Estimating the True Extent of Air Traffic Delays

by

YASMINE EL ALJ
B.Eng. in Civil Engineering (2000)
McGill University, Montreal, Canada

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Signature of Author: ______________________________
Department of Civil and Environmental Engineering
January 21, 2003

Certified by: ______________________________
Amedeo R. Odoni
T. Wilson Professor of Aeronautics and Astronautics
and Civil and Environmental Engineering
Thesis Supervisor

Accepted by: ______________________________
John N. Tsitsiklis
Professor of Electrical Engineering and Computer Science
Co-Director, Operations Research Center

Accepted by: ______________________________
Oral Buyukozturk
Chairman, Departmental Committee on Graduate Studies

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ABSTRACT

Most air traffic delay measures assess delays relative to schedule. Over the past decades, however, airline schedules have been adjusted to take into account airspace congestion and yield better on-time performance. In that context, delay measures that are using scheduled times as a benchmark are of very limited use in assessing airport and airspace system congestion, since delay has already been built into the schedule.

The primary goal of this thesis is to develop a measure that will estimate "true" delays that are not sensitive to schedule adjustments. In order to calculate "true" delays, we compute the difference between the actual gate-to-gate time and a theoretical benchmark, the "baseline". The baseline time to be used is O-D specific and is defined here as the gate-to-gate time from origin to destination under optimal (non-congested) conditions.

We choose the fifteenth percentile of reported statistics on gate-to-gate time as an estimator of the baseline. We then compute baseline times for 618 major O-D pairs. Using the baseline times, we compute "true delays" on these 618 O-D pairs and observe that they are about 40% to 60% larger than delays relative to schedule.

We also develop two methods to attribute O-D delays to the origin and destination airports. Using these methods, we determine that airports incurred about 5 to 13 minutes of delay per operation in 2000, depending on the airport under consideration. Airport rankings according to "true" delays are compared to airport rankings obtained from OPSNET delay statistics. The comparison suggests that, although OPSNET statistics underestimate the magnitude of delays, they yield very comparable airport rankings and can therefore be used to rank airports with respect to congestion.

Finally, we change perspective and look at the development of probabilistic models for designing flight schedules that minimize delays relative to schedule. We use the simple case of an airline scheduling an aircraft for a round trip to illustrate the complexities and uncertainties associated with optimal scheduling.

Thesis Supervisor: Amedeo R. Odoni
T. Wilson Professor of Aeronautics and Astronautics and Civil and Environmental Engineering

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CHAPTER 1: BACKGROUND AND MOTIVATION

1.1- Background: The economic and operational impacts of delays

Air traffic increased dramatically from the 1980s to the year 2000: revenue passenger ton-miles doubled from 1985 to 2000 and grew by about 25% from 1995 to 2000 (Figure 1.1). In this context, it is not surprising that the Air Traffic Control (ATC) system and National Airspace System (NAS) were having trouble managing the increase in traffic and congestion. This growth in air traffic has increased work loads for controllers, strained capacity at certain airports and in some portions of the airspace, as well as increased en-route holding and the number and frequency of ground delay programs.

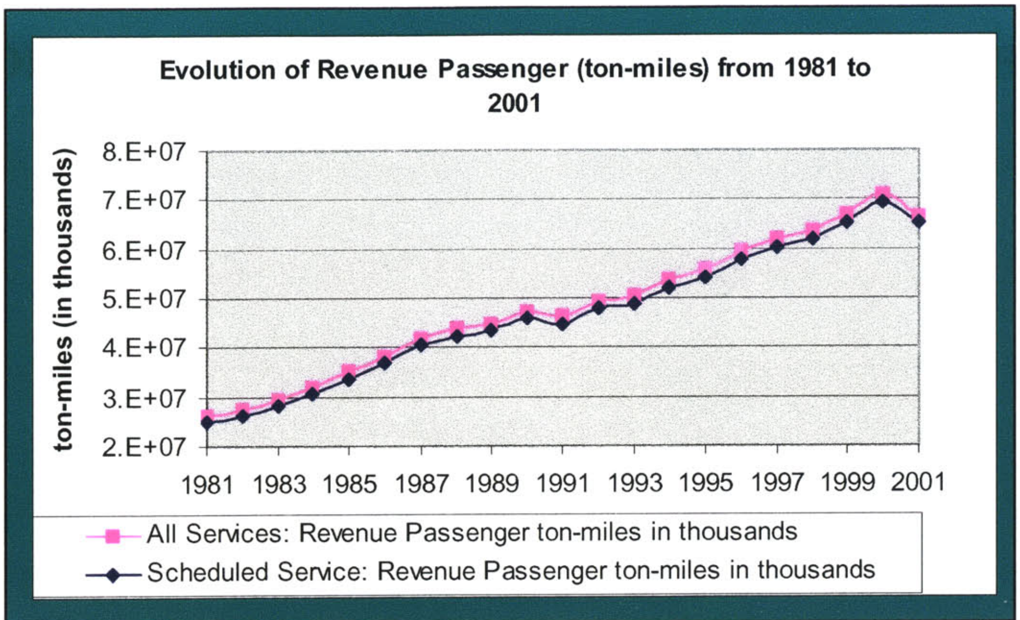

Figure 1.1: Evolution of revenue passenger (ton-miles) from 1981 to 2001[1]

Increased traffic levels have ultimately resulted in congestion and delays at airports and in the airspace. The main goal of this thesis is to estimate the magnitude of these delays and examine their evolution over time.

The resulting delays have had serious adverse impacts on both airlines and passengers. In fact, prior to the events of September 11, 2001-, the poor on-time performance of airlines and the high incidence of flight delays were the focus of much attention by the media[2] and the general public. Delays contribute greatly to a decrease in perceived levels of service for passengers: the larger the delay, the lower the passenger's satisfaction. From the airline's perspective, delays can result in major operational disruptions and significant costs. Delays propagate quickly throughout the airline's network: when a flight is delayed, the next flight using the aircraft is also likely to be delayed, if no slack has been built into the schedule. Some of the negative impacts of delays include crew-scheduling disruptions, flight cancellations, and re-booking of passengers that have missed their connections. Table 1 provides a typical breakdown of delay costs to an airline. The FAA's Office of Aviation Policy and Plans (APO) estimated that in 1994, the direct

[1] Data obtained from the Bureau of Transportation Statistics website

[2] According to Mayer and Sinai, the New York Times, Wall Street Journal, and USA Today alone published 58 articles in 2000 with air traffic delay or airline delay in the title.

operating cost to airlines associated with flight delays in the US exceeded $2.5 billion (based on an average aircraft operating cost of $1500 per hour).

Holding	48%
Yield Reduction (re-booking)	16%
Passenger Care	2%
Bound aircraft capacity	11%
Flight crew	5%
In-flight acceleration	4%
Station cost	3%
Processing cost	1%
Lost Yield	7%
Supplier Capacity	4%

Table 1.1: Typical delay cost breakdown for an airline (Adapted from Source: Booz-Allen & Hamilton)

Since 1987, carriers have been provided with additional incentives to reduce delays relative to schedule and improve their on-time performance, with the introduction of the On-Time Disclosure Rule (OTDR) by the Department of Transportation (DOT). The OTDR makes the on-time performance of US carriers available to the public. In OTDR, a flight is considered on time if it arrives within 15 minutes of its scheduled arrival time. The OTDR rule makes it even more important for airlines to be on time since an airline that incurs substantial delays is likely to suffer from a negative public perception, and in turn will become less attractive to passengers.

Because delays are disruptive and costly, airlines are very interested in improving their on-time performance. An effective way they came up with to deal with this problem is to adjust their scheduled flight times. In his thesis, Shumsky (1993)[3] showed that over the

[3] His work will be examined in more detail in the literature review section.

years, as actual transit times increased because of congestion and inefficiencies in the airspace and in the airport system, carriers kept lengthening their schedules to improve their on-time performance and avoid low ratings on delays.

1.2- Motivation

The delay measure used most commonly is that of the US Department of Transportation (US DOT), which is: *Delay = (Actual Arrival Time) – (Scheduled Arrival time).* This DOT-measured delay is a function of the scheduled arrival time, and is therefore sensitive to changes in the flight schedule.

Schedule adjustments, however, prevent the US DOT delay measure from being effective in estimating the true extent of air traffic delays, or in gauging the state of the airspace and air traffic control systems. Real, congestion-related delays are not being accounted for in this measure because over time they are absorbed in the schedule. Moreover, because delays are measured against an ever-increasing benchmark (i.e. scheduled arrival time), their comparison in time is not always meaningful. Since our goal is to estimate delays due to increased demand levels (which result in congestion) and examine their evolution, we need to develop an alternative metric that will not have the shortcomings of the US DOT measure.

Note that despite the numerous and frequent schedule adjustments made by airlines, the delay definition used by the US DOT continues to accurately measure delays relative to schedule. It also remains a measure of importance to the passengers as it helps them assess how reliable their trip times will be. Later in this thesis, we will show that delays relative to schedule underestimate the true extent of delays.

1.3- Objectives of the thesis

This thesis focuses on deriving a methodology to estimate the true extent of air traffic delays (including congestion-induced delays) and examining long-term trends over time. We develop a new metric to estimate delays due to congestion in airspace and at airports, as well as delays due to other system inefficiencies. Congestion typically exists because of increased demand levels or insufficient capacity. Capacity, in turn, is affected by weather conditions and ATC performance. By comparing the evolution of "true" delays over time, one will be able to monitor the health of the National Airspace System (NAS) and its ability to keep up with the increasing traffic levels.

The proposed alternative delay measure consists of comparing actual gate-to-gate time to a consistent benchmark, the baseline. The idea is to create a baseline, which would approximate the gate-to-gate congestion-free time. The baseline has to be consistent in time, specific to each Origin-Destination pair considered, and independent of competition and demand levels. Under this definition, delays due to late passengers and supporting services will not be taken into account. Only inefficiencies due to congested airspace and airport capacity constraints will be reflected in this new delay measure. This baseline will allow us to calculate true delays on the different O-D pairs, and to monitor their evolution over time.

Another objective of this thesis is the development of methodologies to evaluate relative congestion at each airport. Procedures to attribute "true" O-D delays to airports allow us to pinpoint specific sources responsible for the true delays. Identifying the bottlenecks in the system can help focus efforts towards congestion relief. Lastly, the final chapter demonstrates how complex it is for an airline to schedule its flights so as to minimize delays relative to schedule.

Several applications are illustrated throughout the thesis. All computations are based on a sample of flights operating on 618 O-D pairs, between 27 U.S. airports. However, the methodologies described can be applied to the US network as a whole.

1.4- Literature review

Three papers are summarized in this section:

- the first two papers discuss air traffic delays and appropriate ways to measure delay. Both of these papers show that airlines are indeed lengthening their schedules. They discuss the need for a consistent baseline against which to estimate delays, in order to allow for a consistent monitoring of the performance of the national airspace system and for tracking the evolution of delays. The development of a methodology that has these desirable properties is also the main goal of this thesis.
- the third paper examines the variability in airborne time on a given O-D pair and the attribution of the variability to one of four sources. In this thesis, we will look at the different factors causing variability in gate-to-gate time and we will try to estimate the impact of airport and airspace congestion on gate-to-gate time.

A summary of each paper and its relation to this thesis follows.

1.4.1 Shumsky: "The response of US Air Carriers to the DOT on-time disclosure rule"

In his Master's thesis, Shumsky (1993) examined strategies used by different airlines for producing an optimal schedule with respect to on-time performance, gauged the success of their efforts and evaluated the effectiveness of the OTDR rule. He also proposed some approaches to optimal scheduling.

Upon examination of a 1985-1991 flight sample, Shumsky showed that carriers' reactions to the OTDR differed in the size and timing of their schedule changes. Carriers also used different methods to determine how to distribute those changes among flights. Analysis showed that some airlines used a simple linear relationship between on-time performance of a flight in one year and the number of minutes added to that flight's schedule the next year. Others used a more sophisticated 'marginal gain approach': they seemed to lengthen the scheduled gate-to-gate times of those flights that were most likely to benefit from such lengthening and to decrease the scheduled gate-to-gate times of those that were least likely to suffer from the change.

Shumsky continued by examining the effectiveness of the carriers' scheduling decisions and explored whether past performance could be used to design a schedule that optimized on-time performance. He proposed two strategies for generating a schedule, given a fixed "budget" of extra minutes. The first strategy ignores previous performance and distributes the budget uniformly among all flights (uniform strategy); the second is an optimization procedure (MIP) using on-time performance as the sole objective. The 1991 schedules of American, United, and Delta Airlines were then generated under the two strategies. An examination of expected on-time performance of the flights under both these schedules was then performed. Results showed that the uniform strategy performed as well as both the MIP and the carriers' own schedules.

Shumsky's observations provide the motivation for this thesis. Shumsky showed that as actual flight times got longer, airlines increased their scheduled flight times in order to maintain good on-time performance: if the carriers had not lengthened their schedules from 1987 to 1991, the percentage of flights arriving on-time would have been as much as 20% lower than reported in 1991. He also pointed out that "on-time statistics published in the ATCR are not a reliable indicator of the state of the air traffic system. As actual transit times rise, carriers lengthen their scheduled transit times as well, so that increasing congestion or inefficiency are reflected in the carrier's schedules but not in the on-time statistics." This thesis builds on these observations and attempts to provide an alternative metric that will not depend on the schedule and will accurately measure "true" delays.

1.4.2- Mayer and Sinai: "Hubbing versus the 'Tragedy of the Commons': Why does Every Flight by US Airways from Philadelphia Seem to be Late?"

Mayer and Sinai (2001) explored two hypotheses to explain the extent of air traffic delays: the first is the absence of pricing of the externalities that adding a flight imposes on other users ("the tragedy of the commons") and the second is hubbing.

They showed that a high portion of delays is due to hubbing activity. They also found that hubbing and market concentration have opposing effects on delays: hubbing activity tends to increase delays while market concentration tends to lead to a reduction in delays. The hubbing effect empirically dominates. In their paper, Mayer and Sinai showed that:

- At hubs, airlines partially offset previously documented increases in travel time through padded schedules, but flights to or from a hub still have above average delays and a greater probability of being delayed at least 15 minutes.
- Travel time has increased significantly over the last 13 years and congestion has increased no matter which measure of delay is used.
- The average delay[4] increased by nearly two-thirds between 1988 and 2000 and more than doubled from the best year (1991) to the worst (2000).
- airlines do not appear to account completely for actual gate-to-gate time in setting their schedules. Average actual gate-to-gate time always exceeds scheduled gate-to-gate time in all years. Scheduled travel times, in their findings, seem to increase by only two-thirds of the amount of the increase in actual times.

Due to the fact that on-time performance can be artificially improved by increasing scheduled times for flights, Mayer and Sinai developed an alternative benchmark to measure delays. They used minimum travel time[5] to look at overall change in travel time: they estimated that the average flight, in 2000, arrived 32 minutes later than it would have if it left on time and required the minimum feasible travel time for the route.

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[4] Delay defined as actual arrival time minus scheduled arrival time
[5] Defined as the shortest observed travel time on a given route in a particular month

They also found that over the time period 1989-2000, the minimum travel time has increased from 89 to 94 minutes. They concluded that increases in the total flight load have slowed the performance of the entire air traffic control system. Thus, of the additional nine minutes of travel time on the average route since 1988, approximately 5.2 minutes is due to overall increases in minimum travel time and the remaining 4 minutes is accounted for by increases in average travel time above the minimum travel time.

Mayer and Sinai also advocate the need for an alternative benchmark to accurately measure delays. In their paper, they used the minimum travel time recorded over a month as the benchmark for the delay-free travel time on any given route. In this thesis, we will discuss some of the problems associated with using the minimum travel time and why we choose to use a different benchmark.

1.4.3- Thomas Willemain: "Estimating the Components of Variation in Flight Times"

In his paper, Thomas R. Willemain estimated the systemic component of airborne time variability (caused by weather or by en-route terminal area congestion) from day to day and flight to flight. He also attributed the variability to one of four sources: the regional airspace as a whole (day effect), the airspace at the departure airport (origin effect), the airspace at the arrival airport (destination effect), or the en route airspace (en-route effect).

Willemain outlined two variants of this methodology: one using deviations from long-run average airborne times, and the other using deviations from estimated en route times filed in flight plans. His methodology is based on the assumption that:

Deviation =Day effect + Origin Effect + Destination Effect + En-Route effect

He used a non-linear program that minimizes the sum of absolute values of the residuals (en-route effect) from the fitted additive model to estimate the different effects. The analysis can be repeated for every day of the sample period and the distribution of the estimated effects can then be computed. Unusually high values of an estimate point to a specific source of airborne delays. A large value for the day effect indicates problems throughout the region containing the O-D pairs. Large values associated with origin effects or destination effects indicate a problem with the origin/arrival airport. A large residual suggests delays in the airspace between a particular O-D pair.

This methodology was applied to a sample of flights operating in the Eastern US in the afternoon during the January-March 2001 period. After computing the distribution of estimated day, destination, and origin effect over the period, Willemain observed that:

- there was a strong negative correlation between origin and destination effects at the same airports;
- correlations between en-route pairs ranged from zero to very strong depending on the O-D pairs under consideration. The relative direction of two flights had a large influence on the correlation of their estimated daily en-route effects, which suggested that en-route effects were in fact measuring the impact of winds aloft.

He then decided to analyze deviations from estimated times en-route, in order to exclude the impact of winds aloft and to reduce the effect of nuisance variation caused by the differences in aircraft weights or flight paths. He used a sample of flights from February-April 2001 to estimate the different effects. He found that:

- the estimated origin effects were less variable than the estimated destination effects, and were also more tightly clustered around zero. Destination effects were more pronounced than origin effects;
- the estimated en-route effects were quite pronounced relative to origin and destination effects;
- the correlation between origin and destination effects was very weak: the inverse relationship discovered using deviations from average airborne times on his first sample no longer held;
- the correlations of en-route effects were weaker.

