")=>lognormal(100.7,10.2)
("ORD","FLL")=>lognormal(157.1,8.5)
("ORD","IAD")=lognormal(85.8,8.5)
("ORD","IAH")=lognormal(132.7,11.8)
("ORD","JFK")=lognormal(104.4,6.4)
("ORD","LAS")=lognormal(194.1,8.0)
("ORD","LAX")=lognormal(218.7,8.8)
("ORD","LGA")=lognormal(102.2,10.6)
("ORD","MCO")=lognormal(132.9,9.1)
("ORD","MEM")=lognormal(75.3,5.2)
("ORD","MIA")=lognormal(155.5,7.8)
("ORD","MSP")=lognormal(62.4,7.5)
("ORD","PDX")=lognormal(229.6,7.5)
("ORD","PHL")=lognormal(94.9,8.6)
("ORD","PHX")=lognormal(185.8,8.1)
("ORD","PIT")=lognormal(60.1,4.4)
("ORD","SAN")=lognormal(218.0,7.6)
("ORD","SEA")=lognormal(234.1,8.6)
("ORD","SFO")=lognormal(232.9,9.7)
("ORD","SLC")=lognormal(172.2,8.9)
("ORD","STL")=lognormal(44.8,3.8)
("ORD","TPA")=lognormal(132.9,7.3)
("PDX","ATL")=lognormal(258.4,12.7)
("PDX","CVG")=lognormal(231.0,6.2)
("PDX","DEN")=lognormal(124.4,7.2)
("PDX","DFW")=lognormal(194.9,7.4)
behavior  

("PDX","DTW")=>lognormal(227.8 ,9.3 ) 
("PDX","EWR")=>lognormal(280.3 ,11.3 ) 
("PDX","IAD")=>lognormal(272.2 ,11.5 ) 
("PDX","IAH")=>lognormal(223.7 ,11.2 ) 
("PDX","JFK")=>lognormal(461.9 ,9.0 ) 
("PDX","LAS")=>lognormal(108.0 ,5.5 ) 
("PDX","LAX")=>lognormal(117.1 ,4.1 ) 
("PDX","MDW")=>lognormal(208.9 ,4.8 ) 
("PDX","MSP")=>lognormal(169.3 ,7.6 ) 
("PDX","ORD")=>lognormal(204.8 ,7.9 ) 
("PDX","PHX")=>lognormal(133.5 ,6.2 ) 
("PDX","SAN")=>lognormal(128.1 ,7.4 ) 
("PDX","SEA")=>lognormal(35.4 ,4.0 ) 
("PDX","SFO")=>lognormal(84.7 ,5.5 ) 
("PDX","SLC")=>lognormal(85.1 ,4.9 ) 
("PHL","ATL")=>lognormal(100.2 ,9.5 ) 
("PHL","BOS")=>lognormal(50.9 ,6.6 ) 
("PHL","BWI")=>lognormal(23.6 ,3.3 ) 
("PHL","CLE")=>lognormal(59.8 ,5.1 ) 
("PHL","CLT")=>lognormal(70.0 ,8.7 ) 
("PHL","CVG")=>lognormal(80.0 ,6.2 ) 
("PHL","DCA")=>lognormal(28.5 ,5.9 ) 
("PHL","DEN")=>lognormal(206.4 ,11.3 ) 
("PHL","DFW")=>lognormal(174.3 ,9.6 )
("PHL","DTW")=>lognormal(74.9, 6.1) |
("PHL","EWR")=>lognormal(28.5, 5.9) |
("PHL","FLL")=>lognormal(134.7, 9.0) |
("PHL","IAH")=>lognormal(178.5, 11.2) |
("PHL","JFK")=>lognormal(35.6, 9.8) |
("PHL","LAS")=>lognormal(274.9, 11.3) |
("PHL","LAX")=>lognormal(300.4, 11.8) |
("PHL","LGA")=>lognormal(28.8, 4.4) |
("PHL","MCO")=>lognormal(116.3, 6.3) |
("PHL","MDW")=>lognormal(99.3, 5.8) |
("PHL","MEM")=>lognormal(125.5, 7.1) |
("PHL","MIA")=>lognormal(133.8, 8.4) |
("PHL","MSP")=>lognormal(141.7, 8.4) |
("PHL","ORD")=>lognormal(103.7, 8.9) |
("PHL","PHX")=>lognormal(262.7, 11.4) |
("PHL","PIT")=>lognormal(44.8, 4.5) |
("PHL","SAN")=>lognormal(294.9, 9.4) |
("PHL","SEA")=>lognormal(316.1, 10.5) |
("PHL","SFO")=>lognormal(317.9, 12.2) |
("PHL","SLC")=>lognormal(251.6, 9.4) |
("PHL","STL")=>lognormal(117.1, 6.6) |
("PHL","TPA")=>lognormal(127.3, 8.4) |
("PHX","ATL")=>lognormal(200.8, 11.6) |
("PHX","BOS")=>lognormal(276.9, 11.5) |
"PHX","BWI"=>lognormal(242.0 ,10.6 )
"PHX","CLE"=>lognormal(210.0 ,9.1 )
"PHX","CLT"=>lognormal(216.1 ,8.3 )
"PHX","CVG"=>lognormal(193.6 ,8.9 )
"PHX","DCA"=>lognormal(241.5 ,11.4 )
"PHX","DEN"=>lognormal(84.3 ,8.3 )
"PHX","DFW"=>lognormal(116.2 ,7.0 )
"PHX","DTW"=>lognormal(207.8 ,11.0 )
"PHX","EWR"=>lognormal(262.6 ,14.5 )
"PHX","FLL"=>lognormal(250.4 ,9.3 )
"PHX","IAD"=>lognormal(241.1 ,10.1 )
"PHX","IAH"=>lognormal(134.2 ,7.8 )
"PHX","JFK"=>lognormal(308.2 ,75.8 )
"PHX","LAS"=>lognormal(43.7 ,3.5 )
"PHX","LAX"=>lognormal(56.4 ,3.7 )
"PHX","MCO"=>lognormal(232.1 ,8.9 )
"PHX","MDW"=>lognormal(178.9 ,8.1 )
"PHX","MEM"=>lognormal(159.7 ,6.2 )
"PHX","MIA"=>lognormal(249.9 ,5.9 )
"PHX","MSP"=>lognormal(161.5 ,7.8 )
"PHX","ORD"=>lognormal(178.9 ,8.4 )
"PHX","PDX"=>lognormal(137.8 ,5.3 )
"PHX","PHL"=>lognormal(255.9 ,15.2 )
"PHX","PIT"=>lognormal(217.4 ,8.5 )
("PHX","SAN")=lognormal(48.5 ,6.3 )
("PHX","SEA")=lognormal(151.5 ,6.1 )
("PHX","SFO")=lognormal(93.9 ,7.6 )
("PHX","SLC")=lognormal(72.8 ,4.1 )
("PHX","STL")=lognormal(160.2 ,6.8 )
("PHX","TPA")=lognormal(223.3 ,6.9 )
("PIT","ATL")=lognormal(80.6 ,8.2 )
("PIT","BOS")=lognormal(74.1 ,6.5 )
("PIT","BWI")=lognormal(45.2 ,8.1 )
("PIT","CLT")=lognormal(62.7 ,6.5 )
("PIT","CVG")=lognormal(48.0 ,4.8 )
("PIT","DCA")=lognormal(41.0 ,5.0 )
("PIT","DEN")=lognormal(173.8 ,9.6 )
("PIT","DFW")=lognormal(144.9 ,9.3 )
("PIT","DTW")=lognormal(41.0 ,4.6 )
("PIT","EWR")=lognormal(60.9 ,9.0 )
("PIT","FLL")=lognormal(136.1 ,7.3 )
("PIT","IAD")=lognormal(40.0 ,4.9 )
("PIT","IAH")=lognormal(158.1 ,10.8 )
("PIT","JFK")=lognormal(66.8 ,8.4 )
("PIT","LAS")=lognormal(240.7 ,10.7 )
("PIT","LAX")=lognormal(265.3 ,9.6 )
("PIT","LGA")=lognormal(59.0 ,7.8 )
("PIT","MCO")=lognormal(110.5 ,5.8 )
("PIT","MDW")=lognormal(62.3 ,4.6 )
("PIT","MIA")=lognormal(142.2 ,6.8 )
("PIT","MSP")=lognormal(110.7 ,7.3 )
("PIT","ORD")=lognormal(67.2 ,8.9 )
("PIT","PHL")=lognormal(49.2 ,6.1 )
("PIT","PHX")=lognormal(232.3 ,11.5 )
("PIT","SAN")=lognormal(262.7 ,9.6 )
("PIT","SEA")=lognormal(283.3 ,10.1 )
("PIT","SFO")=lognormal(283.1 ,11.4 )
("PIT","TPA")=lognormal(117.5 ,9.1 )
("SAN","ATL")=lognormal(236.7 ,12.9 )
("SAN","BOS")=lognormal(306.0 ,10.1 )
("SAN","BWI")=lognormal(279.3 ,12.0 )
("SAN","CLE")=lognormal(241.6 ,5.2 )
("SAN","CLT")=lognormal(250.3 ,9.0 )
("SAN","CVG")=lognormal(229.0 ,9.7 )
("SAN","DEN")=lognormal(114.1 ,5.1 )
("SAN","DFW")=lognormal(152.1 ,5.7 )
("SAN","DTW")=lognormal(240.0 ,14.2 )
("SAN","EWR")=lognormal(291.2 ,13.3 )
("SAN","IAD")=lognormal(304.1 ,69.2 )
("SAN","IAH")=lognormal(168.6 ,8.2 )
("SAN","JFK")=lognormal(403.6 ,92.2 )
("SAN","LAS")=lognormal(50.8 ,4.3 )
\begin{align*}
("SAN","LAX") &= \text{lognormal}(28.5, 2.7) \\
("SAN","MDW") &= \text{lognormal}(213.7, 8.5) \\
("SAN","MSP") &= \text{lognormal}(193.3, 9.3) \\
("SAN","ORD") &= \text{lognormal}(214.8, 7.7) \\
("SAN","PDX") &= \text{lognormal}(124.7, 4.8) \\
("SAN","PHL") &= \text{lognormal}(284.9, 12.7) \\
("SAN","PHX") &= \text{lognormal}(51.7, 4.1) \\
("SAN","PIT") &= \text{lognormal}(252.1, 10.4) \\
("SAN","SEA") &= \text{lognormal}(138.5, 5.3) \\
("SAN","SFO") &= \text{lognormal}(63.0, 3.4) \\
("SAN","SLC") &= \text{lognormal}(82.5, 99.2) \\
("SAN","STL") &= \text{lognormal}(193.8, 8.1) \\
("SEA","ATL") &= \text{lognormal}(257.3, 12.8) \\
("SEA","BOS") &= \text{lognormal}(284.2, 9.6) \\
("SEA","CLE") &= \text{lognormal}(228.5, 5.7) \\
("SEA","CLT") &= \text{lognormal}(264.9, 9.1) \\
("SEA","CVG") &= \text{lognormal}(228.0, 7.6) \\
("SEA","DCA") &= \text{lognormal}(272.4, 16.9) \\
("SEA","DEN") &= \text{lognormal}(128.2, 6.2) \\