Willemain examined the systemic variability of airborne times and developed a methodology to attribute it to one of four sources. In this thesis, we will use a similar reasoning and attribute O-D delays to the airport of origin, the airport of destination, and the airspace. In contrast to his approach, we are not interested in analyzing the causes of daily fluctuations; we are only concerned with long-term variability and trends in gate-to-gate times.

1.5- Thesis Outline

The principal goals of this thesis are:

- To define consistent baseline times for flights operating between 27 of the busiest airports in the United States (which represent about 600 major Origin-Destination pairs). 59% of total passenger enplanements in the US take place at the 27 selected airports.
- To estimate the true extent of air traffic delays and compare their evolution from 1995 to 2000.
- To define a suitable methodology for attributing O-D delays to airports and to examine the correlation between average delay on a specific O-D and its airports of origin and destination.
- To compare delay results based on the methodologies developed in this thesis to results based on commonly used delay measures.
- To develop a model that illustrates the complexities associated with designing airline schedules with the goal of minimizing delays relative to schedule.

Chapter 2 focuses on terminology and delay measures, including a case study of three specific O-D pairs illustrating the type of information that can be extracted from the data. Properties of the "delay relative to schedule" measure are compared with a measure that would involve taking the difference between actual gate-to-gate time and a baseline. Factors affecting gate-to-gate time variability (seasonality, day of the week, time of day, weather/winds, runway configurations and gate assignments, flight path, aircraft type, direction of travel, congestion of en-route space, congestion of airports and terminal airspace around them) and their potential impact on the baseline derivation are discussed. Lastly, the properties of potential baseline estimators are discussed and compared. After examining many estimates, we decide that for our purposes it would be most appropriate to use a percentile of gate-to-gate time in the 5-20% range.

Chapter 3 outlines the procedure used to define consistent O-D-specific baseline times. Baseline times for each of the 618 O-D pairs under consideration are computed using the fifteenth percentile of gate-to-gate time, averaged over a four-month period. "True" O-D delays are then computed by taking the difference between actual gate-to-gate time and the baseline. Their evolution from 1995 to 2000 is analyzed. We find that the average "true" delay on the 618 O-D pairs has increased from 11.1 minutes per flight in 1995 to 16.9 minutes in 2000 (52% increase). On 75 of the 618 O-D pairs considered, true delays more than doubled over the 1995-2000 period. When "true" delays are compared to delays relative to schedule, we find that "true" delays were about 40% to 60% greater than delays relative to schedule. Analysis of "delays relative to scheduled transit time" and "delays relative to schedule" also suggests that although airlines seem to be able to accurately predict gate-to-gate times, they are not good at predicting departure times, which is the reason why delays relative to schedule are incurred.

Chapter 4 details two methodologies to be used to attribute O-D delays to airports, as airports are usually the bottlenecks in the air transportation system. The first method is an iterative method based on the attribution of a variable portion of the overall O-D delay to the airports of origin and destination, depending on the relative congestion at those airports. The second method is based on the decomposition of gate-to-gate time into its three components (taxi out time, airborne time, taxi in time), the calculation of individual component delays, and the attribution of component delays to the relevant airport. Results obtained using both methods show that airport delays increased over the 1995-2000 period: the average increase in delays at the 27 airports considered was of the order of 2 to 3 minutes per operation, which represents an increase of 40% to 53% depending on the method used. Further analysis on individual component delays suggests that there is a strong correlation between taxi out delay and airport of origin, as well as between taxi in delay and destination airport.

Chapter 5 focuses on two applications of the methodologies outlined in Chapters 3 and 4. The first application consists of the estimation of total annual delays at Logan airport (BOS) using average delay figures obtained from Chapter 4. Our best estimates showed that annual "true" delays at Logan were on the order of 80,000 to 105,000 hours for the year 2000. The second application consists of deriving delay-rankings of airports based on the individual airport delays obtained from Chapter 4, and comparing them with the FAA's and DOT's airport rankings (such as OPSNET delays, ASPM delays, etc) using the Spearman correlation test. We find that, although OPSNET statistics severely underestimate delays, they yield very similar rankings to those obtained using the methods we derived in Chapter 4.

In Chapter 6, we change our perspective and show why it may be very difficult for airlines to optimize their schedules so as to achieve high schedule compliance records. We use a simple case (an aircraft scheduled for a round trip, uniform probability density functions for actual transit times) to point out some of the complexities and interdependences in the schedule that make airline scheduling so complex. We also examine the impact of the choice of the objective function on the optimal scheduling solution obtained. In our example, scheduling strategies depend on the relative perceived costs of reduced aircraft utilization, on the one hand, and of delays, on the other. Results obtained in our example show the importance of ensuring that the schedule minimizes the delay on the first leg of the trip, so as to avoid the propagation of delays on the remaining legs of an aircraft's itinerary.

Finally, Chapter 7 provides a summary of the findings of this thesis and suggests potential areas for future research.

CHAPTER 2: ANATOMY OF FLIGHT TIME

The principal objective of this thesis is to determine a set of baseline times that can be used now and in the future to estimate "true" delays for flights between 27 of the busiest airports in the United States. The goal of Chapter 2 is to discuss appropriate estimates for these baselines, upon examination of the factors affecting the variability of gate-to-gate times. Section 2.1 introduces terminology. Section 2.2 takes a closer look at some of the factors affecting gate-to-gate times. Section 2.3 describes the data used and illustrates the type of information that can be extracted from the data. Section 2.4 discusses in more detail the purpose of the baselines and proposes estimates to approximate them.

2.1- Terminology

A flight can be decomposed into three time segments:

1. Taxi-out time
2. Airborne time
3. Taxi-in time.

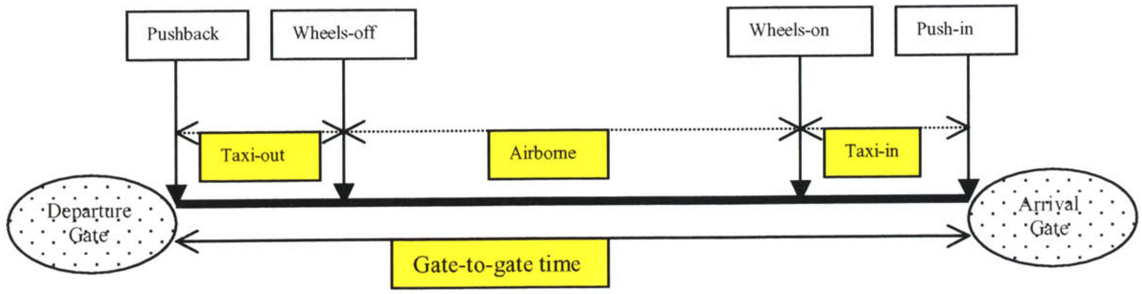

Figure 2.1: Flight time decomposition

In this connection, the following time instants and intervals can be defined (Figure 2.1):

- Push-out Time: The time at which the aircraft leaves its departure gate. This time corresponds to the moment at which the doors are closed and the brake is released. At that time, a switch is activated and the time is recorded.

- Wheels-Off Time: The time at which the wheels leave the ground (take-off time). A switch that is activated when the wheels leave the ground records this time.

- Wheels-On Time: The time at which the wheels make contact with the ground (landing time). A switch that is activated when the wheels touch the ground records this time.

- Push-in Time: The time at which the aircraft reaches its arrival gate. It is taken as the time at which the brake is secured.

- Taxi-out: This is the time between pushback and wheels-off.
  Taxi-out time= (Wheels-off time) - (Push-out time)

- Airborne time: This is the time between wheels-on and wheels-off.
  Airborne time= (Wheels-on time)- (Wheels-off time)

- Taxi-in: This is the time between wheels-on and push-in.
  Taxi-in time= (Push-in time)- (Wheels-on time)

- Actual Gate-to-Gate time or Actual Block Time: This represents the actual transit time and is defined as the time interval between pushback and push-in.
  Actual Gate-to-Gate time= (Push-in time) – (Push-out time)

- Scheduled gate-to-gate time: this represents the total scheduled block time, from scheduled departure time to scheduled arrival time.
  Scheduled gate-to-gate time=(Scheduled arrival time) – (Scheduled departure time)

2.1.1 Delay relative to schedule vs. true delay

There is a fundamental difference between true delay and delay relative to schedule. The US DOT measure of delay, *(Actual arrival time)- (Scheduled arrival time)*, is a measure of delay relative to schedule. The benchmark against which the delay is measured is represented by the scheduled arrival time of each flight, which in turn depends on the scheduled gate-to-gate time. As discussed in the previous chapter, this measure is sensitive to propagation of delays in the network as well as to adjustments to the scheduled duration of flights, and does not allow for a meaningful comparison of delays over time.

On the contrary, in the case of true delay, the benchmark should be a "baseline" which represents a standard estimated gate-to-gate time for completing a particular flight under congestion-free conditions. Thus, *True Delay= (Actual gate-to-gate time) – (Baseline).* The baseline, which will be defined in more detail in Chapter 3, should be characteristic of each origin-destination pair for any given type of aircraft. The baseline should also be independent of demand levels.

2.2 Factors affecting gate-to-gate time

As indicated, true delay is measured as the difference between actual gate-to-gate time and a benchmark. It is therefore useful to first take a closer look at some of the factors that contribute to gate-to-gate variability on a given origin-destination pair. It will be important to keep all those factors in mind when deciding which baseline to choose, in order to ensure consistency over time.

The following are potential factors contributing to the variability in gate-to-gate times on a given O-D pair.

2.2.1 Seasonality

Seasonality may impact gate-to-gate time for at least two reasons. First, scheduled operations (frequency, departure times) vary with the season. For example, summer and fall are typically the busiest seasons for air travel. With more flights scheduled during these seasons, the airspace and airports become more congested and gate-to-gate times may increase. Second, seasonality may be strongly linked to weather. Bad weather usually results in major delays; flights operating during the winter may therefore incur greater gate-to-gate times.

2.2.2 Day of Week

Day of the week may influence gate-to-gate time. Some days of the week are busier than others. Friday is typically the busiest day for air travel in the United States, as business travelers return home for the weekend and leisure travelers fly to their chosen destination. In contrast, Saturday is the least busy day for air travel in most areas. This might translate into shorter gate-to-gate times for flights operating on Saturdays and longer gate-to-gate times for those operating on Fridays.

2.2.3 Time-of-day

Time-of-day may influence gate-to-gate time because the number of scheduled operations may vary with the time of the day. For example, very few operations are usually scheduled at off-peak hours (between 10 PM and 6AM) because they are not convenient for passengers. Because of the relatively small number of aircraft operating during these hours, there is very little congestion, which may result in shorter than average gate-to-gate times.

2.2.4 Weather/ Winds

Winds may have a strong influence on airborne time, especially for longer-haul flights. Favorable winds can significantly decrease airborne time while unfavorable winds can result in longer airborne times and higher fuel consumption.

Weather can affect both airspace conditions and airport conditions. A particularly bad weather pattern along the preferred flight path can result in a flight modifying its route, resulting in a longer gate-to-gate time. Bad weather at an airport is likely to result in increased holding time in the airspace.

Bad weather also results in reduced airport capacity by causing increases in minimum separations and longer queues for take-off and landing. It may also result in ground holding, increased taxi out and taxi in times, and, in turn, increased gate-to-gate times.

2.2.5 Runway and Gate Assignments

The runway configuration in use at an airport may affect the three components of gate-to-gate time: taxi out, airborne and taxi in. Taxi out/in times are affected by the location of the departure/arrival gate with respect to the location of the departure/arrival runway. Airborne time can also be affected by the runway assignment: taking off from any given runway configuration leads to a specific ascent path, which might be very different from the path associated with another departure runway, therefore potentially increasing or decreasing flight distance.

2.2.6 Route/ Flight Path

The flight path may affect airborne time. Flight paths depend on weather conditions, runway configurations in use, and demand levels (see "airspace congestion" below). They may also depend on the airline and the pilot.

2.2.7 Aircraft Type

Aircraft type may influence airborne time, because of the different speeds and altitudes at which different aircraft fly. Aircraft size may also affect queuing time, if air traffic controllers attempt to sequence aircraft on landing or take-off in light of wake vortex separation requirements.

2.2.8 Direction of Travel on any given O-D pair

Gate-to-gate times on a given O-D pair may depend strongly on the direction of travel, due to prevailing direction of winds aloft (e.g., jet stream) and the orientation of the runways at the airports of origin and destination.

2.2.9 Congestion of en-route airspace

Airspace congestion affects airborne times and may result in aircraft flying at less than optimal speed or on non-optimal flight paths or, on some occasions, being subjected to airborne or ground holding. This is particularly true on short to medium hauls for aircraft heading to popular airports. For example, aircraft heading from Chicago to New York can be "queuing" (miles-in-trail) almost from their departure and until landing and are therefore never able to reach their optimal speed. In Chapter 4, we shall estimate how much of the O-D delay is actually attributable to en-route congestion.

2.2.10 Congestion of airports and terminal airspace around them

Increases in demand levels can lead to airport congestion, as more flights attempt to depart or arrive at an airport. Bad weather usually compounds the situation because it results in reduced airport capacity. In Chapter 5, the relationship between delays at a given airport and reduced airport capacity will be illustrated.

Variability in gate-to-gate times attributable to the factors described above is due to the fact that flights on a given O-D pair will not always operate under the same set of periodic (season, time, day), meteorological (wind, weather), or physical conditions (runway configuration and gate assignment, flight path, etc). In this thesis, we are only concerned with variability due to airspace and airport congestion. However, the existence of other factors complicates the task of estimating the exact impact of airspace and airport congestion on gate-to-gate times. For example, two flights operating on the same route, but under a different set of conditions can have significantly different gate-to-gate times, even if both flights experienced no delay due to airspace or airport congestion. The potential influence of some of these factors is illustrated in the next section, using three specific O-D pairs as examples. Some statements on the significance of these factors for the estimation of the baseline times will be made in section 2.4.

2.3 Data

The data used in this thesis were obtained from the Airline System for Quality and Performance (ASQP) database. The ASQP database is maintained by the US Department of Transportation (DOT). ASQP encompasses data for the ten major air carriers in the US. The data are reported by the airlines themselves. The reporting carriers are Alaska, America West, American, Continental, Delta, Northwest, Southwest, TWA, United and US Airways.

ASQP reports four time events for each flight: push-out, wheels-off, wheels-on and push-in (Section 2.1). These times are recorded automatically through the Air Carrier Automated Reporting System (ACARS). In addition to the four time events, ASQP also indicates for each flight the scheduled departure and arrival times, the scheduled gate-to-gate time, the actual gate-to-gate time, and the taxi out, taxi in, and airborne times.

It is important to note that gate-holding delays that may be imposed by the Air Traffic Flow Management (ATFM) system are not included in the actual gate-to-gate times reported by ASQP since they occur before the brake is released (i.e. the push-out time). Only ground holding delays occurring on the tarmac after push-out are taken into account in the data. One potential way of estimating gate-holding delays might be to assume that any departure delay - defined as the time between scheduled departure and actual push-out - constitutes a gate-holding delay. But this method can result in a potentially gross overestimation of gate-holding delays, as the delay in leaving the gate may be due to a late arrival of the aircraft (i.e. delay propagation, in which case the delay would be double-counted) or to reasons entirely unrelated to the airport or to traffic conditions (e.g., a delay due to mechanical problems or to late-boarding passengers). This is one of the principal limitations of the data utilized in this thesis.

The following material illustrates the kind of information that can be extracted from the ASQP database. The evolution of gate-to-gate, airborne, taxi out, and taxi in times for three origin-destination pairs during the 1995-2000 period is examined. Data pertaining to the following Origin-Destination pairs were used: BOS-DCA, DCA-BOS, LGA-ORD, and DEN-SFO. These three specific pairs were chosen to illustrate results for short, medium, and long-range markets. Note that the statements made in the remainder of this section apply only to the three routes examined. They do, however, suggest a number of hypotheses about all the routes examined.