("SEA","DFW") &= \text{lognormal}(197.5, 7.4) \\
("SEA","DTW") &= \text{lognormal}(221.2, 10.1) \\
("SEA","EWR") &= \text{lognormal}(280.0, 12.8) \\
("SEA","IAD") &= \text{lognormal}(266.6, 9.8) \\
("SEA","IAH") &= \text{lognormal}(225.7, 9.8) 
\end{align*}
("SEA","JFK")=>lognormal(335.0,82.1)
("SEA","LAS")=>lognormal(119.0,5.6)
("SEA","LAX")=>lognormal(129.5,4.7)
("SEA","MCO")=>lognormal(299.7,9.0)
("SEA","MDW")=>lognormal(205.6,6.1)
("SEA","MEM")=>lognormal(222.1,10.4)
("SEA","MIA")=>lognormal(309.5,6.4)
("SEA","MSP")=>lognormal(164.5,8.2)
("SEA","ORD")=>lognormal(202.8,8.3)
("SEA","PDX")=>lognormal(32.9,2.4)
("SEA","PHL")=>lognormal(277.9,14.4)
("SEA","PHX")=>lognormal(144.2,8.6)
("SEA","PIT")=>lognormal(243.6,5.3)
("SEA","SAN")=>lognormal(140.7,6.8)
("SEA","SFO")=>lognormal(103.2,7.5)
("SEA","SLC")=>lognormal(90.6,4.9)
("SEA","STL")=>lognormal(200.2,6.0)
("SFO","ATL")=>lognormal(256.5,13.0)
("SFO","BOS")=>lognormal(311.7,10.7)
("SFO","BWI")=>lognormal(284.8,10.9)
("SFO","CLE")=>lognormal(247.3,7.7)
("SFO","CLT")=>lognormal(271.2,9.2)
("SFO","CVG")=>lognormal(240.3,8.2)
("SFO","DEN")=>lognormal(121.1,6.1)
("SFO","DFW")=>lognormal(179.6,7.6)
("SFO","DTW")=>lognormal(242.3,11.2)
("SFO","EWR")=>lognormal(301.2,12.9)
("SFO","IAD")=>lognormal(284.1,10.6)
("SFO","IAH")=>lognormal(207.5,11.7)
("SFO","JFK")=>lognormal(306.6,13.5)
("SFO","LAS")=>lognormal(65.7,5.3)
("SFO","LAX")=>lognormal(55.7,2.9)
("SFO","MCO")=>lognormal(292.8,7.6)
("SFO","MDW")=>lognormal(217.4,6.4)
("SFO","MEM")=>lognormal(218.4,14.0)
("SFO","MIA")=>lognormal(304.1,8.6)
("SFO","MSP")=>lognormal(188.0,9.7)
("SFO","ORD")=>lognormal(219.6,8.2)
("SFO","PDX")=>lognormal(74.8,3.3)
("SFO","PHL")=>lognormal(299.0,12.3)
("SFO","PHX")=>lognormal(93.3,4.5)
("SFO","PIT")=>lognormal(264.0,8.2)
("SFO","SAN")=>lognormal(70.0,4.5)
("SFO","SEA")=>lognormal(92.0,4.6)
("SFO","SLC")=>lognormal(81.4,5.3)
("SFO","STL")=>lognormal(206.9,7.1)
("SLC","ATL")=>lognormal(199.5,12.4)
("SLC","BOS")=>lognormal(251.4,11.4)
("SLC","BWI")=>lognormal(227.9, 8.7 ) |
("SLC","CVG")=>lognormal(179.7, 7.0 ) |
("SLC","DCA")=>lognormal(222.7, 10.8 ) |
("SLC","DEN")=>lognormal(59.9, 4.9 ) |
("SLC","DFW")=>lognormal(126.2, 5.6 ) |
("SLC","DTW")=>lognormal(184.7, 11.6 ) |
("SLC","EWR")=>lognormal(237.7, 12.8 ) |
("SLC","FLL")=>lognormal(256.4, 12.7 ) |
("SLC","IAD")=>lognormal(217.2, 9.8 ) |
("SLC","IAH")=>lognormal(158.6, 7.1 ) |
("SLC","JFK")=>lognormal(267.3, 50.5 ) |
("SLC","LAS")=>lognormal(56.4, 2.6 ) |
("SLC","LAX")=>lognormal(84.8, 3.8 ) |
("SLC","MCO")=>lognormal(234.7, 8.4 ) |
("SLC","MDW")=>lognormal(155.6, 5.3 ) |
("SLC","MSP")=>lognormal(126.9, 7.9 ) |
("SLC","ORD")=>lognormal(158.1, 7.1 ) |
("SLC","PDX")=>lognormal(88.4, 4.2 ) |
("SLC","PHL")=>lognormal(232.2, 12.0 ) |
("SLC","PHX")=>lognormal(74.2, 4.7 ) |
("SLC","SAN")=>lognormal(87.5, 5.1 ) |
("SLC","SEA")=>lognormal(98.4, 5.3 ) |
("SLC","SFO")=>lognormal(88.1, 7.1 ) |
("SLC","STL")=>lognormal(98.0, 256.1 ) |
\[
\begin{align*}
    ("SLC","TPA") &= \text{lognormal}(229.6,7.7) \\
    ("STL","ATL") &= \text{lognormal}(61.5,137.1) \\
    ("STL","BOS") &= \text{lognormal}(135.1,7.4) \\
    ("STL","BWI") &= \text{lognormal}(99.8,7.1) \\
    ("STL","CLE") &= \text{lognormal}(70.8,6.5) \\
    ("STL","CLT") &= \text{lognormal}(84.4,9.1) \\
    ("STL","CVG") &= \text{lognormal}(51.7,4.0) \\
    ("STL","DCA") &= \text{lognormal}(96.9,6.6) \\
    ("STL","DEN") &= \text{lognormal}(110.2,7.6) \\
    ("STL","DFW") &= \text{lognormal}(79.4,9.2) \\
    ("STL","DTW") &= \text{lognormal}(68.7,6.2) \\
    ("STL","EWR") &= \text{lognormal}(125.6,9.4) \\
    ("STL","FLL") &= \text{lognormal}(146.0,12.0) \\
    ("STL","IAH") &= \text{lognormal}(103.0,10.3) \\
    ("STL","JFK") &= \text{lognormal}(126.6,8.5) \\
    ("STL","LAS") &= \text{lognormal}(178.1,7.4) \\
    ("STL","LAX") &= \text{lognormal}(201.7,6.7) \\
    ("STL","LGA") &= \text{lognormal}(123.3,11.1) \\
    ("STL","MCO") &= \text{lognormal}(121.6,8.1) \\
    ("STL","MDW") &= \text{lognormal}(42.7,4.6) \\
    ("STL","MEM") &= \text{lognormal}(48.5,4.9) \\
    ("STL","MIA") &= \text{lognormal}(140.4,5.1) \\
    ("STL","MSP") &= \text{lognormal}(72.9,7.9) \\
    ("STL","ORD") &= \text{lognormal}(44.1,6.0) 
\end{align*}
\]
(("STL","PHL")=>lognormal(108.1,6.7))
(("STL","PHX")=>lognormal(168.9,9.0))
(("STL","SAN")=>lognormal(198.1,7.1))
(("STL","SEA")=>lognormal(231.8,5.9))
(("STL","SFO")=>lognormal(222.9,8.0))
(("STL","SLC")=>lognormal(156.6,8.1))
(("STL","TPA")=>lognormal(118.3,8.0))
(("TPA","ATL")=>lognormal(69.3,8.9))
(("TPA","BOS")=>lognormal(154.3,6.6))
(("TPA","BWI")=>lognormal(114.5,6.0))
(("TPA","CLE")=>lognormal(126.1,6.2))
(("TPA","CLT")=>lognormal(76.7,5.7))
(("TPA","CVG")=>lognormal(108.2,6.6))
(("TPA","DCA")=>lognormal(111.8,7.9))
(("TPA","DEN")=>lognormal(194.0,5.9))
(("TPA","DFW")=>lognormal(129.5,8.0))
(("TPA","DTW")=>lognormal(133.0,6.9))
(("TPA","EWR")=>lognormal(142.5,12.3))
(("TPA","FLL")=>lognormal(39.5,5.2))
(("TPA","IAD")=>lognormal(110.0,6.3))
(("TPA","IAH")=>lognormal(106.2,7.3))
(("TPA","JFK")=>lognormal(136.9,10.3))
(("TPA","LAS")=>lognormal(251.5,7.6))
(("TPA","LAX")=>lognormal(263.1,7.6))
fun taxiin(d)=
  case (d) of
  ("ATL")=>lognormal(10.3 ,29.0 )|
  ("BOS")=>lognormal(7.5 ,3.6 )|
  ("BWI")=>lognormal(6.1 ,6.4 )|
  ("CLE")=>lognormal(6.0 ,20.4 )|
  ("CLT")=>lognormal(6.1 ,4.1 )|
  ("CVG")=>lognormal(5.6 ,18.4 )|
  ("DCA")=>lognormal(5.6 ,5.8 )|
  ("DEN")=>lognormal(7.8 ,5.2 )|
  ("DFW")=>lognormal(13.5 ,13.8 )|
  _=>0;

("TPA","LGA")=>lognormal(139.5 ,13.4 )|
("TPA","MDW")=>lognormal(131.2 ,6.2 )|
("TPA","MEM")=>lognormal(92.0 ,8.1 )|
("TPA","MIA")=>lognormal(40.6 ,6.1 )|
("TPA","MSP")=>lognormal(171.4 ,7.5 )|
("TPA","ORD")=>lognormal(139.4 ,11.2 )|
("TPA","PHL")=>lognormal(128.9 ,8.0 )|
("TPA","PHX")=>lognormal(232.8 ,8.2 )|
("TPA","PIT")=>lognormal(117.3 ,7.0 )|
("TPA","SLC")=>lognormal(241.4 ,9.1 )|
("TPA","STL")=>lognormal(115.7 ,5.9 )|
("DTW")=>lognormal(9.4 ,5.9 )
("EWR")=>lognormal(9.0 ,4.9 )
("FLL")=>lognormal(4.3 ,2.7 )
("IAD")=>lognormal(6.9 ,3.9 )
("IAH")=>lognormal(8.5 ,5.3 )
("JFK")=>lognormal(11.7 ,8.8 )
("LAS")=>lognormal(7.6 ,5.8 )
("LAX")=>lognormal(8.2 ,5.6 )
("LGA")=>lognormal(7.7 ,5.6 )
("MCO")=>lognormal(6.2 ,4.1 )
("MDW")=>lognormal(5.2 ,4.1 )
("MEM")=>lognormal(6.1 ,4.1 )
("MIA")=>lognormal(8.1 ,8.2 )
("MSP")=>lognormal(6.8 ,4.8 )
("ORD")=>lognormal(9.1 ,7.0 )
("PDX")=>lognormal(3.8 ,1.8 )
("PHL")=>lognormal(7.8 ,7.0 )
("PHX")=>lognormal(6.6 ,5.1 )
("PIT")=>lognormal(10.1 ,72.3 )
("SAN")=>lognormal(4.0 ,3.3 )
("SEA")=>lognormal(6.4 ,3.1 )
("SFO")=>lognormal(5.9 ,3.3 )
("SLC")=>lognormal(7.4 ,19.4 )
("STL")=>lognormal(6.4 ,46.8 )
\begin{verbatim}
("TPA")=>\lognormal(5.1 ,5.2 )|
_=>0;