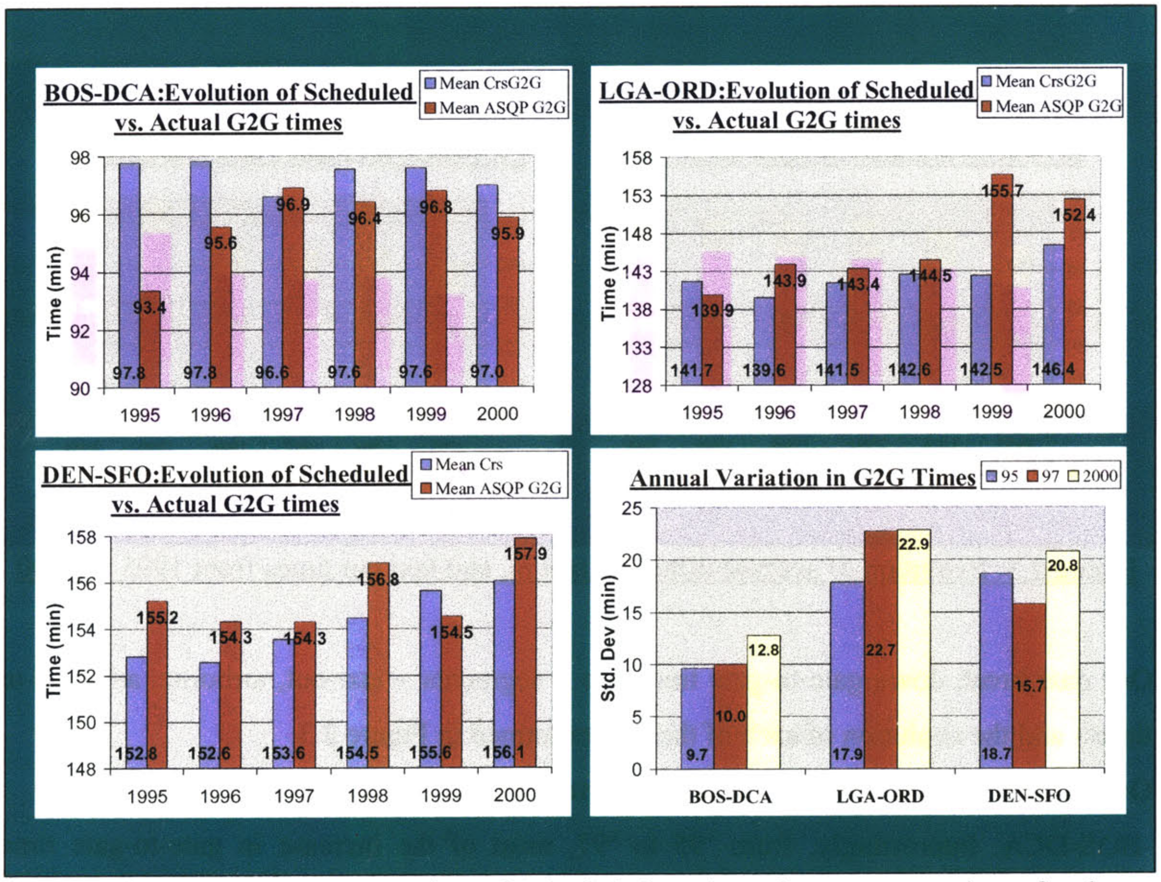

Figure 2.2: Variation and evolution of Scheduled vs. Actual gate-to-gate times for three origin-destination pairs

Figure 2.2 shows the evolution of annual average scheduled versus actual gate-to-gate times from '95 to 2000. The average actual gate-to-gate time has increased by about 3 minutes from '95 to 2000 for BOS-DCA and DEN-SFO, and by 12 minutes for LGA-ORD. In contrast, the average scheduled gate-to-gate time has remained constant for BOS-DCA over the '95-2000 period; it has increased by 5 minutes for LGA-ORD and by 3 minutes for DEN-SFO. This suggests that although scheduled gate-to-gate time may be increasing over the years (except for BOS-DCA), it may not be increasing as fast as the actual average gate-to-gate time[6].

While the average gate-to-gate time has increased from '95 to 2000, the variability in gate-to-gate time has also increased, as shown by the increase in standard deviations computed for the three O-D pairs. This may be due to increasing congestion, which reduces travel time reliability.

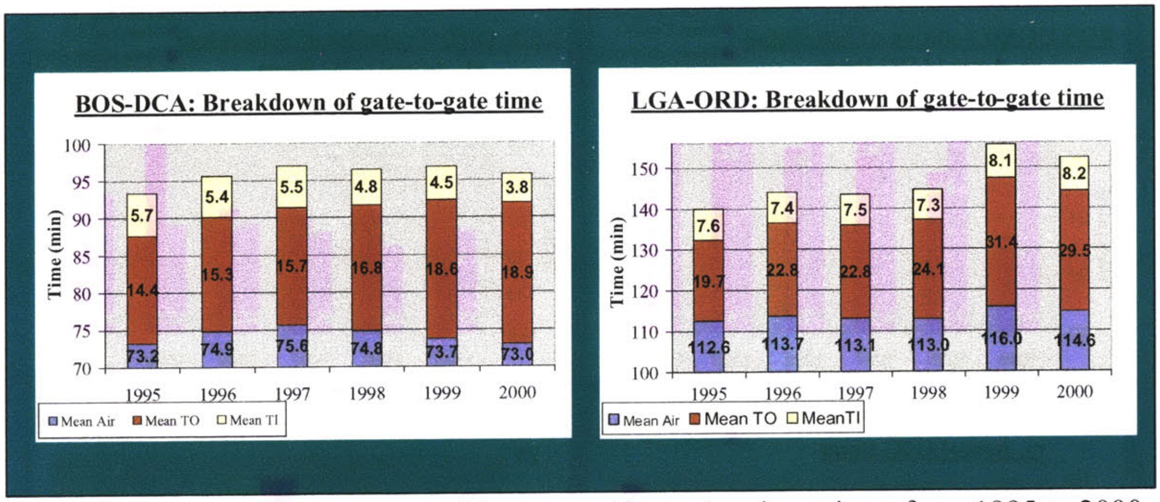

Figure 2.3: Evolution of average airborne, taxi in, and taxi out times from 1995 to 2000

Our data break down gate-to-gate time into 3 segments – taxi-out, airborne, and taxi-in times- and the evolution of each of these is examined in Figure 2.3.

Overall, gate-to-gate time seems to have increased from '95 to 2000.

-BOS-DCA: Interestingly, from '95 to '97, most of the increase in gate-to-gate time seems to be due to an increase in airborne time. From '97 to 2000, the gate-to-gate time remained relatively stable; however, the breakdown of gate-to-gate has not remained constant: average taxi-out time increased significantly while average airborne and average taxi-in times decreased.

- LGA-ORD: Average airborne time has remained relatively stable from '95 to '98, before increasing slightly in '99. While average taxi-out increased by over 4 minutes between '95 and '98, average taxi-in time seems to have remained relatively stable during

[6] This is consistent with Mayer and Sinai's observations [Mayer and Sinai (2001)]

that period. From '98 to 2000, average taxi-in and average airborne time increased by about 1 minute, while average taxi-out increased by another 5 minutes.

Similar analysis can be performed for the DEN-SFO O-D pair.

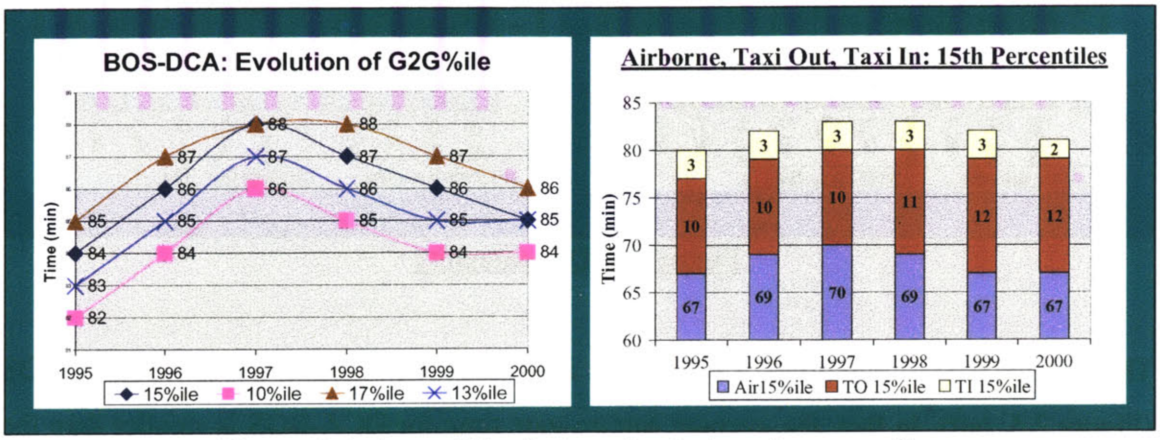

Figure 2.4: Annual Evolution of gate-to-gate percentiles

Gate-to-gate times achieved by 10%, 13%, 15%, and 17% of the flights each year are reported here as 'percentiles'. For BOS-DCA, percentiles have increased from '95 to '97 before slowly decreasing again from '97 to 2000 (Figure 2.4). Over the '95-2000 period, however, percentiles have increased by about 2 minutes, reflecting the fact that low times achievable earlier could not be met in later years. It is also interesting to note that there is only a minor difference in time (about 2-3 minutes) between the 10^{th} and the 17^{th} percentiles. The individual components of the gate-to-gate times may undergo more significant changes. For example, the 15^{th} percentile of taxi out time has increased by 20% from '95 to 2000, as seen in the right part of Figure 2.4.

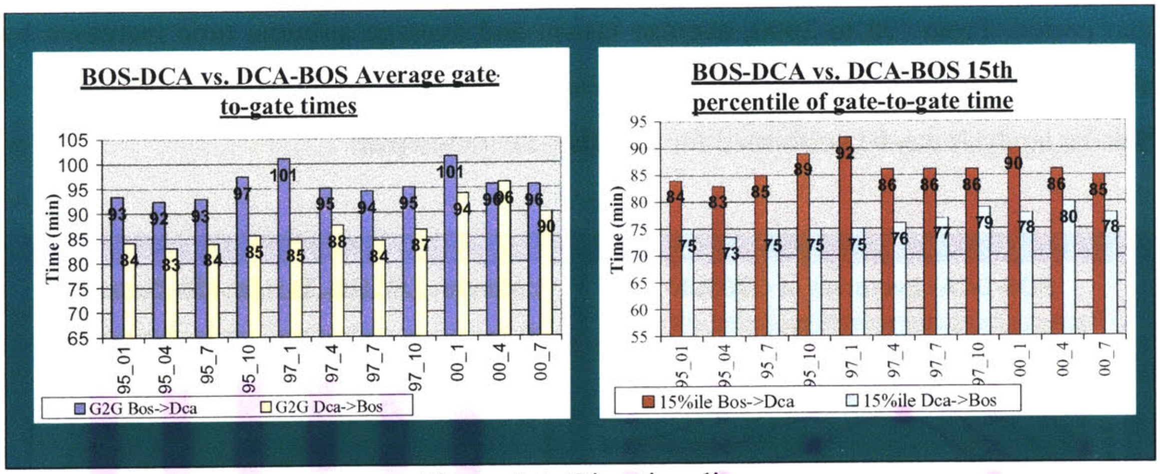

Figure 2.5: Directionality

The average gate-to-gate time of BOS-DCA is consistently higher than that of DCA-BOS (Figure 2.5, left). In fact, the average gate-to-gate time for DCA-BOS is smaller than the 15th percentile of the BOS-DCA gate-to-gate time for certain months. The same observation can be made when comparing the 15th percentile of BOS-DCA to the 15th percentile of DCA-BOS for the same periods (Figure 2.5, right). In part, this is the result of favorable directional winds in the DCA-BOS direction and suggests the importance of treating each direction separately.

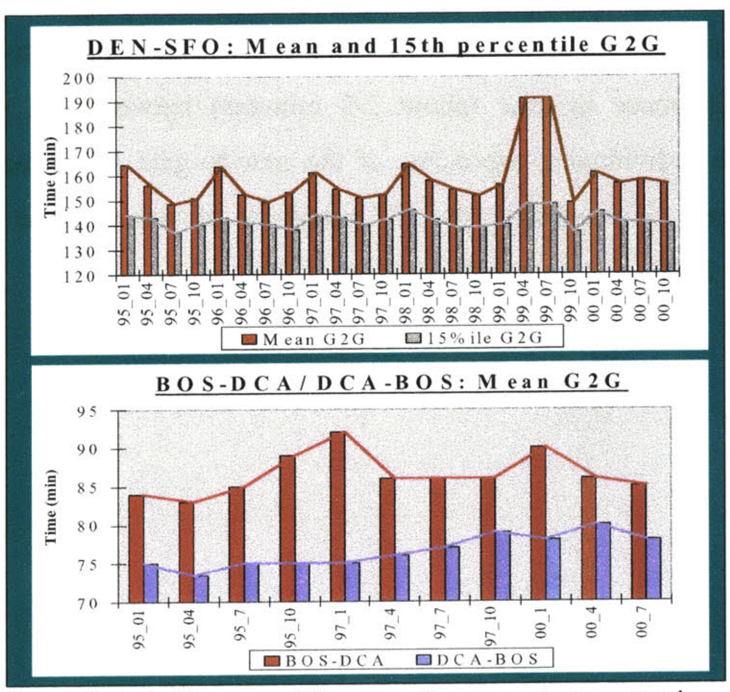

Figure 2.6: Influence of Seasonality on gate-to-gate times

Figure 2.6 suggests that seasonality may influence gate-to-gate time significantly. This is shown by the cyclical pattern for the DEN-SFO route. The average and 15th percentile of gate-to-gate time tend to be high in January, to then decrease until July, and start increasing again after the month of July. Different O-D pairs may have different cyclical patterns.

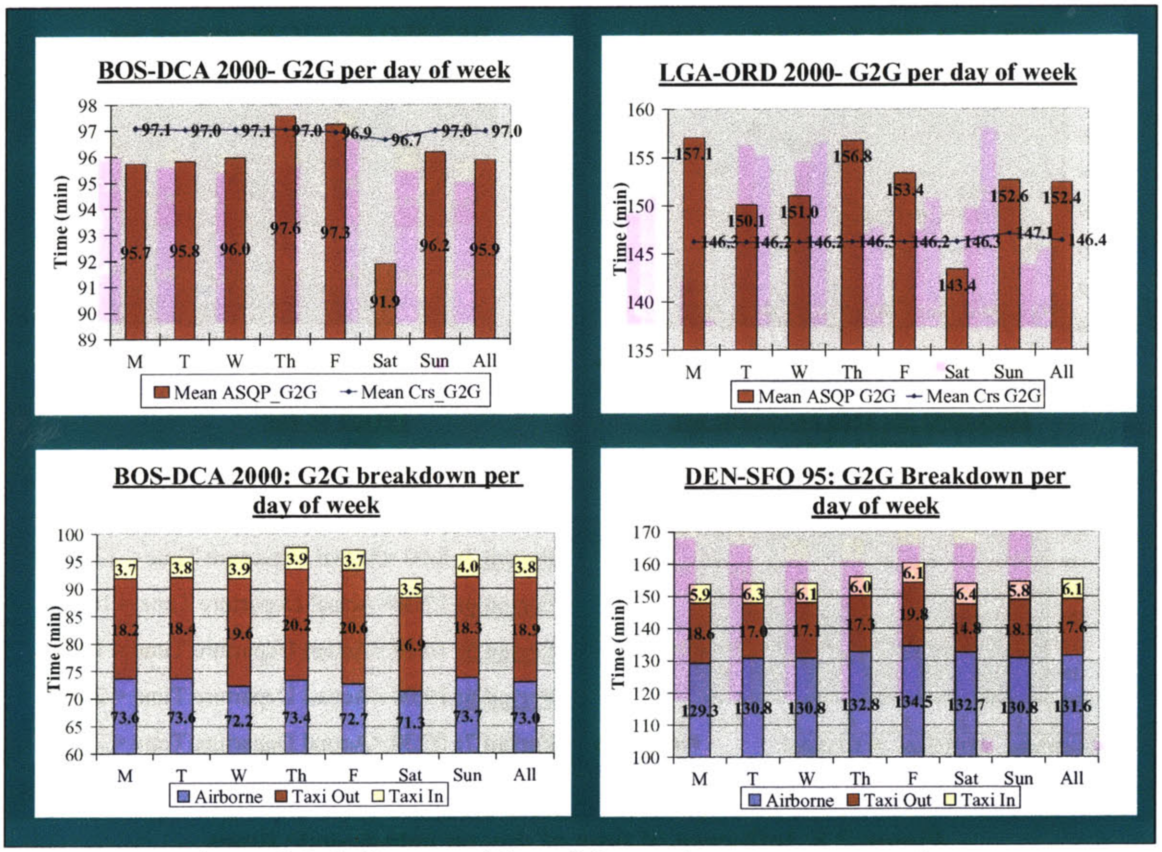

Figure 2.7: Influence of day of the week on gate-to-gate times

As shown in Figure 2.7, average gate-to-gate time varies slightly depending on the day of the week. As expected, Saturdays seem to have the lowest average gate-to-gate time for the three O-D pairs considered. This can be explained by the lower demand for travel on Saturday and, consequently, the lower number of operations generally scheduled on that day, which result in less congestion.

Thursdays and Fridays seem to have the largest average gate-to-gate times (and the largest average airborne, taxi out and taxi in times).

While the average actual gate-to-gate time varies depending on the day of the week, the scheduled gate-to-gate time remains relatively constant for the two O-D pairs shown in Figure 2.7. This suggests the hypothesis that airlines may not consider day of the week as an important factor when making scheduling decisions.