fun mct(d)=
  case (d) of
    ("ATL")=>floor(normal(27.5 ,13.8 ))+mctgap|
    ("BOS")=>floor(normal(20.0 ,10.0 ))+mctgap|
    ("BWI")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("CLE")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("CLT")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("CVG")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("DCA")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("DEN")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("DFW")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("DTW")=>floor(normal(22.5 ,11.3 ))+mctgap|
    ("EWR")=>floor(normal(30.0 ,15.0 ))+mctgap|
    ("FLL")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("IAD")=>floor(normal(22.5 ,11.3 ))+mctgap|
    ("IAH")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("JFK")=>floor(normal(30.0 ,15.0 ))+mctgap|
    ("LAS")=>floor(normal(17.5 ,8.8 ))+mctgap|
    ("LAX")=>floor(normal(35.0 ,17.5 ))+mctgap|
    ("LGA")=>floor(normal(25.0 ,12.5 ))+mctgap|
    ("MCO")=>floor(normal(25.0 ,12.5 ))+mctgap|
\end{verbatim}
fun adjBWI(d,f,ts)=
case (d,f) of
("ATL",35)=> max(ts,660)|
("ATL",36)=> max(ts,720)|
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</tr>
<tr>
<td>SLC</td>
<td>9874</td>
<td>1030</td>
</tr>
</tbody>
</table>
("SLC",9876) => max(ts,1030) |
("SLC",10305) => max(ts,1030) |
("SLC",10306) => max(ts,1030) |
("SLC",10307) => max(ts,1030) |
("SLC",10308) => max(ts,1030) |
("SLC",13469) => max(ts,1030) |
("SLC",14362) => max(ts,1030) |
("SLC",15996) => max(ts,1030) |
("SLC",16334) => max(ts,1030) |
("SLC",16336) => max(ts,1030) |
("SLC",16599) => max(ts,1025) |
("STL",1038) => max(ts,1055) |
("STL",1040) => max(ts,1055) |
("STL",1043) => max(ts,1055) |
("STL",1045) => max(ts,1055) |
("STL",1988) => max(ts,745) |
("STL",1990) => max(ts,745) |
("STL",1992) => max(ts,960) |
("STL",4424) => max(ts,1055) |
("STL",4426) => max(ts,1055) |
("STL",4427) => max(ts,1055) |
("STL",4428) => max(ts,1055) |
("STL",6256) => max(ts,745) |
("STL",6257) => max(ts,960) |
("STL", 9870) => max(ts, 745) |
("STL", 9871) => max(ts, 745) |
("STL", 9873) => max(ts, 745) |
("STL", 9874) => max(ts, 960) |
("STL", 9876) => max(ts, 960) |
("STL", 10305) => max(ts, 745) |
("STL", 10306) => max(ts, 745) |
("STL", 10307) => max(ts, 960) |
("STL", 10308) => max(ts, 960) |
("STL", 10896) => max(ts, 1055) |
("STL", 11760) => max(ts, 1055) |
("STL", 11762) => max(ts, 1055) |
("STL", 13469) => max(ts, 960) |
("STL", 15996) => max(ts, 960) |
("STL", 16334) => max(ts, 745) |
("TPA", 38) => max(ts, 880) |
("TPA", 41) => max(ts, 1190) |
("TPA", 1039) => max(ts, 880) |
("TPA", 1041) => max(ts, 880) |
("TPA", 1042) => max(ts, 880) |
("TPA", 1044) => max(ts, 1190) |
("TPA", 1046) => max(ts, 1190) |
("TPA", 1047) => max(ts, 1190) |
("TPA", 1988) => max(ts, 550) |
("TPA", 1990) => max(ts, 960) |
("TPA", 1992) => max(ts, 960) |
("TPA", 1994) => max(ts, 1290) |
("TPA", 2361) => max(ts, 880) |
("TPA", 2366) => max(ts, 1190) |
("TPA", 4425) => max(ts, 880) |
("TPA", 6255) => max(ts, 880) |
("TPA", 6256) => max(ts, 960) |
("TPA", 6257) => max(ts, 960) |
("TPA", 6258) => max(ts, 1290) |
("TPA", 6259) => max(ts, 1190) |
("TPA", 7916) => max(ts, 1290) |
("TPA", 8510) => max(ts, 1290) |
("TPA", 8512) => max(ts, 1290) |
("TPA", 9870) => max(ts, 690) |
("TPA", 9871) => max(ts, 690) |
("TPA", 9872) => max(ts, 880) |
("TPA", 9873) => max(ts, 960) |
("TPA", 9874) => max(ts, 960) |
("TPA", 9875) => max(ts, 880) |
("TPA", 9876) => max(ts, 960) |
("TPA", 9877) => max(ts, 1290) |
("TPA", 9878) => max(ts, 1190) |
("TPA", 9879) => max(ts, 1290) |
("TPA",10305) => max(ts, 690) |
("TPA",10306) => max(ts, 960) |
("TPA",10307) => max(ts, 960) |
("TPA",10308) => max(ts, 960) |
("TPA",10309) => max(ts, 1290) |
("TPA",10310) => max(ts, 1290) |
("TPA",10311) => max(ts, 1290) |
("TPA",13469) => max(ts, 960) |
("TPA",13470) => max(ts, 1290) |
("TPA",13473) => max(ts, 1290) |
("TPA",14362) => max(ts, 1290) |
("TPA",14363) => max(ts, 1290) |
("TPA",15612) => max(ts, 1290) |
("TPA",15996) => max(ts, 960) |
("TPA",16334) => max(ts, 690) |
("TPA",16335) => max(ts, 880) |
("TPA",16336) => max(ts, 1290) |
("TPA",16337) => max(ts, 1290) |
("TPA",16338) => max(ts, 1190) |
("TPA",16339) => max(ts, 1290) |
_ => ts;

-- DUE TO SPACE LIMIATION, adjX FUNCTIONS FOR THE LEFT 33 AIRPORTS

-- ARE LISTED WITH ONLY NAMES AS FOLLOWS:
fun adjATL(d,f,ts)
fun adjBOS(d,f,ts)
fun adjCLE(d,f,ts)
fun adjCLT(d,f,ts)
fun adjCVG(d,f,ts)
fun adjDCA(d,f,ts)
fun adjDEN(d,f,ts)
fun adjDFW(d,f,ts)
fun adjDTW(d,f,ts)
fun adjEWR(d,f,ts)
fun adjFLL(d,f,ts)
fun adjIAD(d,f,ts)
fun adjIAH(d,f,ts)
fun adjJFK(d,f,ts)
fun adjLAS(d,f,ts)
fun adjLAX(d,f,ts)
fun adjLGA(d,f,ts)
fun adjMCO(d,f,ts)
fun adjMDW(d,f,ts)
fun adjMEM(d,f,ts)
fun adjMIA(d,f,ts)
fun adjMSP(d,f,ts)
fun adjORD(d,f,ts)
fun adjPDX(d,f,ts)
fun adjPHL(d,f,ts)
fun adjPHX(d,f,ts)
fun adjPIT(d,f,ts)
fun adjSAN(d,f,ts)
fun adjSLC(d,f,ts)
fun adjSEA(d,f,ts)
fun adjSFO(d,f,ts)
fun adjSTL(d,f,ts)
fun adjTPA(d,f,ts)
Appendix E: Code Segments in PFS

-- TRANSITION X_CLUSTER, NOTE: X=ANY OEP34 AIRPORT

input (r',d',p',s',sd',sa',i',f',ts',pp');
output (t);
action
if s'>0 then
(adjX(d',f',ts')-ts')
else (0);