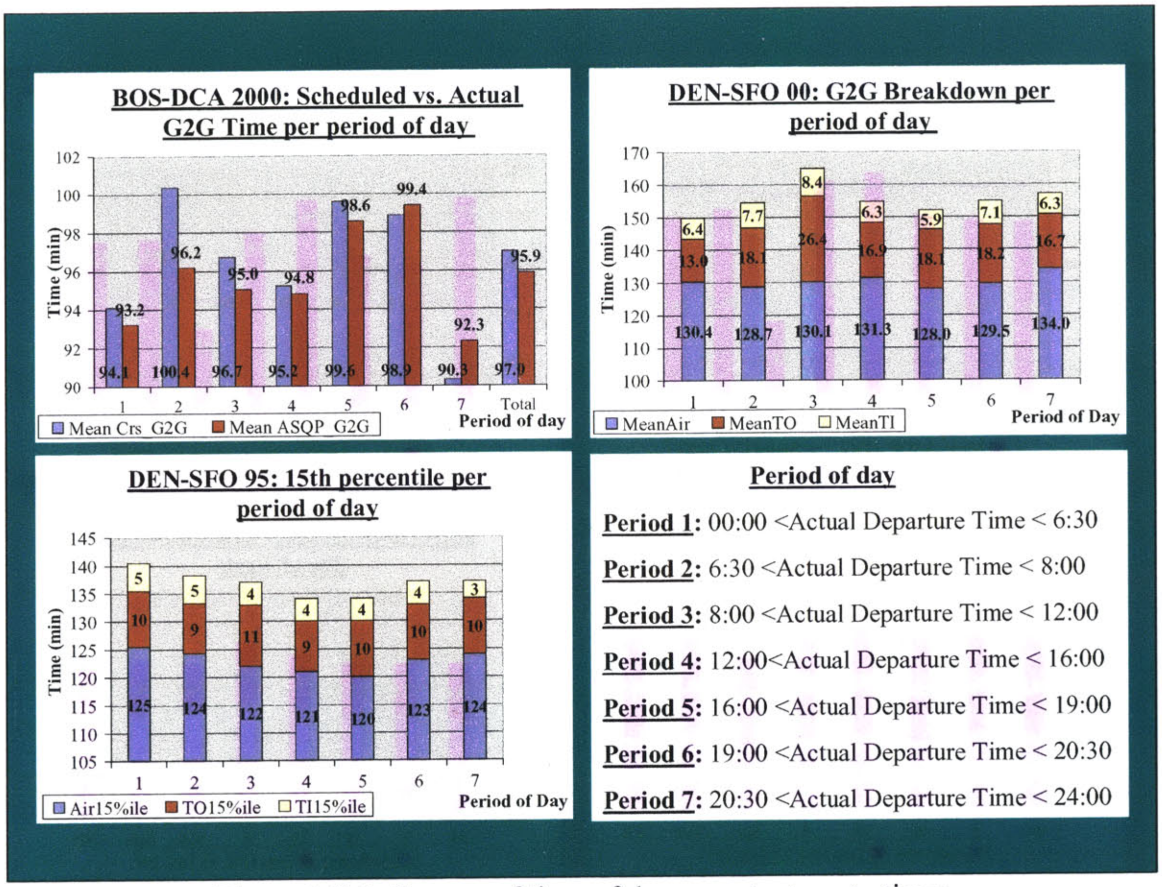

Figure 2.8: Influence of time of day on gate-to-gate times

Average actual gate-to-gate time may fluctuate depending on the time of the day as shown in figure 2.8. For example, for BOS-DCA in 2000, the average actual gate-to-gate time in period 7 is about 7 minutes smaller than the average in period 6.

Average scheduled gate-to-gate time also varies with the time of day in Figure 2.8. One may hypothesize that airlines believe that time of the day significantly influences gate-to-gate times. They may therefore assign different scheduled times depending on the time of the day.

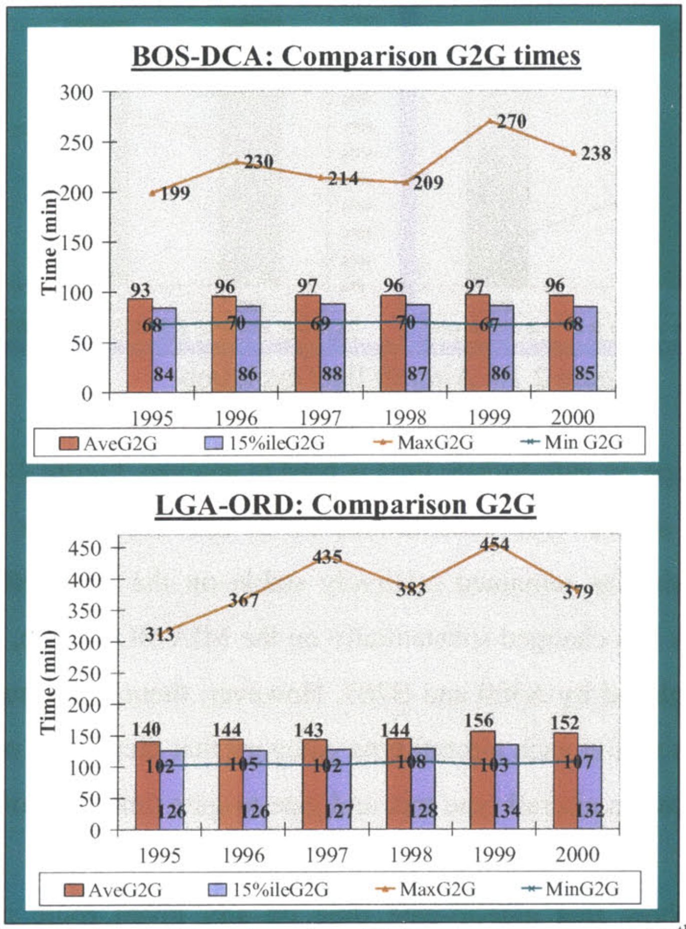

Figure 2.9: Comparison of maximum, minimum, average, and 15th percentile gate-to-gate times

The minimum gate-to-gate time reported in the ASQP data has remained relatively constant over the years for BOS-DCA and has increased by 5 minutes from '95 to 2000 for LGA-ORD (Figure 2.9). The maximum gate-to-gate time has fluctuated significantly during the '95-2000 period for both O-D pairs. Maximum gate-to-gate times can be as much as three to four times higher than minimum gate-to-gate times. This can be attributed primarily to the possibility of aircraft experiencing very long ground holding times after pushback.

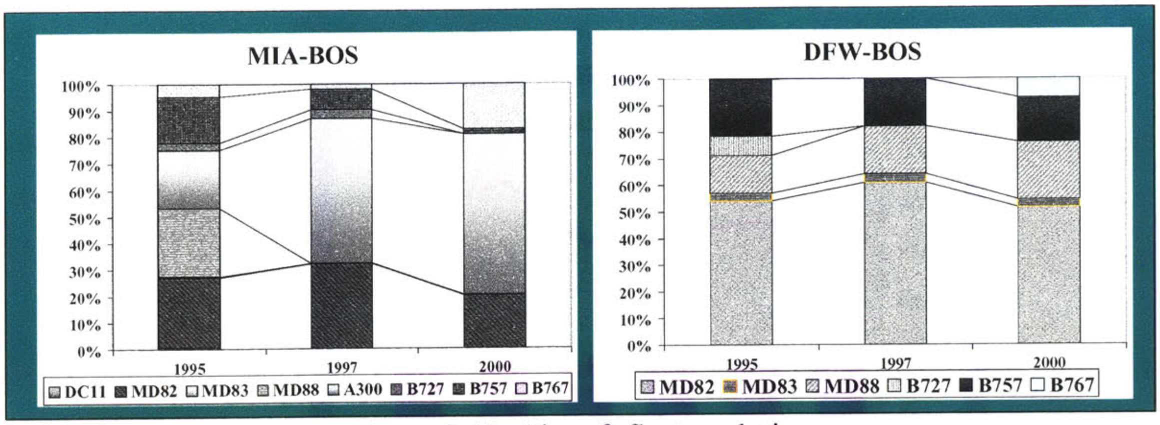

Figure 2.10: Aircraft fleet evolution

The impact of aircraft type on gate-to-gate time is hard to analyze. Figure 2.10 shows that there have been some aircraft type substitutions on certain routes over the '95-2000 period. Aircraft type mix has remained relatively stable on the DFW-BOS route. By contrast, the aircraft mix has changed substantially on the MIA-BOS route, where MD88 and B757 have been replaced by A300 and B767. However, there is so much variability in the gate-to-gate times within each aircraft type category that there does not seem to be any clear correlation between aircraft type mix and gate-to-gate time performance.

The examples above show that gate-to-gate time on any given route may fluctuate considerably. Although several factors (seasonality, day of the week, time of the day, aircraft type) appear to influence gate-to-gate time, their effect on the overall, year-to-year average gate-to-gate times may not be significant. In particular, due to their periodic nature, the factors of seasonality, day of week and time of day, may simply be the cause of fluctuations around the yearly averages. The effect of directionality, however, is clearly something to be taken into account. For the remainder of this thesis, we will consider directional Origin-Destination pairs.

2.4 Potential measures of delay

The primary goal of this thesis is to develop a measure that monitors the evolution of true delays over time. This will involve taking the difference between two times: the actual gate-to-gate time, and a theoretical benchmark, the "baseline", which is yet to be determined. This approach will ensure that delays are not double-counted (since our measure will be insensitive to delay propagation), and that the schedule adjustments made by the airlines (i.e., lengthening of scheduled gate-to-gate times as actual gate-to-gate times increase) do not influence the metric.

The principal use of these baselines will be for policy purposes. Once developed, they could be used to monitor the approximate size of delays nationally (if the 27 airport database is extended to more airports), or at individual airports. They could also be used to assess whether or not the airport system and the air traffic management system (ATM) system are keeping up with the traffic on aggregate. Therefore, we are primarily concerned with identifying long-term trends[7] and changes, not the day-to-day fluctuations that are due to periodic variability or to stochasticity in the system.

The baseline time to be used will be O-D specific and is defined here as the gate-to-gate time from origin to destination under optimal (non-congested) conditions. We have shown in sections 2.2 and 2.3 that gate-to-gate time may be sensitive to the following factors:

1- Seasonality
2- Day of the week
3- Time of day
4- Weather/Winds
5- Runway configurations and gate assignments
6- Flight path
7- Aircraft type
8- Direction of travel
9- Congestion of en-route space
10- Congestion of airports and terminal airspace around them

[7] i.e.: performing year-to-year comparisons, as well as obtaining rough absolute values

Since we will be looking at aggregate changes, we need to differentiate between the factors that will "average out" over the period considered and those that will not.

Seasonality, day-of-the-week, and time-of-day are of a periodic nature (see section 2.3). Weather/winds, runway and gate assignments, and flight path are of a stochastic nature. While from day-to-day or from flight-to-flight they can all make a significant difference, their impact will cause only small fluctuations around long-term averages computed over hundreds or thousands of flights. They will introduce error terms in the long-term trends (e.g., we may have a year with particularly bad or good weather) but overall their aggregate effects will be those of perturbations. Therefore, we should not be too concerned with these factors, as they will not make a significant difference on aggregate, and we are not interested in examining day-to-day fluctuations.

Aircraft type may be significant in the long run, especially for long-range flights. A switch from non-jets to jets for example could have significant effects. However, all the data we have used refer to jet flights and the substitution of one jet type for another has only a small impact on travel times, especially on short-range routes. The pace of changes in airline fleets during the years examined (1995-2000) was relatively slow and there does not seem to be a major change in the trends due to this factor. The effects of the introduction of large numbers of regional jets may, in the future, have a more significant effect, whenever these jets replace non-jets on specific routes.

Directionality is sufficiently important to necessitate treating each O-D pair as two distinct routes, A-to-B and B-to-A. Airspace and airport congestion (factors 9 and 10) are the focus of this research. However, it is hard to determine from the data how much of the increase in gate-to-gate times is due to en-route airspace congestion and how much to airport congestion. This will be examined in more detail in Chapter 4.

Some potential candidates to serve as estimates for the baseline gate-to-gate times include:

- Average gate-to-gate time:

$B_{ij} = Ave(G2G_{ij})$

The baseline for each O-D pair, in this case, would be approximated by the average of gate-to-gate times on this O-D pair. The sample over which the average would be computed would cover a full year, to ensure that periodic factors such as seasonality, day of the week and time of the day average out. The baseline would be the lowest average observed in any of the years under consideration. (For our data, this would be 1995 in most cases, since gate-to-gate times seem to have increased over time). A flight will be considered late if its actual gate-to-gate time exceeds the baseline average gate-to-gate time[8]. A crucial drawback of this measure is that the average gate-to-gate time is heavily influenced by delay whenever congestion is present. Thus, unless a "delay-free" year is identified for setting the baseline, using average gate-to-gate time as the baseline would almost certainly lead to serious underestimation of true delays.

- Minimum gate-to-gate time:

$B_{ij} = Min(G2G_{ij})$

The baseline for each O-D pair would be the shortest observed actual travel time on that O-D pair, for the sample under consideration. A similar measure has been suggested by Mayer and Sinai (2001) as an estimate of the congestion-free time[9]. The reasoning behind the use of this metric is that if any flight was able to achieve the minimum reported time, any other aircraft might be able to reproduce this time in uncongested conditions. However, it can be argued that this is an overly optimistic estimate as the minimum gate-to-gate time could have been the result of a particularly favorable combination of runway configuration and favorable winds, conditions that might be very difficult to reproduce. Use of this baseline is likely to lead to the overestimation of true delays.

- Percentile of gate-to-gate time:

$B_{ij} = G2G_{ij}^{p}$, such that $\Pr(G2G_{ij} \le B_{ij}) = p$ where p is a specified percentile.

[8] Note that use of this estimate as an appropriate baseline will also require that "negative delays" (which occur when a flight's actual gate-to-gate time is shorter than the baseline) be counted as null delay.

[9] Note however that Mayer and Sinai (2001) propose to use the shortest observed travel time on each O-D pair EACH MONTH. Therefore, their baseline evolves in time.

The baseline for each O-D pair would be approximated by a percentile of gate-to-gate times observed on that specific O-D pair. If the percentile used is in the 5^{th} -20^{th} percentile range, this measure could have desirable properties: it would be a realistic optimal time since a rather significant percentage of flights were able to achieve this performance; it would be neither overly optimistic nor overly conservative; and it would cover a broad range of periodic and meteorological conditions, and runway configurations. It is important to note that not all percentile measures are appropriate: the properties described above do not hold if the percentile chosen is too low (overestimation of delays) or too high (underestimation of delays). Note that the minimum travel time is a special case of this measure with p=0.

In addition to these simple measures, one could envision estimating the baseline time by using the following type of modeling approach:

- Baseline as a function of seasonality, time of the day, and day of the week

$B_{ij} = b_0 + b_1 * f(time) + b_2 * f(dow) + b_3 * f(Season)$

b_0: O-D-specific constant

b_1: Coefficient associated with time of the day parameter

$f(time)$: Function of the time of day

b_2: Coefficient associated with day of the week parameter

$f(dow)$: Function of the day of the week

b_3: Coefficient associated with seasonality

$f(Season)$: Function of the season

According to the above estimate, each flight would have its own baseline depending on the periodic conditions under which it is operating. Use of this estimate assumes that periodic factors -seasonality, time of the day, and day of the week- strongly influence gate-to-gate time and should therefore be taken into account when deriving the benchmark. The above estimate would then represent a more realistic optimal time for each flight, "adjusted" for each given set of conditions.

Note that this approach does not include stochastic factors in the baseline estimation because of the difficulty in obtaining data on these factors and their stochastic nature. Moreover, including the stochastic terms would render the model less usable and less informative, as discussed below.

One of the advantages of using this baseline is that we are controlling for periodic factors that could result in potential discrepancies in gate-to-gate time. The delay measure obtained in this way- difference between actual gate-to-gate time and the baseline defined above- would consist primarily of congestion-related delay, as the periodic factors would have been accounted for in the baseline. However, there are two arguments against using that estimate for our purposes. First, we have already mentioned that we are not interested in day-to-day fluctuations and are only looking at long-term trends. Using that baseline would give us added precision that we do not need. Second, this metric might not lead to a correct estimation of true delays: one can view seasonality, time of the day, and day of the week as periodic factors affecting gate-to-gate time in the sense that these factors are strongly associated with fluctuations in demand levels (scheduled operations). However, we are not interested in adjusting the baseline to account for the different demand levels because the baseline's goal is precisely to estimate the impact of those demand levels on gate-to-gate times. The baseline should therefore be independent of demand levels because it is intended to be used to estimate the inefficiencies in the system that are created by excessive demand and lack of proper infrastructure to accommodate it.

It is a challenging task to define a baseline that will approximate a congestion-free time while being conservative enough that it accounts for a variety of runway configurations, flight paths, and wind directions. Given the above discussion, it seems that using a percentile measure in the 5-20% range to compute the baseline would be most appropriate. Chapter 3 examines in greater detail which percentile to choose and the data that will be used to derive this estimate.

CHAPTER 3: BASELINE ESTIMATION

Chapter 3's goal is to describe the methodology used to derive baseline times for the 618 O-D pairs under consideration. Section 3.1 details the methodology used. Section 3.2 shows two applications for the use of baselines: the calculation of true delays; and the comparison of the evolution of true delays versus delays relative to schedule.

3.1 **Baseline time estimation methodology**

It was argued in Chapter 2 that it is appropriate to use a percentile measure in the 5^{th}-20^{th} percentile range as a means of estimating the baseline time of a specific O-D pair. The baselines are supposed to approximate "congestion-free" gate-to-gate times. They are also supposed to be "achievable", meaning that a substantial percentage of flights operating on that O-D pair should be able to achieve a similar performance.

If the percentile chosen is in this range, the resulting baselines will have these desired properties. Percentiles in that range are low enough that they will yield baseline times that do not encompass significant delays, making them a good approximation of "congestion-free" times. The associated baseline times are also long enough to be achievable by many other flights under a range of meteorological conditions and runway configurations.

The baseline time for a given O-D pair (i,j) using the x^{th} percentile was calculated as follows: (See Appendix A for more details on the notation used)

B_{ij}^{x}=MIN ($AP_{ij}^{x}(95)$, $AP_{ij}^{x}(97)$, $AP_{ij}^{x}(00)$)............................(3.1)

with

$AP_{ij}^{x}(95)$= ($P_{ij}^{x}(1,95)$+ $P_{ij}^{x}(4,95)$+ $P_{ij}^{x}(7,95)$+ $P_{ij}^{x}(10,95)$)/4......... (3.2)

$AP_{ij}^{x}(97)$= ($P_{ij}^{x}(1,97)$+ $P_{ij}^{x}(4,97)$+ $P_{ij}^{x}(7,97)$+ $P_{ij}^{x}(10,97)$)/4..........(3.3)

$AP_{ij}^{x}(00)$= ($P_{ij}^{x}(1,00)$+ $P_{ij}^{x}(4,00)$+ $P_{ij}^{x}(7,00)$)/3........................(3.4)

where

B_{ij}^{x}: baseline time for O-D pair (i,j) using the x^{th} percentile

P_{ij}^{x}(m,y): gate-to-gate time associated with the x^{th} percentile of gate-to-gate time on (i,j) in a given month *m* for year *y*

AP_{ij}^{x}(y): average gate-to-gate time associated with the x^{th} percentile of gate-to-gate time on (i,j) in year *y*

Note that in the calculation of the baseline, only three months (January, April, and July) were used for the year 2000 because of the unavailability of data for the month of October 2000 at the time of the study. To ensure that this approximation would not skew our results, we also computed the average gate-to-gate time for all available months in 2000 (January through September, and November 2000)[10]. Since no significant difference between the results was found, we concluded that this approximation would not weaken our findings.