-- TRANSITION LOAD CONNPAX AT X, NOTE: X=ANY OEP34 AIRPORT

input (p',s',sd',sa',i1,f',ts',o01,d01,p01,s01,sd01,
sa01,i01,f01,ts01);
action
outfile:=TextIO.openAppend("Connection_Results.txt");
if (p'>0 andalso ts'<=ts01) then
if (p01+p'<=s01) then
TextIO.output(!outfile, "\n"^o01^","^d01^","^Int.toString(p')
","^Int.toString(sa')^",^Int.toString(sa01)^","^Int.toString(ts')^", ^Int.toString(ts01)^",^Int.toString(f')
","^Int.toString(f01)^",^"conn"")
else TextIO.output(!outfile, "\n"^o01^","^d01^","
```
"Int.toString(s01-p01)"","Int.toString(sa')","Int.toString(sa01)"","Int.toString(ts')"","Int.toString(ts01)"","Int.toString(f')"","Int.toString(f01)"","conn"
else TextIO.closeOut(!outfile);

TextIO.closeOut(!outfile);

-- TRANSITION LOAD CANCPAX & MISSCONN PAX AT X,

-- NOTE: X=ANY OEP34 AIRPORT

input (p,s,sd,sa,i2,f,ts,pp,o00,d00,p00,s00,sa00,i00,f00,ts00);

action

outfile:=TextIO.openAppend("Connection_Results.txt");

if (ts<=ts00 andalso p>0) then
    if pp=0 then
        if (p00+p<=s00) then
            TextIO.output(!outfile, \n"^o00","^d00","Int.toString(p)"","Int.toString(sa)"","Int.toString(sa00)"","Int.toString(ts)"","Int.toString(ts00)"","Int.toString(f)"","Int.toString(f00)"","missconn")
        else TextIO.output(!outfile, \n"^o00","^d00","Int.toString(s00-p00)"","Int.toString(sa)"","Int.toString(sa00)"","Int.toString(ts)"","Int.toString(ts00)"","Int.toString(f)"","Int.toString(f00)"","missconn")
    else
        TextIO.output(!outfile, \n"^o00","^d00","Int.toString(p)"","Int.toString(sa)"","Int.toString(sa00)"","Int.toString(ts)"","Int.toString(ts00)"","Int.toString(f)"","Int.toString(f00)"","missconn")
    else
        TextIO.output(!outfile, \n"^o00","^d00","Int.toString(p)"","Int.toString(sa)"","Int.toString(sa00)"","Int.toString(ts)"","Int.toString(ts00)"","Int.toString(f)"","Int.toString(f00)"","missconn")
else
```
if (p00+p<=s00) then
    TextIO.output(!outfile, "\n"^o00^","^d00^","^Int.toString(p)^","^Int.toString(sa)^","^Int.toString(sa00)^","^Int.toString(ts)^"^Int.toString(ts00)^","^Int.toString(f)^","^Int.toString(f00)^","^"canc")
else TextIO.output(!outfile, "\n"^o00^","^d00^",^Int.toString(s00-p00)^","^Int.toString(sa)^","^Int.toString(sa00)^","^Int.toString(ts)^","^Int.toString(ts00)^","^Int.toString(f)^"^Int.toString(f00)^","^"canc")
else TextIO.closeOut(!outfile);

TextIO.closeOut(!outfile);

-- TRANSITION TAXIOUT
input (f);
output (t);
action
(taxiout(f));

-- TRANSITION AIRTIME
input (f);
output (t);
action
(airtime(f));
-- TRANSITION TAXIIN

input (r, d, p, s, sd, sa, i, f, ts, pp);
output (t);
action
let
val t = taxiin(f) + delaygap;
in
outfile := TextIO.openAppend("Enroute_Results.txt");
TextIO.output(outfile, "\n" ^ r ^ ", " ^ d ^ ", " ^ Int.toString(p) ^ ", " ^ Int.toString(s) ^ ", " ^ Int.toString(sd) ^ ", " ^ Int.toString(sa) ^ ", " ^ Int.toString(i) ^ ", " ^ Int.toString(f) ^ ", " ^ Int.toString(ts) ^ ", " ^ Int.toString(Mtime() + t) ^ ", " ^ Int.toString(pp) ^ );
TextIO.closeOut(outfile);
(t)
end;

-- INITIAL TOKENS IN AIRLINE QUEUE FOR ALL OEP34 AIRPORTS
-- DUE TO SPACE LIMIT, ONLY ATL IS LISTED HERE

1'(1,"DFW"),[])+1'(1,"LGA"),[])+1'(1,"MIA"),[])+1'(1,"ORD"),[])
++1'(4,"CLE"),[])+1'(4,"EWR"),[])+1'(4,"IAH"),[])+1'(5,"IAD"),[])
++1'(6,"BOS"),[])+1'(6,"BWI"),[])+1'(6,"CLE"),[])+1'(6,"CLT"),[])
++1'(6,"CVG"),[])+1'(6,"DCA"),[])+1'(6,"DEN"),[])+1'(6,"DFW"),[])
++1'(6,"DTW"),[])+1'(6,"EWR"),[])+1'(6,"FLL"),[])+1'(6,"IAD"),[])
++1'(6,"IAH"),[])+1'(6,"JFK"),[])+1'(6,"LAS"),[])+1'(6,"LAX"),[])

++1'((6,"LGA"),[])+1'((6,"MCO"),[])+1'((6,"MDW"),[])+1'((6,"MEM"),[])
++1'((6,"MIA"),[])+1'((6,"MSP"),[])+1'((6,"ORD"),[])+1'((6,"PDX"),[])
++1'((6,"PHL"),[])+1'((6,"PHX"),[])+1'((6,"PIT"),[])+1'((6,"SAN"),[])
++1'((6,"SEA"),[])+1'((6,"SFO"),[])+1'((6,"SLC"),[])+1'((6,"STL"),[])
++1'((6,"TPA"),[])+1'((7,"DEN"),[])+1'((8,"BOS"),[])+1'((8,"BWI"),[])
++1'((8,"CLT"),[])+1'((8,"DCA"),[])+1'((8,"DEN"),[])+1'((8,"DFW"),[])
++1'((8,"EWR"),[])+1'((8,"FLL"),[])+1'((8,"IAD"),[])+1'((8,"LAS"),[])
++1'((8,"LAX"),[])+1'((8,"LGA"),[])+1'((8,"MCO"),[])+1'((8,"MDW"),[])
++1'((8,"MEM"),[])+1'((8,"MIA"),[])+1'((8,"MSP"),[])+1'((8,"PHL"),[])
++1'((8,"PIT"),[])+1'((8,"SFO"),[])+1'((8,"TPA"),[])+1'((9,"LAS"),[])
++1'((9,"PHX"),[])+1'((10,"DTW"),[])+1'((10,"MEM"),[])
1'((10,"MSP"),[])+1'((13,"DEN"),[])+1'((13,"ORD"),[])+1'((13,"SFO"),[])
++1'((14,"CLT"),[])+1'((14,"DCA"),[])+1'((14,"PHL"),[])

-- THE FOLLOWING ARC FUNCTIONS ARE USED TO DISTRIBUTE CONNPAX TO
-- THEIR SECOND-LEG FLIGHTS
-- ARC FUNCTIONS FOR OEP 34 AIRPORT
-- DUE TO SPACE LIMIT, ONLY ARC FUNCTION FOR ATL HUB IS LISTED HERE

if i = 1 then
1'(d,"DFW",p*40 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"LGA",p*16 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"MIA",p*21 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"ORD",p*23 div 100,s,sa,i,f,Mtime()+t,pp)
else if i = 4 then
  1'(d,"CLE",p*21 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"EWR",p*36 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"IAH",p*43 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 5 then
  1'(d,"IAD",p*100 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 6 then
  1'(d,"BOS",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"BWI",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"CLE",p*2 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"CLT",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"CVG",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"DCA",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"DEN",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"DFW",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"DTW",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"EWR",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"FLL",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"IAD",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"IAH",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"JFK",p*2 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"LAS",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"LAX",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
  1'(d,"LGA",p*5 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MCO",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"MDW",p*1 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"MEM",p*3 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"MIA",p*3 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"MSP",p*3 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"ORD",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"PDX",p*1 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"PHL",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"PHX",p*2 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"PIT",p*3 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"SAN",p*2 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"SEA",p*2 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"SFO",p*2 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"SLC",p*3 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"STL",p*2 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"TPA",p*4 div 100,s,sa,i,f,Mtime()+t,pp)
else if i = 7 then
1'(d,"DEN",p*100 div 100,s,sa,i,f,Mtime()+t,pp)
else if i = 8 then
1'(d,"BOS",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"BWI",p*5 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"CLT",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"DCA",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"DEN",p*4 div 100,s,sa,i,f,Mtime()+t,pp)++
1'(d,"DFW",p*6 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"EWR",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"FLL",p*6 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"IAD",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"LAS",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"LAX",p*3 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"LGA",p*7 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MCO",p*11 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MDW",p*7 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MEM",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MIA",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MSP",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"PHL",p*5 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"PIT",p*4 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"SFO",p*2 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"TPA",p*6 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 9 then
1'(d,"LAS",p*20 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"PHX",p*80 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 10 then
1'(d,"DTW",p*50 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MEM",p*14 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"MSP",p*36 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 13 then
1'(d,"DEN",p*15 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"ORD",p*69 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"SFO",p*16 div 100,s,sd,sa,i,f,Mtime()+t,pp)
else if i = 14 then
1'(d,"CLT",p*11 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"DCA",p*49 div 100,s,sd,sa,i,f,Mtime()+t,pp)++
1'(d,"PHL",p*40 div 100,s,sd,sa,i,f,Mtime()+t,pp)
Curriculum Vitae

Danyi Wang obtained in 2000 her B.S. in Computer Science at Wuhan University of Technology in Wuhan city, P. R. China. In the Fall 2000, she began her M.S. program at Systems Engineering and Operations Research Department at George Mason University. Danyi Wang joined the Center of Air Transportation Systems Research (CATSR) as a research assistant for her Ph.D program in 2003. In this capacity, she contributed to research efforts related to Air Transportation Systems. Her research interests include system performance evaluation and passenger flow simulation in the Air Transportation System.