We saw in Chapter 2 that day of the week, time of the day, and seasonality might be factors influencing the gate-to-gate time. However, it was argued that these factors may

[10] At this time, we do not have the October 2000 file

not have a systematic influence on long-term averages. Therefore, we will not consider them explicitly in the baseline derivation.

3.1.1 Sensitivity Analysis

In this thesis, we chose to use the fifteenth percentile of gate-to-gate time in order to compute the baseline. It was decided that the fifteenth percentile would be suitable, as it offers a reasonable trade-off between the objectives of capturing both "congestion-free times" and "achievable times". The fifteenth percentile encompasses little significant delay, yet it yields a sufficiently conservative estimate of travel time.

We used a sample of the 26 O-D pairs originating at BOS to illustrate the sensitivity of the baseline to the percentile chosen. This sensitivity analysis also provided an opportunity to test our choice of the fifteenth percentile. We started by calculating individual baselines for each of the 26 O-D pairs originating in BOS (according to equations (3.1) through (3.4)), successively using the 5^{th}, 7^{th}, 10^{th}, 13^{th}, 15^{th}, 17^{th}, and 20^{th} percentile. Results are shown in Appendix B. To compare efficiently the results obtained, we aggregated the individual O-D results by computing a "weighted baseline" for each of the seven percentiles used. The weighted baseline consists of taking the weighted average[11] of the 26 O-D baseline times, as shown in equation 3.5.

$$WB^{x}_{i=BOS} = (\sum_{j} B^{x}_{i=BOS,j} * TF_{i=BOS,j}(00)) / (\sum_{j} TF_{i=BOS,j}(00)) \quad \text{......(3.5)}$$

where

$$TF_{i=BOS,j}(00) = F_{i=BOS,j}(1,00) + F_{i=BOS,j}(4,00) + F_{i=BOS,j}(7,00) \quad \text{......(3.6)}$$

and

$F_{i=BOS,j}(m,y)$= number of flown flights in month m of year y on route (BOS,j).

"x" is the value of the percentile used to calculate the baseline.

[11] Weighted by number of flights flown

The sensitivity of the weighted baseline to the percentile chosen is shown in Figure 3.1 below.

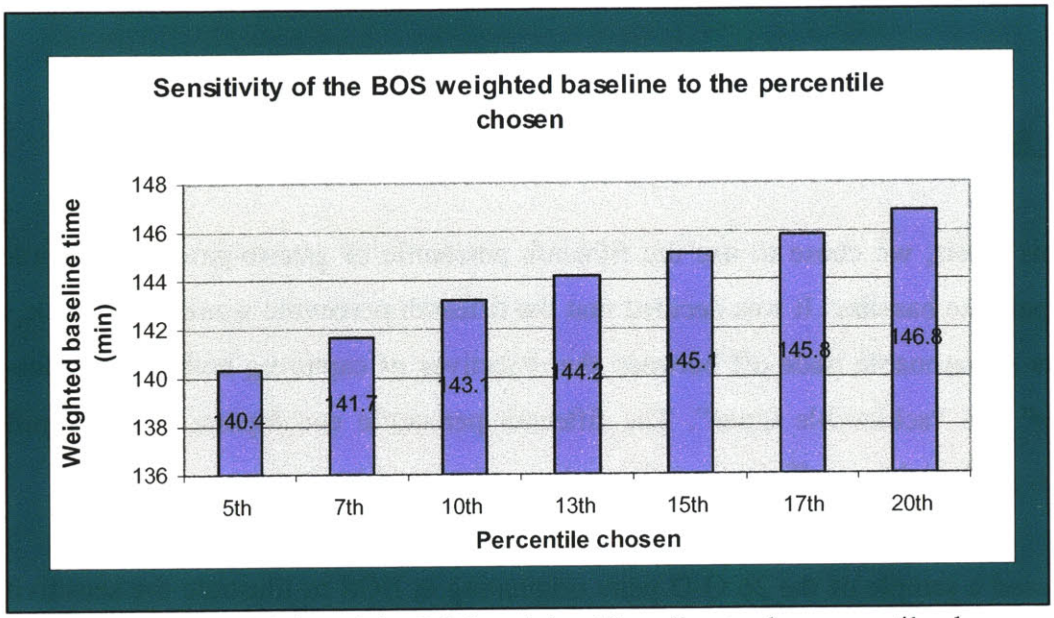

Figure 3.1: Sensitivity of the BOS weighted baseline to the percentile chosen

The difference between the weighted baseline obtained using the lowest percentile (fifth) and the highest one (twentieth) is only of the order of 5%. This suggests that any of the percentiles in the 5-20 range, including the fifteenth percentile, would be appropriate for use in the baseline estimation. It is important to remember that the baselines will be used as benchmarks against which delays can be consistently measured over time. In that respect, the exact value of the baseline is not especially critical to our measure of the evolution of true delays.

The exact value of the percentile to be chosen for an "optimal' baseline is not an issue that we will consider further in this thesis. Note that the methodologies outlined in the remainder of this thesis could be used with any percentile in the 5-20 range.

3.1.2 Results

Figure 3.2 shows the baseline times, estimated using the fifteenth percentile, for all the O-D pairs considered.

DESTINATION AIRPORT	ORIGIN AIRPORT																										
	ATL	BOS	BWI	CLE	CLT	CMH	CVG	DCA	DEN	DFW	DTW	EWR	FLL	IAD	IAH	LAX	LGA	MCO	MEM	MIA	MSP	ORD	PHL	PHX	PIT	SFO	TPA
ATL		148	98	92	56	80	72	97.4	153	109	103	126	97.4	93.3	103	229	129	76.7	63.5	101	135	99.3	111	191	90.3	253	77.8
BOS	134		70	92	112	97	111	74.6	209	198	99.8	58.2	164	75.8	205	303	49.8	154	154	179	148	120	60	273	83.3	312	160
BWI	92	75		60	68.5		73		179	157	79.4		137		161	271	50.5	116		140	129	94.5	37		52.5	282	121
CLE	89	105	62		78.8		51.3	66.2	154	141	39.8	82.8	154		145	249	83.2	131	94.5	157	94.1	61.3	72	212		250	133
CLT	51	121	70	75		63		65.6	167	132	84.3	94.4	105	63	125	249	98.3	86	77	110	129	93.2	82	217	72.9	266	85.8
CMH	77	114			66.5		37	64.5	148	133	45.3	90			135	234	91	122			93.8	59.5	74	198	40.1		121
CVG	72	125	83	50		37		80	136	118	56.1	102	139			225	109	119	70.4	143	91.5	58	92	187	57	238	117
DCA	89	85		61	65	58	69.5			152	75	56.7	132		158		54.5	113	107	136	124	90.8	43		50		119
DEN	176	252	210	177	203	166	160			108	168	233		204	129	122	235	210	136	239	108	136	222	93	188	131	206
DFW	123	229	183	157	155	146	130	181	100		156	207	169	176	56	166	211	155	79.5	174	136	129	195	124	165	187	145
DTW	100	117	83	43	91.3	50	59	85.3	150	142		98.5	167	79.7	146	241	99.8	147	98.8	169	88.3	60	92	209	52.5	249	147
EWR	117	68		77	92.2	84	95.5	55.9	196	185	85.3		154		184	290		138	140	161	140	107		256	67.3	299	143
FLL	96	177	140	156	103		131	138		146	160	157		141	130	275	160	46.3				160	147		146		
IAD	88	83			63.6				173	149	73.8		135		153	266	59.5	112		133	127	89.5	43	224	46.7	271	116
IAH	112	232	176	161	141	147		178	123	52.5	160	205	146	176		175	209	135		148	157	137	194	139	168	206	122
LAX	262	352	313	285	291	276	257		129	180	273	334	314	304	193			297	229	314	217	239	323	69.3	289	68.3	289
LGA	114	52	47	77	89.8	79	95.7	48.3	195	179	88.8		156	53.1	184			138	134	160	141	107	38		65.3		141
MCO	73	166	119	131	80.5	115	108	121	188	137	140	146	43.7	118	120	259	146		104	50.3	171	137	132	226	122	288	32.9
MEM	66	172		105	90.3		72.8	121	119	73.2	104	150				197	151	115		137	105	84.8	140	159		218	108
MIA	96	182	139	152	106		133	139	211	149	162	163		140	129	273	162	50.3	124		197	162	149	245	147	303	
MSP	142	172	143	107	152	106	101	145	100	126	98.5	160		144	146	192	160		111	212		70.8	154	167	120	194	187
ORD	104	142	110	69	105	64	60	106	123	118	59.5	126	171	102	132	218	127	151	88.8	175	64		117	180	79.5	222	147
PHL	105	70	37	67	78.4	68	83.3	46.3	189	168	80		144	48.2	174	277	41.8	129	124	149	133	102		250	55.3	292	133
PHX	223	319		246	254	230	216		97.5	136	234	302		268	150	64.3		259			180	200	290		252	101	
PIT	87	93	51		71.6	39	53.5	52.5	163	147	48.3	72	146	47.9	148	253	73	126		150	106		58	219		262	128
SFO	286	363	329	303	314		269		141	208	285	351		314	228	65.3		322	249	343	225	249	339	108	305		
TPA	74	179	128	139	85.3	119	113	127	185	130	143	155	46	121	110	258	160	32.9	98	46.5	172	138	141		129		

Figure 3.2: Baseline Times per O-D pair

	ORIGIN AIRPORT																									
DESTINATION AIRPORT	ATL	BOS	BWI	CLE	CLT	CMH	CVG	DCA	DEN	DFW	DTW	EWR	FLL	IAD	IAH	LAX	LGA	MCO	MEM	MIA	MSP	ORD	PHL	PHX	PIT	SFO	TPA
ATL		22.1	15.5	17.1	19.6	13.4	18.6	14.8	13.9	16.8	18.6	18.8	17.0	16.7	17.0	22.2	22.8	12.4	13.0	15.5	15.8	15.1	23.1	21.1	16.3	14.3	14.4
BOS	19.8		15.8	18.0	19.7	13.2	19.2	18.7	18.3	24.0	17.8	21.7	32.9	20.4	23.3	22.4	23.8	23.9	17.8	19.9	20.8	22.3	23.3	18.2	17.1	17.9	25.2
BWI	15.0	13.4		12.2	11.2		16.5		13.9	15.6	11.6		11.4		17.2	14.6	22.2	10.8		12.8	14.8	15.2	13.0		10.5	15.9	10.4
CLE	16.6	15.8	11.9		16.8		11.8	15.1	12.9	15.5	13.4	20.8	14.2		14.3	12.2	22.2	14.1	7.7	14.8	16.4	13.2	21.4	10.4		12.7	12.3
CLT	12.1	17.8	10.5	13.0		9.8		12.8	9.5	12.8	15.9	18.6	12.4	15.0	15.4	14.4	20.4	10.7	12.2	10.2	11.4	12.6	21.1	12.0	11.5	13.9	9.4
CMH	12.7	12.5			10.9		12.3	13.4	12.3	10.6	12.5	20.9			14.4	9.2	20.2	11.1			11.1	10.5	20.9	17.0	8.9		11.9
CVG	16.0	20.1	12.4	14.2		11.8		15.7	13.0	14.6	17.1	19.6	13.9			21.1	22.1	13.3	14.8	15.9	15.5	14.1	20.7	17.9	15.4	16.3	14.0
DCA	12.0	12.1		9.8	10.1	8.5	11.2			15.7	10.7	15.5	10.5		16.0		16.6	12.4	12.9	10.0	14.1	14.6	14.7		9.6		10.2
DEN	19.0	18.1	21.3	18.5	11.0	20.8	16.3			12.5	17.6	27.3		22.4	12.1	13.1	21.8	21.0	11.2	18.3	15.0	16.8	31.1	11.9	14.4	13.7	19.5
DFW	15.5	21.4	14.1	17.1	14.0	12.3	15.0	15.0	9.7		16.1	22.7	15.3	16.1	11.7	12.6	21.9	12.5	13.2	12.5	15.8	14.0	22.3	13.5	14.7	16.3	12.1
DTW	15.9	17.0	13.7	14.5	16.2	12.1	13.2	12.8	13.2	13.6		18.8	15.3	17.7	17.8	17.0	21.4	14.4	11.2	13.9	17.1	14.1	18.7	16.0	15.1	15.7	12.9
EWR	19.7	13.6		17.1	14.7	14.1	19.4	15.2	25.0	23.9	16.3		20.8		23.0	22.4		17.7	15.5	18.8	18.3	20.6		20.5	16.2	20.7	18.4
FLL	12.8	30.5	12.5	11.3	9.8		14.7	12.0		17.1	15.0	25.3		13.6	13.1	13.6	22.5	5.7				15.0	16.7		11.5		
IAD	17.9	18.1			13.5				16.6	22.2	17.8		16.7		24.6	18.1	21.7	16.3		17.6	13.7	18.6	20.1	22.6	15.0	23.7	15.3
IAH	14.8	19.5	28.4	14.7	18.0	11.9		12.1	12.4	11.9	17.1	20.6	11.5	15.2		19.0	22.7	8.9		10.3	14.5	15.4	24.5	14.2	15.7	14.0	10.3
LAX	20.9	20.0	19.8	13.3	16.2	15.9	24.6		13.4	11.6	22.3	31.4	13.3	22.2	16.4			16.4	12.2	18.2	20.3	19.1	27.6	11.6	21.0	15.0	15.5
LGA	19.6	19.2	18.6	14.9	16.4	13.9	19.4	16.0	16.7	23.4	14.5		20.4	18.9	19.4			17.4	17.6	22.1	17.1	18.6	13.9		16.0		18.1
MCO	12.6	23.4	12.3	11.0	10.4	9.9	15.4	14.4	12.4	13.2	16.4	20.4	7.9	13.3	13.4	20.6	19.5		9.4	11.6	15.6	14.6	16.8	11.4	11.3	11.8	7.1
MEM	11.2	17.3		10.7	10.4		12.1	13.2	10.7	13.1	14.8	15.4				17.1	16.7	8.6		10.6	12.0	12.2	17.3	17.3		11.3	8.1
MIA	14.4	18.7	16.0	17.1	10.2		12.6	13.3	13.0	14.7	16.0	20.5		17.3	12.7	20.3	22.3	9.6	9.7		13.3	14.9	17.8	13.1	10.1	15.0	
MSP	19.0	20.9	19.9	18.5	19.7	13.5	21.5	17.9	12.5	18.8	16.5	23.4		19.8	20.2	13.1	22.5		12.7	17.4		16.1	25.2	13.7	17.3	13.3	17.7
ORD	20.5	23.9	15.5	20.5	18.4	15.3	17.3	20.7	16.9	21.2	19.4	27.3	21.4	21.5	20.9	17.0	26.3	19.8	13.1	22.2	16.0		25.7	21.0	18.4	17.2	19.5
PHL	20.1	22.4	11.9	20.5	17.9	17.8	19.7	10.2	18.6	21.1	18.9		17.7	10.4	22.4	23.3	16.7	15.6	14.0	17.7	20.2	18.5		17.1	18.0	19.2	18.4
PHX	19.5	24.2		13.9	9.5	15.8	23.1		10.6	13.0	21.2	27.5		26.6	13.5	11.6		13.2			18.3	20.6	21.1		12.8	10.0	
PIT	15.1	15.4	9.9		11.3	9.9	17.1	8.9	9.9	14.7	12.9	18.2	12.9	18.3	16.2	11.0	21.7	11.7		14.2	10.9		18.2	12.7		12.8	12.7
SFO	24.7	27.2	24.8	17.3	18.2		28.2		17.5	21.4	27.1	31.1		33.9	19.9	13.3		19.0	17.9	20.4	24.4	25.4	32.7	12.8	22.5		
TPA	12.7	21.9	11.1	12.4	10.4	9.6	12.8	12.4	9.9	11.0	14.1	21.9	7.3	12.8	15.1	10.8	21.5	10.1	7.8	15.0	12.7	13.2	20.1		11.2		

Figure 3.3: Average "true" delays per O-D pair in 2000 (min/op)

The O-D baseline times shown in Figure 3.2 are computed from expression (3.1). It is interesting to note that in the great majority of cases (63%), the minimum of the quantities included in (3.1) is the fifteenth percentile associated with 1995. The second higher number of minima is associated with 1997 (27%) while only a small number of entries (10%) is associated with 2000. This suggests that there was an overall upward trend in transit times between 1995 and 2000, a point to be noted in a number of instances later in this thesis.

3.2 Application: Evolution of O-D delays from 1995 to 2000

3.2.1 Calculation of O-D delays

Having established the baselines, we can now calculate "true" delays for each O-D pair. The average true O-D delay in each year can be computed as the difference between the average gate-to-gate time in that year and the baseline time.

The average O-D delay on route (i, j) in year y is defined as:

$$D_{ij}^{15}(y) = AG_{ij}(y) - B_{ij}^{15} \quad \text{...(3.7)}$$

Note that the average O-D delay in equation (3.7) is computed by taking the average of gate-to-gate time in year y minus the baseline time. This is equivalent to taking the average of individual flight delays in year y, where an individual flight delay is defined as the actual gate-to-gate time of this flight minus the baseline. Flights incurring gate-to-gate times smaller than the baseline incur a "negative" delay.

True delays incurred in the year 2000 are shown for each O-D pair in Figure 3.3. The delay is in minutes per operation.

"True" delays in 2000 on the routes considered range from about 5 minutes to 34 minutes per operation. Over the months of January, April and July 2000, 94% of the 618 routes considered experienced an average delay per operation of at least 10 min; 56% a delay of at least 15 minutes; 21% a delay of at least 20 minutes; and 4% a delay of over 25 minutes.

In order to analyze their evolution, O-D delays were calculated for each O-D pair in 1995, 1997, and 2000. We then aggregated the data by forming the overall weighted delay, which is defined as the weighted average of delays incurred on each of the 618 O-D pairs (3.8). Details are shown in appendix B.

$$WD_{ALL}(y) = \sum_{i}\sum_{j \neq i} TF_{ij}(y) * D_{ij}(y) / (\sum_{i}\sum_{j \neq i} TF_{ij}(y)) \qquad \text{.........................(3.8)}$$

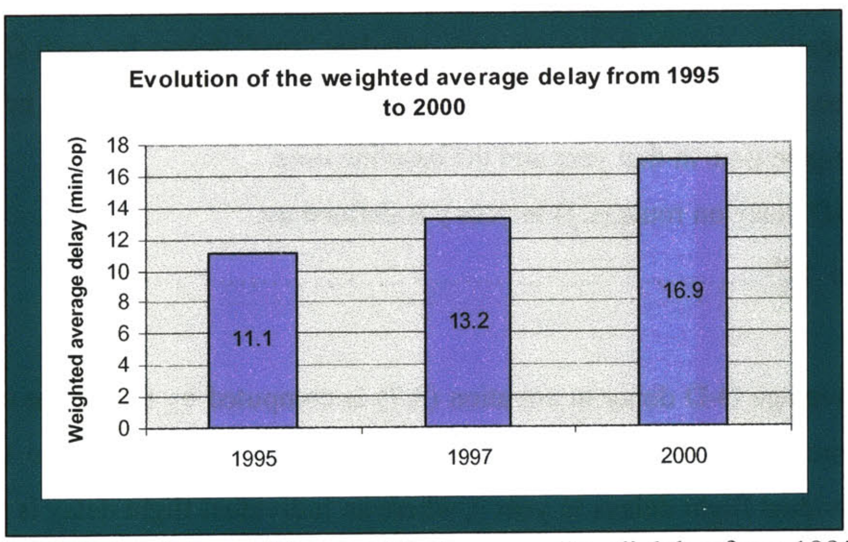

Figure 3.4: Evolution of the weighted average "true" delay from 1995 to 2000

The overall weighted average of "true" delays on the 618 O-D pairs has increased from 11.1 minutes per operation in 1995 to 16.9 minutes in 2000. This represents an increase in "true" delay of about 52%. Routes on which true delays have increased most during that period are those originating in PHL, IAD, CVG, LGA, and BOS on which delays on average have increased by more than 78%.

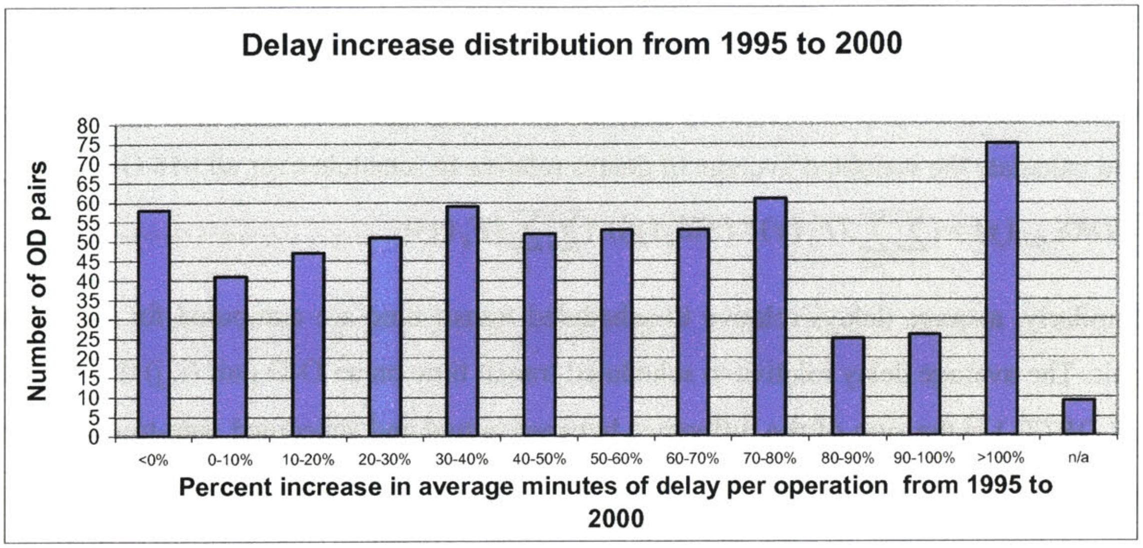

Figure 3.5: Distribution of the delay increase between 1995 and 2000

Figure 3.5 illustrates the magnitude of the increase in delays at the O-D pair level[12]. Only 57 of the 618 O-D pairs experienced a drop in the average "true" delay per operation in the 1995-2000 period. All other pairs experienced an increase; 75 pairs saw delays more than double from 1995 to 2000.

3.2.2 Comparison with DOT statistics and delay relative to schedule

The next step consists of examining the implications of using the "true" delay definition versus alternative delay definitions such as "delay relative to schedule" and "delay relative to scheduled transit time".

Average delays relative to schedule are computed as follows for each O-D pair. The total delay on an O-D pair (i, j) during year *y* is the sum of the difference between actual and scheduled arrival times for each flight in the months of January, April, July, and October[13]. The total delay is then divided by the number of flights flown in those months.

[12] n/a includes routes that were not flown either in 1995 or 2000
[13] In 2000, only the months of January, April, and July are used.

$$DRS_{ij}(y) = (\sum_{flights \in (i,j) in y} (ActualArrivalTime - ScheduledArrivalTime)) / TF_{ij}(y) \quad (3.9)$$

In order to allow for an efficient comparison, we aggregate delays relative to schedule and calculate the weighted average of delays relative to schedule over all 618 O-D pairs.

$$WDRS_{ALL}(y) = (\sum_{i}\sum_{j \neq i} TF_{ij}(y) * DRS_{ij}(y)) / (\sum_{i}\sum_{j} TF_{ij}(y)) \quad (3.10)$$

Similarly, average delays relative to scheduled transit time are computed for each O-D pair. The average delay relative to scheduled transit time on an O-D pair (i, j) during year y ($DRTT_{ij}$) is the sum of the difference between actual and scheduled gate-to-gate times for each flight in the months of January, April, July, and October[14] of year *y*, divided by the total number of flights flown in those months in year y.

$$DRTT_{ij}(y) = (\sum_{flights \in (i,j) in y} (Actual\_G2GTime - Scheduled\_G2GTime)) / TF_{ij}(y) \quad (3.11)$$

We also calculate the weighted average of delays relative to scheduled transit time over all 618 O-D pairs as follows:

$$WDRTT_{ALL}(y) = (\sum_{i}\sum_{j \neq i} TF_{ij}(y) * DRTT_{ij}(y)) / (\sum_{i}\sum_{j} TF_{ij}(y)) \quad (3.12)$$

A comparison of weighted average "true" delays, delays relative to schedule, and delays relative to scheduled transit times is shown in Figure 3.6.

[14] In 2000, only the months of January, April, and July are used.

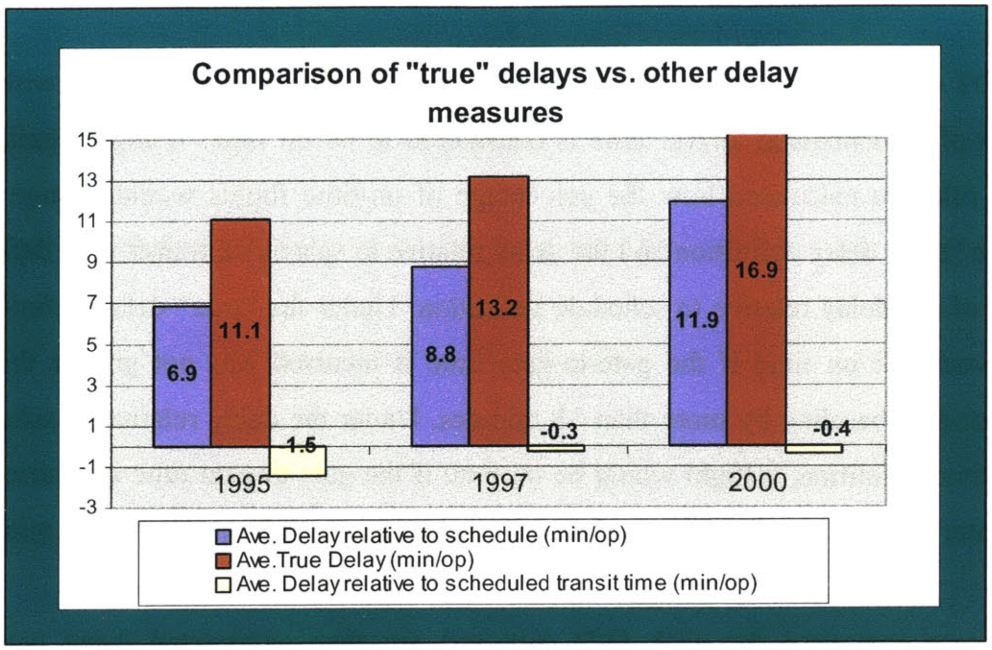

Figure 3.6: Comparison of overall average true delay versus other delay measures

Figure 3.6 shows that on aggregate, both true delays and delays relative to schedule have increased over the 1995-2000 period. In 1995, true delays were larger than delays relative to schedule by about 4 minutes; in 2000 they were larger by about 5 minutes. It seems that the gap between true delays and delays relative to schedule is remaining rather stable over the years. Overall, average true delays seem to be about 40% to 60% larger than delays relative to schedule.

Average scheduled transit time has increased on average by 10.5 minutes from 1995 to 2000, based on the analysis of the 618 routes under consideration (See Appendix B for more details). This is an illustration of the point made in Chapter 2 about airlines "adjusting" their schedules constantly to achieve better on-time performance.

Figure 3.6 shows that in all years considered, the average delay relative to scheduled transit time was slightly negative on average, which means that actual gate-to-gate time was on average shorter than scheduled gate-to-gate time. This observation suggests that airlines are good at predicting gate-to-gate times. However, Figure 3.6 also shows that flights arrive on average 7 to 12 minutes behind schedule. One can therefore conclude that although airlines seem to be able to accurately predict gate-to-gate times, they are not good at predicting departure times, which results in delays relative to schedule.

The DOT definition of on-time performance implies that any flight arriving within 15 minutes of its scheduled arrival time is considered to be on time. Using a similar 15-minute rule, we calculated how the percentage of on-time flights would change if we used the "true" delay definition and the delay relative to scheduled transit time definition instead of the delay relative to schedule definition. Under the "true" delay definition, a flight would be on time if the gate-to-gate time it incurred was not greater than the corresponding baseline by more than 15 minutes. Under the delay relative to scheduled transit time definition, a flight would be on time if the gate-to-gate time it incurred was not greater than the corresponding scheduled gate-to-gate time by more than 15 minutes.

Results are computed for each O-D pair and are then aggregated using weighted averages.

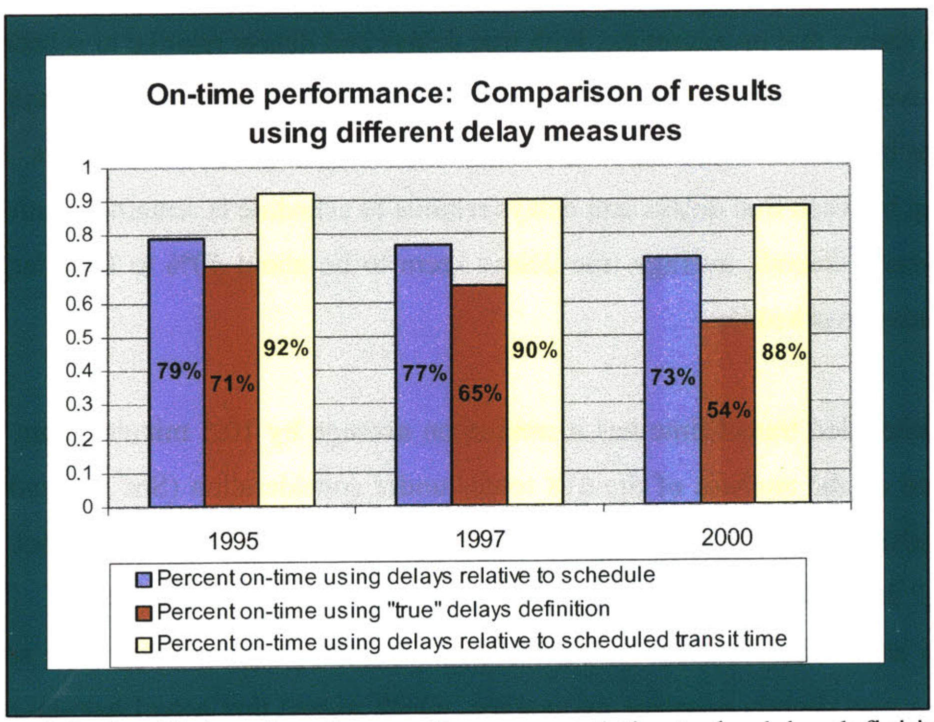

Figure 3.7: Sensitivity of on-time performance statistics to the delay definition used

Using the "true" delay definition yields considerably lower on-time performances in all years. If the "true" delay definition had been used in 2000, only 54% of all flights operating on the 618 O-D pairs would have been considered "on-time".

In this chapter, we established a methodology for the estimation of true delays on a given O-D pair. It was proposed that for national policy purposes, it may be appropriate to use the fifteenth percentile as a robust estimate of the baseline transit times. This methodology can be extended to the entire national network.

In Chapter 4, we will outline different procedures to attribute the O-D true delays to the origin and destination airports.

CHAPTER 4: ROLE OF AIRPORTS IN GENERATING DELAYS

One of the challenges remaining once O-D-specific delays are computed is to attribute these delays to airports. Most of the delay on an O-D pair occurs at the origin or the destination airport, as airports typically constitute the bottleneck in the air transportation system. Some of the problems exacerbating congestion and delays at the US airports include the absence of demand management measures as well as the reduction in capacity that results from bad weather.

Section 4.1 will examine different methodologies that can be used to attribute O-D delays to the relevant airports. Section 4.2 will present an analysis and discussion of the results obtained in Section 4.1.

4.1 Estimation of airport delays

In this chapter, we are only concerned with allocating O-D delays to the airports of origin and destination. Many methods can be used to do so. Two methods are examined in detail in this chapter.

4.1.1 Method A

4.1.1.1 Step A1

In Method A, it is assumed that O-D delays are due exclusively to the airports of origin and destination. We will initially assume that the origin airport and the destination airport both contribute equally to the O-D delay (Step A1). Although this is a crude approximation of what happens in reality, this simplification will allow us to obtain a preliminary estimate of the extent of congestion at each airport.

Half of the delay on any given O-D pair is therefore attributed to the airport of origin, and is called departure delay. The other half is attributed to the destination airport and is called arrival delay. In order to calculate the average origin delay at a given airport a ($OrgAD1_a(y)$), the weighted average of the departure delays occurring at this airport is computed through (4.1).

$$OrgAD1_a(y) = 0.5 * \left(\sum_j D_{aj}^{15}(y) * TF_{aj}(y)\right) / \left(\sum_j TF_{aj}(y)\right) \qquad (4.1)$$

Similarly, the average destination delay at a given airport a ($DestAD1_a(y)$) is a weighted average of the arrival delays occurring at airport a:

$$DestAD1_a(y) = 0.5 * \left(\sum_i D_{ia}^{15}(y) * TF_{ia}(y)\right) / \left(\sum_i TF_{ia}(y)\right) \qquad (4.2)$$

Finally the average overall delay at airport a ($A_a1(y)$) is the weighted average of the average origin and average destination delays at that airport[15]:

[15] In principle, taking the weighted average should be the same as taking the average of the origin and destination delay at each airport, since the number of arrivals at an airport should be the same as the number of departures. However, in our case, because we are only considering flights operating between 27 airports, not all departures and arrivals are represented. Moreover, the data set has gaps, since only the months of January, April, July and October were used.

$$A_a1(y) = [\, OrgAD1_a(y) * (\sum_j TF_{aj}(y)) + DestAD1_a(y) * (\sum_i TF_{ia}(y))\,] \;/\; [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y)\,] \qquad (4.3)$$

Step A1 is described in Appendix C in greater detail.

For the years 1995, 1997, and 2000, Step A1 yields Table 4.1, which allows for a preliminary comparison of the evolution of delays at each of the 27 airports under consideration. Table 4.1 indicates estimated delay per *airport operation*, not per *flight*.

	METHOD A (Step A1)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	5.7	5.6	5.6	5.9	7.6	6.7	8.3	8.7	8.5
BOS	5.6	5.6	5.6	7.1	7.0	7.1	9.9	10.7	10.3
BWI	4.9	4.6	4.8	5.0	4.6	4.8	7.1	6.6	6.8
CLE	5.0	4.9	4.9	6.0	6.0	6.0	7.7	7.5	7.6
CLT	4.7	4.6	4.6	5.4	5.7	5.6	7.3	6.9	7.1
CMH	4.4	4.4	4.4	5.4	5.5	5.4	6.4	6.6	6.5
CVG	4.7	4.2	4.5	6.2	6.3	6.2	8.7	8.0	8.3
DCA	5.2	4.6	4.9	6.3	5.4	5.8	7.7	6.6	7.2
DEN	5.6	5.6	5.6	6.3	6.0	6.1	7.1	8.4	7.7
DFW	5.9	6.6	6.2	7.5	7.6	7.5	8.2	7.6	7.9
DTW	5.9	5.6	5.8	6.5	6.4	6.5	8.4	7.8	8.1
EWR	7.1	6.0	6.6	9.0	7.8	8.4	11.4	9.6	10.5
FLL	4.8	5.6	5.2	5.4	6.2	5.8	8.0	8.3	8.1
IAD	5.3	4.8	5.1	6.3	6.1	6.2	9.4	9.1	9.3
IAH	5.5	6.1	5.8	6.2	6.4	6.3	8.3	7.6	8.0
LAX	5.7	6.3	6.0	7.3	6.9	7.1	7.9	8.6	8.2
LGA	6.2	5.2	5.7	7.7	6.0	6.8	11.0	9.2	10.1
MCO	4.8	5.5	5.1	5.5	6.2	5.9	7.3	7.4	7.4
MEM	4.7	4.8	4.7	5.9	5.8	5.8	6.4	6.4	6.4
MIA	6.5	6.4	6.4	6.8	7.1	6.9	8.0	7.7	7.8
MSP	5.9	5.4	5.7	6.6	7.0	6.8	8.1	8.7	8.4
ORD	5.5	5.9	5.7	6.5	7.2	6.9	8.5	10.3	9.4
PHL	5.4	4.6	5.0	7.2	6.5	6.8	11.1	9.5	10.3
PHX	5.0	5.1	5.0	6.4	5.7	6.0	7.3	7.7	7.5
PIT	5.2	4.5	4.9	5.4	5.3	5.3	7.5	7.0	7.2
SFO	5.9	7.1	6.5	7.3	7.0	7.2	7.8	10.5	9.1
TPA	4.7	5.2	4.9	5.7	5.7	5.7	7.3	6.7	7.0
	5.5	5.5	5.5	6.6	6.6	6.6	8.4	8.4	8.4

Table 4.1: Average airport delays (min/op) obtained using Step A1

According to Step A1, the airport with the highest overall delay incurred on average 10.5 minutes of delay per operation in 2000. The airport with the lowest overall delay incurred on average 6.4 minutes of delay per operation in 2000.

4.1.1.2 Step A2

The accuracy of Method A can be improved by relaxing the simple approximation made in Step A1. The airports of origin and destination are no longer assumed to contribute equally to the O-D delay. Some airports are more sensitive than others to increased traffic, bad weather, and congestion; the model can be improved by taking this into account. In Step A2, the attribution of the O-D delays depends on the relative weights of the airports of origin and destination.

Each O-D delay is allocated between the origin and the destination airport according to the relative weights of these airports. The procedure followed is iterative. Initially (first iteration), the weights ($CORG_{ij}(y), CDES_{ij}(y)$) are taken to be a function of the origin delay and destination delay calculated in Step A1:

$$CORG_{ij,iter=0}(y) = OrgAD1_i(y) / (DestAD1_j(y) + OrgAD1_i(y)) \quad \text{............(4.4a)}$$

$$CDES_{ij,iter=0}(y) = DestAD1_j(y) / (OrgAD1_i(y) + DestAD1_j(y)) \quad \text{............(4.5a)}$$

In each succeeding iteration, the relative weights will be a function of delay results obtained in the previous iteration, as given in equations (4.4b) and (4.5b).

$$CORG_{ij,iter=k+1}(y) = OrgAD2_{i,iter=k}(y) / (DestAD2_{j,iter=k}(y) + OrgAD2_{i,iter=k}(y)) \quad \text{..(4.4 b)}$$ [16]

$$CDES_{ij,iter=k+1}(y) = DestAD2_{j,iter=k}(y) / (OrgAD2_{i,iter=k}(y) + DestAD2_{j,iter=k}(y)) \quad \text{..(4.5b)}$$ [17]

The departure delay on an O-D pair ($DepD_{ij,iter=k}(y)$) is calculated by equation (4.6) and is attributed to the origin airport.

$$DepD_{ij,iter=k}(y) = CORG_{ij,iter=k}(y) * D_{ij}^{15} \quad \text{..(4.6)}$$

[16] $OrgAD2_{i,iter=k}(y)$ is to be determined in equation (4.8)

[17] $DestAD2_{j,iter=k}(y)$ is to be determined in equation (4.9)

The arrival delay on an O-D pair ($ArrD_{ij,iter=k}(y)$) is calculated by equation (4.7) and is attributed to the destination airport.

$$ArrD_{ij,iter=k}(y) = CDES_{ij,iter=k}(y) * D_{ij}^{15} \qquad (4.7)$$

The origin delay at a specific airport a ($OrgAD2_{a,iter=k}(y)$) is then obtained by averaging the departure delays attributed to this airport, using (4.8).

$$OrgAD2_{a,iter=k}(y) = (\sum_j DepD_{aj,iter=k}(y) * TF_{aj}(y)) / (\sum_j TF_{aj}(y)) \qquad (4.8)$$

Similarly, each airport's destination delay ($DestAD2_{a,iter=k}(y)$) is computed by averaging the arrival delays attributable to that airport, as shown in (4.9).

$$DestAD2_{a,iter=k}(y) = (\sum_i ArrD_{ia,iter=k}(y) * TF_{ia}(y)) / (\sum_i TF_{ia}(y)) \qquad (4.9)$$

The procedure is then iterated until "convergence", as shown in Figure 4.1.

The average overall delay is then computed by taking the weighted average of the origin and destination delays at each airport (4.10).

$$A_a 2(y) = [OrgAD2_a(y) * (\sum_j TF_{aj}(y)) + DestAD2_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))] \qquad (4.10)$$

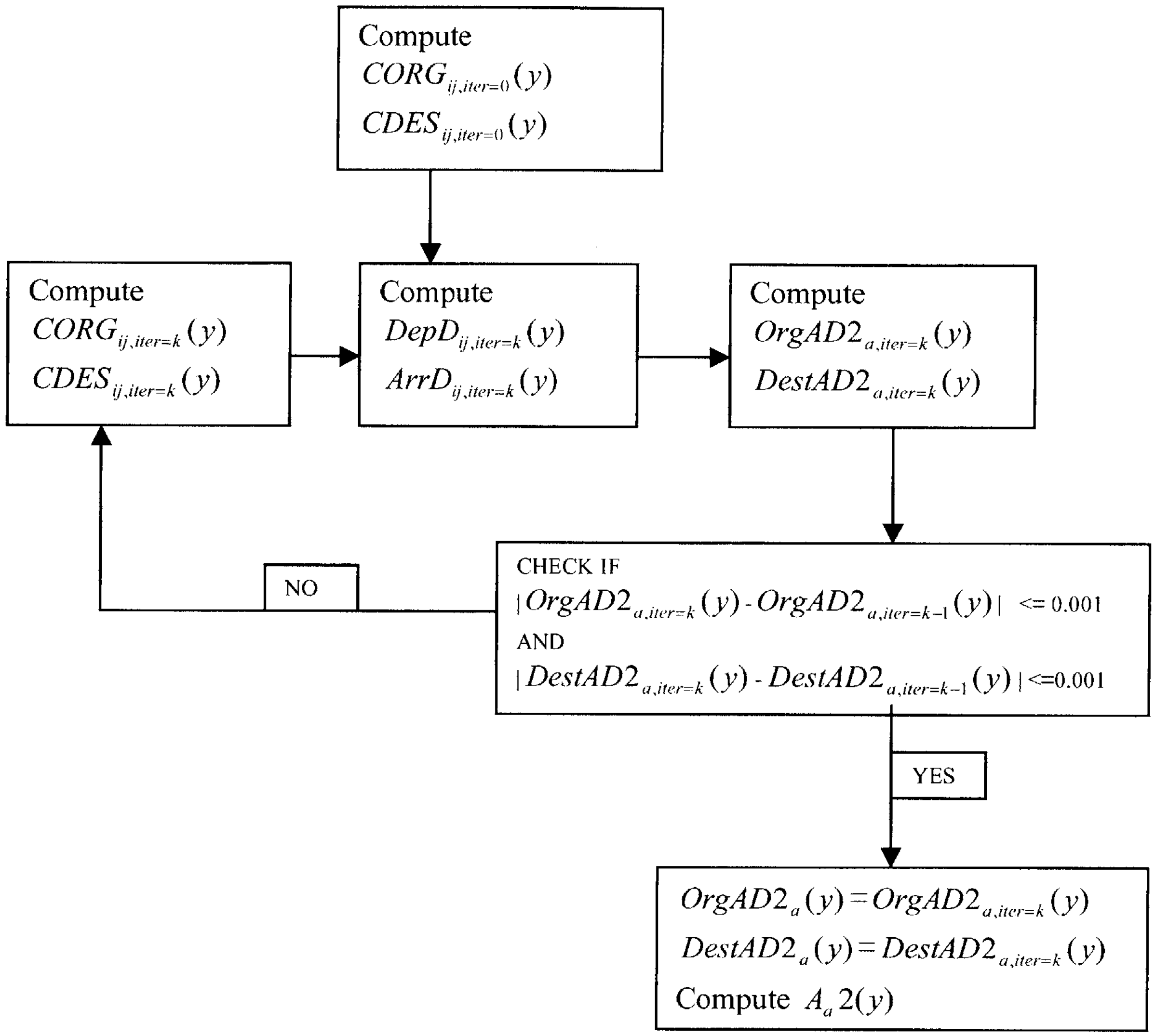

Figure 4.1: Step A2 – Description of the iterative process

Airport delays in 1995, 1997, and 2000 were thus computed, as shown in Table 4.2.

	METHOD A (step 2)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	6.0	5.7	5.8	5.5	8.7	7.1	8.5	8.9	8.7
BOS	5.7	5.5	5.6	7.8	7.4	7.6	11.6	12.8	12.2
BWI	4.4	3.8	4.1	3.5	3.2	3.4	6.7	5.6	6.1
CLE	4.6	4.3	4.4	5.5	5.4	5.5	7.2	6.4	6.8
CLT	4.0	3.7	3.9	4.3	5.0	4.6	6.5	5.2	5.9
CMH	3.6	3.1	3.4	4.4	4.3	4.3	4.9	4.8	4.8
CVG	4.0	3.0	3.5	5.8	6.0	5.9	8.9	7.8	8.3
DCA	4.8	3.5	4.1	5.6	4.0	4.8	6.6	4.3	5.4
DEN	5.3	5.6	5.4	5.7	5.1	5.4	5.2	8.2	6.7
DFW	6.4	7.8	7.1	8.6	8.7	8.7	8.1	6.9	7.5
DTW	6.5	5.9	6.2	6.5	6.5	6.5	8.6	7.3	8.0
EWR	8.6	6.7	7.6	11.5	9.4	10.5	14.8	11.8	13.3
FLL	4.2	5.3	4.7	4.0	5.5	4.7	7.2	6.4	6.8
IAD	4.6	4.1	4.3	5.9	5.6	5.8	9.9	10.2	10.0
IAH	5.1	6.6	5.9	5.8	6.1	5.9	8.4	7.1	7.7
LAX	5.4	7.2	6.3	7.9	7.1	7.5	6.9	9.0	8.0
LGA	6.9	5.0	5.9	8.8	6.0	7.4	14.1	10.6	12.3
MCO	4.2	5.4	4.8	4.5	5.6	5.0	5.8	5.7	5.8
MEM	3.5	3.8	3.6	4.6	4.8	4.7	4.6	4.3	4.5
MIA	7.3	7.0	7.1	6.7	7.3	7.0	7.2	6.5	6.9
MSP	6.3	5.4	5.9	6.7	7.5	7.1	7.8	9.1	8.4
ORD	5.5	6.2	5.8	6.3	7.4	6.9	8.4	11.8	10.1
PHL	5.5	4.0	4.8	8.0	7.1	7.5	14.1	11.3	12.7
PHX	3.7	4.6	4.1	5.8	4.4	5.1	5.8	7.2	6.5
PIT	4.9	3.6	4.3	4.3	4.0	4.1	6.5	5.2	5.9
SFO	5.9	8.7	7.3	8.0	7.2	7.6	6.7	12.6	9.6
TPA	4.1	4.8	4.5	4.9	5.1	5.0	6.1	4.5	5.3
	5.5	5.6	5.5	5.5	7.7	6.6	8.4	8.4	8.4

Table 4.2: Average airport delays (min/op) obtained using Step A2

Comparison of Table 4.1 and Table 4.2 shows that:

- At the aggregate level, both Step A1 and Step A2 yield identical aggregate overall delay figures, as should be the case since the total amount of delay remains unchanged between the two steps. However, they yield different average aggregate origin and average aggregate destination delay figures due to the different weights attributed to the origin and destination airports.
- At the individual airport level, average overall delay results are different for Step A1 and Step A2. It is interesting to note that in all years, airports with delays greater than average under Step A1 (5.5 min/op in 1995, 6.6 min/op in 1997, and 8.4 min/op in 2000) were assigned even higher delays in Step A2. Similarly, airports with delays smaller than average in Step A1 were assigned even smaller delays in Step A2. Therefore Step A2 resulted in an increase in spread among

delays experienced at different airports. This is illustrated in Figure 4.2[18], for year 2000.

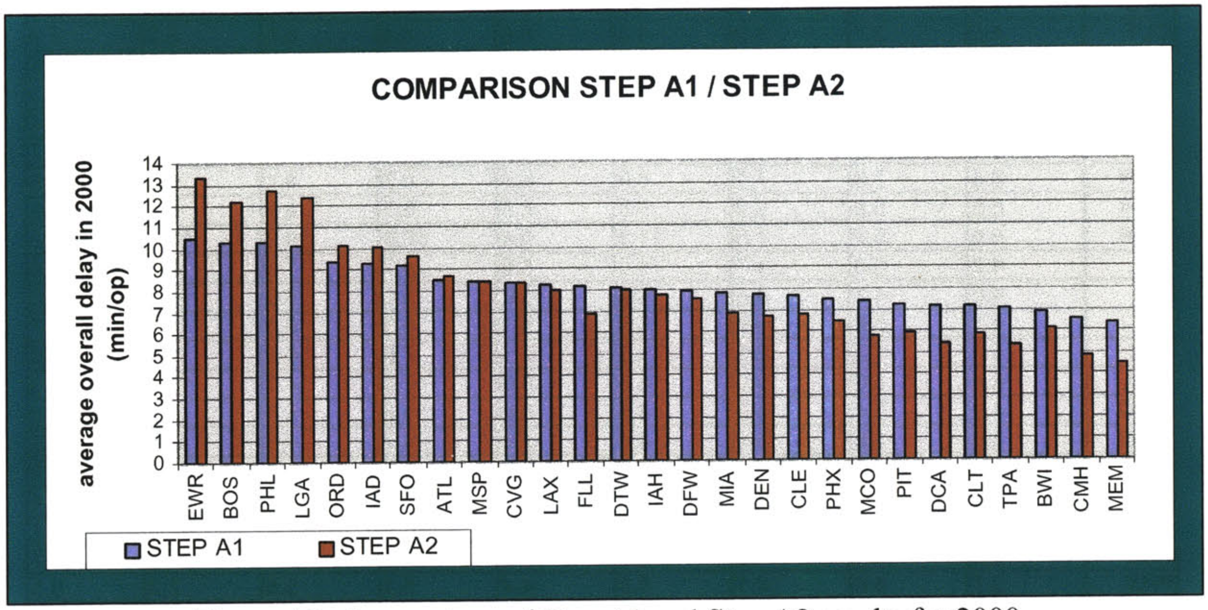

Figure 4.2: Comparison of Step A1 and Step A2 results for 2000

In 2000, the spread has more than doubled from 4.2 minutes per operation in Step A1 to 8.8 minutes per operation in Step A2. The magnitude of the increase or decrease in average delay from Step A1 to Step A2 does not depend solely on the delay results obtained in Step A1. It also depends on the relative congestion level of the airports that are connected to the airport under consideration. For example, FLL and DTW had very similar delays as computed in Step A1. However, in Step A2, the delays at FLL decreased by over 1 minute while the delays at DTW barely decreased. This can be explained by the fact that FLL is less congested than most of the airports it is connected to. DTW, on the other hand, is connected for the most part with airports that operate at similar congestion levels.

In the rest of the Chapter, we will only be referring to the results of Step A2 under Method A.

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[18] Note that the same phenomenon can be observed for 1995 and 1997.

4.1.2 Method B

4.1.2.1 Step B1

Method B, unlike Method A, is based on the decomposition of gate-to-gate time into its three components: taxi out, airborne, and taxi in times. The initial assumption (Step B1) for Method B is that taxi out delay, taxi in delay, and airborne delay can be computed independently and are completely uncorrelated.

In Step B1 it is assumed that:

- Taxi out delay is a result of congestion at the airport of origin and can therefore be attributed to the airport of origin.
- Taxi in delay is a result of congestion at the destination airport and can therefore be attributed to the destination airport.
- Airborne delay is a result of congestion at the destination airport and can therefore be attributed to the destination airport.

The cause of airborne delay is usually not as clear as that of taxi out or taxi in delay. Airborne delay can be caused by airspace congestion unrelated to any airport or can be due to an airport other than the origin or destination airport of a specific flight. It can also be caused by congestion at the destination airport, which results in the aircraft being held airborne for a longer period of time. In Step B1, we will assume that airborne delay is fully attributable to the destination airport.

The gate-to-gate time for each flight is thus decomposed into three segments: taxi-out, airborne and taxi-in. The baseline for each of the three O-D segments (BTO_{ij}^{15}, BTI_{ij}^{15}, $BAIR_{ij}^{15}$) is then calculated using the fifteenth percentile method (similar to that used for the calculation of the gate-to-gate baseline time in Chapter 3).

Taxi out, taxi in and airborne delays (DTO_{ij}^{15}, DTI_{ij}^{15}, $DAIR_{ij}^{15}$) are calculated for each O-D pair. Taxi out delay is taken as the difference between the average actual taxi out time and the taxi out baseline calculated as described above:

$DTO_{ij}^{15} = ATO_{ij}(y) - BTO_{ij}^{15}$ ....(4.11)

Similarly, taxi in and airborne delays are calculated as the difference between the average actual taxi in (airborne) time and the taxi in (airborne) baseline:

$DTI_{ij}^{15} = ATI_{ij}(y) - BTI_{ij}^{15}$ ....(4.12)

$DAIR_{ij}^{15} = AAIR_{ij}(y) - BAIR_{ij}^{15}$ ....(4.13)

Average origin delay at a given airport a is taken to be the weighted average of taxi out delays at that airport:

$OrgAD3_a(y) = (\sum_j DTO_{aj}^{15}(y) * TF_{aj}(y)) / \sum_j TF_{aj}(y)$ ....(4.14)

Average destination delay at a given airport a is taken to be the weighted average of taxi-in and airborne delays at that airport:

$DestAD3_a(y) = (\sum_i (DTI_{ia}^{15}(y) + DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y)$ ....(4.15)

Average overall delay at airport a is then taken to be the weighted average of origin and destination delay at airport a (4.16).

$A_a 3(y) = [OrgAD3_a(y) * (\sum_j TF_{aj}(y)) + DestAD3_a(y) * (\sum_i TF_{ia}(y))] /$

$[\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$ ....(4.16)

Additional details can be found in Appendix C.

Table 4.3 shows airport delays in 1995, 1997, and 2000, computed according to Step B1.

	METHOD B (step 1)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	7.9	11.3	9.6	7.4	13.9	10.6	10.4	13.2	11.8
BOS	5.2	9.9	7.6	6.3	12.1	9.2	10.4	15.7	13.1
BWI	4.1	8.1	6.1	3.6	7.9	5.7	6.3	9.4	7.9
CLE	4.7	8.1	6.4	6.5	9.7	8.1	9.4	10.2	9.8
CLT	5.1	8.6	6.9	5.3	10.2	7.8	8.1	9.8	8.9
CMH	3.4	6.6	5.0	4.2	8.0	6.1	5.4	8.0	6.7
CVG	5.3	7.2	6.3	6.6	9.9	8.3	9.5	10.5	10.0
DCA	5.1	7.7	6.4	5.8	8.5	7.1	8.1	8.8	8.5
DEN	5.4	11.7	8.5	5.9	11.6	8.8	6.5	13.8	10.1
DFW	8.0	14.9	11.5	8.8	15.7	12.2	8.6	13.4	11.0
DTW	7.5	11.7	9.6	8.3	11.9	10.1	10.9	12.8	11.9
EWR	9.2	10.8	10.0	12.8	14.0	13.4	15.5	14.6	15.0
FLL	3.8	10.0	6.7	3.7	10.7	7.0	6.8	11.3	8.9
IAD	4.3	7.9	6.1	5.0	10.4	7.7	9.7	13.8	11.7
IAH	5.5	12.3	8.9	6.6	12.5	9.5	8.8	12.6	10.7
LAX	5.8	13.3	9.5	6.2	13.5	9.8	7.4	14.8	11.1
LGA	7.7	9.0	8.3	9.9	10.6	10.2	15.5	12.5	14.0
MCO	4.0	10.1	7.1	3.7	10.7	7.2	5.5	10.0	7.8
MEM	4.3	8.4	6.4	6.0	9.7	7.9	5.8	9.1	7.5
MIA	8.1	13.1	10.6	7.5	13.4	10.5	8.1	12.3	10.2
MSP	6.5	10.9	8.7	7.8	13.1	10.4	9.9	14.6	12.2
ORD	6.0	10.8	8.5	6.8	12.4	9.6	9.6	15.1	12.4
PHL	4.9	8.3	6.6	7.5	11.8	9.6	14.0	14.5	14.2
PHX	4.0	9.5	6.7	5.1	10.2	7.6	6.7	12.6	9.7
PIT	4.8	8.1	6.5	4.5	8.8	6.6	7.3	9.2	8.2
SFO	6.3	13.5	9.9	7.3	12.7	10.0	7.9	16.7	12.3
TPA	3.4	9.3	6.5	4.3	9.8	7.2	5.2	9.1	7.2
	6.0	10.6	8.3	6.9	11.8	9.4	9.2	12.8	11.0

Table 4.3: Average airport delays (min/op) obtained using Step B1

The airport with the highest delays in 2000 incurred 15 minutes of delay per operation. Similarly the airport with the least delays in 2000 incurred 6.7 minutes of delay per operation. The spread between the highest overall delay incurred and lowest overall delay is therefore rather large (about 8.3 minutes).

In comparison to the results obtained in Steps A1 and A2, Step B1 delay results are significantly higher. This could be an indicator of potential correlation between taxi out, taxi in, and airborne times, which needs to be adjusted for.

4.1.2.2 Step B2

Step B2 of Method B corrects for the potential correlation between taxi out, taxi in, and airborne times by applying a factor of correction to the delay figures calculated in Step B1.

The taxi out, taxi in, and airborne delays obtained from Step B1 are multiplied by a correction factor $CORR_{ij}$, specific to each O-D pair. This correction factor is taken to be equal to the ratio of the sum of the taxi out, taxi in, and airborne baselines divided by the gate-to-gate baseline time, as shown in (4.17).

$$CORR_{ij}(y) = (BTO_{ij}^{15} + BTI_{ij}^{15} + BAIR_{ij}^{15}) / B_{ij}^{15} \quad (4.17)$$

Note that $(BTO_{ij}^{15} + BTI_{ij}^{15} + BAIR_{ij}^{15}) \leq B_{ij}^{15}$. This is due to the fact that when taxi out, taxi in, and airborne times are treated independently, we are looking at the best performance on each individual segment. For example, the smallest taxi out times might be associated with a particular runway configuration, which might generate the best taxi out times but might not generate the best airborne time.

Origin delay is computed by averaging the adjusted departure delays:

$$OrgAD4_a(y) = (\sum_j CORR_{aj}(y) * DTO_{aj}^{15}(y) * TF_{aj}(y))) / \sum_j TF_{aj}(y) \quad (4.18)$$

Similarly, destination delay is computed by averaging the adjusted arrival delays.

$$DestAD4_a(y) = (\sum_i CORR_{ia}(y) * (DTI_{ia}^{15}(y) + DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y) \quad (4.19)$$

Average overall delay is then taken to be the weighted average of origin and destination delay at airport *a*:

$$A_a 4(y) = [OrgAD4_a(y) * (\sum_j TF_{aj}(y)) + DestAD4_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))] \quad (4.20)$$

Airport delays in 1995, 1997, and 2000 were computed using Step B2 as shown in Table 4.4.

	METHODB (step 2)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	7.5	10.7	9.1	7.0	13.2	10.1	9.8	12.5	11.2
BOS	5.0	9.4	7.2	6.0	11.5	8.7	10.0	15.0	12.5
BWI	3.9	7.7	5.8	3.4	7.5	5.5	6.0	9.0	7.5
CLE	4.5	7.7	6.1	6.2	9.2	7.7	8.9	9.7	9.3
CLT	4.9	8.2	6.5	5.1	9.7	7.4	7.7	9.4	8.5
CMH	3.2	6.3	4.8	4.0	7.6	5.8	5.1	7.6	6.3
CVG	5.0	6.9	6.0	6.3	9.5	7.9	9.0	10.1	9.5
DCA	4.8	7.3	6.0	5.5	8.0	6.8	7.6	8.4	8.0
DEN	5.2	11.2	8.2	5.7	11.1	8.4	6.2	13.2	9.7
DFW	7.7	14.1	10.9	8.4	14.9	11.6	8.2	12.7	10.4
DTW	7.1	11.0	9.0	7.8	11.2	9.5	10.3	12.1	11.2
EWR	8.6	10.3	9.5	12.1	13.3	12.7	14.6	14.0	14.3
FLL	3.7	9.5	6.5	3.5	10.2	6.7	6.6	10.9	8.6
IAD	4.2	7.6	5.9	4.8	10.0	7.4	9.3	13.3	11.3
IAH	5.3	11.7	8.5	6.3	11.9	9.1	8.5	12.0	10.2
LAX	5.6	12.7	9.1	6.0	12.9	9.4	7.1	14.2	10.7
LGA	7.2	8.6	7.9	9.3	10.1	9.7	14.6	12.0	13.3
MCO	3.9	9.6	6.8	3.5	10.2	6.9	5.3	9.6	7.5
MEM	4.1	8.0	6.1	5.7	9.3	7.5	5.5	8.7	7.1
MIA	7.7	12.5	10.1	7.2	12.8	10.0	7.8	11.7	9.8
MSP	6.2	10.4	8.3	7.4	12.6	9.9	9.4	13.9	11.6
ORD	5.7	10.3	8.1	6.5	11.8	9.2	9.2	14.4	11.8
PHL	4.7	7.9	6.3	7.1	11.3	9.2	13.3	13.8	13.6
PHX	3.9	9.1	6.5	4.9	9.7	7.3	6.5	12.1	9.3
PIT	4.5	7.7	6.1	4.3	8.4	6.3	7.0	8.8	7.8
SFO	6.0	13.0	9.5	7.0	12.2	9.6	7.6	16.2	11.9
TPA	3.3	8.8	6.2	4.1	9.4	6.9	5.0	8.7	6.9
	5.7	10.1	7.9	6.5	11.3	8.9	8.8	12.2	10.5

Table 4.4: Average airport delays (min/op) obtained using Step B2

The following observations can be made when comparing the results of Step B1 and Step B2:

- Step B2 yields smaller delay figures for all airports. Reductions in average overall delays resulting from the adjustment for potential correlation range from 3.6% to 5.8%, depending on the individual airport. The average reduction is of the order of 4.8%.
- The spread between average delay incurred by the airport with the most (EWR) and the least delay (CMH) remains relatively stable from Step B1 (8.3 minutes per operation) to Step B2 (8.0 minutes per operation), in 2000.

		AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
		ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
Weighted Average	Step A2	5.5	5.6	5.5	5.5	7.7	6.6	8.4	8.4	8.4
	Step B2	5.7	10.1	7.9	6.5	11.3	8.9	8.8	12.2	10.5

Table 4.5: Comparison at the aggregate level of airport delays obtained using Step A2 and Step B2

At the aggregate level[19] (Table 4.5), the difference in average overall delay between Step A2 and Step B2, in each year, is consistent. It ranges from 2.1 to 2.4 minutes per operation. This discrepancy seems to arise from the fact that destination delay calculated using Step B2 is significantly higher than that calculated using Step A2. Note that Steps A2 and B2 are not expected to yield the same overall aggregate delay figures because they are based on two fundamentally different methods. Method A is an iterative method based on the attribution of a variable portion of the overall O-D delay to the airports of origin and destination, depending on the relative congestion at those airports. Method B is based on the decomposition of gate-to-gate time into its three components (taxi out time, airborne time, taxi in time), the calculation of individual component delays, and the attribution of entire component delays to the relevant airport (taxi out delay to the origin airport, taxi in and airborne delay to the destination airport).

At the individual airport level:

- Step B2 always yields higher destination and higher overall average delay, in all years, for all individual airports. However, it does not always yield higher origin delays.
- In Step B2, destination delay is higher than origin delay in all years, except for LGA and EWR in 2000. Results obtained using Step A2, however, do not show a systematically higher destination delay.

[19] At the aggregate level, we can consider the average delay per airport, obtained as a weighted average of the delays incurred by the 27 individual airports.

Although origin delays in Step A2 and B2 are comparable at the individual or aggregate level, it is evident that even after adjustments for potential correlation, destination delays in Step B2 are significantly higher than those obtained in Step A2. Step B2's systematic overestimation of destination delays suggests that the assumption that airborne delays are fully attributable to the destination airport may be invalid.

4.1.2.3 Step B3

Step B3 does not use the assumption that airborne delay is fully attributable to the destination airport. Instead, airborne delay is assumed to be due exclusively to airspace congestion unrelated to any specific origin-destination airport pair. In this respect, it should not be attributed to any airport.

Taxi-out and taxi-in delays are then calculated as in Step B1.

Average origin delay at airport a is also calculated as in Step B1:

$$OrgAD5_a(y) = OrgAD3_a(y) \qquad (4.21)$$

Average destination delay at airport a is taken to be the weighted average of taxi-in delays at that airport:

$$DestAD5_a(y) = (\sum_i (DTI_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y) \qquad (4.22)$$

Average overall delay is then taken to be the weighted average of origin and destination delay at the airport a:

$$A_a 5(y) = [OrgAD5_a(y) * (\sum_j TF_{aj}(y)) + DestAD5_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))] \qquad (4.23)$$

Table 4.6 shows airport delays in 1995, 1997, and 2000, computed according to Step B3.

	METHODB (Step B3)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	7.9	2.4	5.2	7.4	2.8	5.1	10.4	3.9	7.1
BOS	5.2	2.4	3.8	6.3	2.7	4.5	10.4	4.2	7.3
BWI	4.1	1.7	2.9	3.6	1.8	2.7	6.3	2.3	4.3
CLE	4.7	2.0	3.4	6.5	1.6	4.1	9.4	1.6	5.4
CLT	5.1	2.2	3.7	5.3	2.2	3.8	8.1	2.5	5.3
CMH	3.4	1.4	2.4	4.2	1.7	3.0	5.4	1.8	3.6
CVG	5.3	1.5	3.4	6.6	1.8	4.2	9.5	2.3	5.9
DCA	5.1	2.5	3.8	5.8	2.7	4.2	8.1	1.9	4.9
DEN	5.4	2.9	4.2	5.9	2.9	4.4	6.5	3.9	5.2
DFW	8.0	4.6	6.3	8.8	5.6	7.2	8.6	4.9	6.8
DTW	7.5	4.2	5.9	8.3	4.7	6.5	10.9	5.1	8.0
EWR	9.2	2.6	5.9	12.8	3.0	7.9	15.5	4.2	9.8
FLL	3.8	1.3	2.6	3.7	1.4	2.6	6.8	2.2	4.7
IAD	4.3	1.6	3.0	5.0	1.8	3.4	9.7	2.7	6.2
IAH	5.5	2.6	4.0	6.6	2.5	4.5	8.8	2.8	5.9
LAX	5.8	3.8	4.8	6.2	4.2	5.2	7.4	4.7	6.1
LGA	7.7	2.3	5.0	9.9	2.9	6.4	15.5	4.0	9.7
MCO	4.0	2.2	3.1	3.7	1.7	2.7	5.5	2.1	3.8
MEM	4.3	1.6	3.0	6.0	2.2	4.1	5.8	2.1	4.0
MIA	8.1	3.1	5.6	7.5	3.5	5.5	8.1	3.5	5.8
MSP	6.5	2.2	4.4	7.8	2.8	5.4	9.9	3.2	6.6
ORD	6.0	3.2	4.6	6.8	3.5	5.2	9.6	4.9	7.2
PHL	4.9	1.9	3.5	7.5	2.7	5.2	14.0	4.0	8.9
PHX	4.0	1.5	2.8	5.1	2.1	3.6	6.7	3.1	5.0
PIT	4.8	2.0	3.4	4.5	1.8	3.1	7.3	2.4	5.0
SFO	6.3	2.1	4.2	7.3	2.3	4.8	7.9	2.6	5.3
TPA	3.4	1.4	2.4	4.3	1.8	3.0	5.2	2.0	3.5
	6.0	2.6	4.3	6.9	2.9	4.9	9.2	3.5	6.4

Table 4.6: Average airport delays (min/op) obtained using Step B3

Step B3 yields very small destination delay results. These destination results are much smaller than those obtained through Method A (Step A2). They are on the order of half the destination delays obtained in Step A2. This observation suggests that the assumption that airborne delays are exclusively caused by airspace congestion is not valid, either. In fact, it seems that some portion of the airborne delays should indeed be attributed to the destination airport.

4.1.2.4 Step B4

In view of the results obtained in Step B1, Step B2 and Step B3, it is reasonable to assume that neither one of the hypotheses used in Steps B1, B2 and B3 regarding the allocation of airborne delays is well-founded. In fact, it would be more reasonable to assume that a portion of the airborne delay is due to the destination airport and the remaining portion is due to airspace congestion. In Step B4, we will assume that a fraction p of the airborne delay is due to the destination airport, while the remainder is due to airspace congestion. The magnitude of airport delays will depend on the fraction p chosen. We will choose p such that the differences between average overall delay results obtained using Step A2 and Step B4 are minimized.

This problem is equivalent to:

$$Min\left\{\sum_a (A_a 2(95) - A_a 6(95))^2 + \sum_a (A_a 2(97) - A_a 6(97))^2 + \sum_a (A_a 2(00) - A_a 6(00))^2\right\}$$

where

$$OrgAD6_a(y,p) = (\sum_j DTO_{aj}^{15}(y) * TF_{aj}(y)) / \sum_j TF_{aj}(y) \quad \text{.......(4.24)}$$

$$DestAD6_a(y,p) = (\sum_i (DTI_{ia}^{15}(y) + p * DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y) \quad \text{.......(4.25)}$$

$$A_a 6(y,p) = [\, OrgAD6_a(y,p) * (\sum_j TF_{aj}(y)) + DestAD6_a(y,p) * (\sum_i TF_{ia}(y))\,] \;/\; [\sum_i TF_{aj}(y) + \sum_i TF_{ia}(y))\,] \quad \text{.......(4.26)}$$

Figure 4.3 illustrates the effect of the choice of p on the aggregate average overall delay. The aggregate average overall delay increases by about 4 to 5 minutes per operation when using p=1 rather than p=0. This shows that the choice of p has a very significant impact.

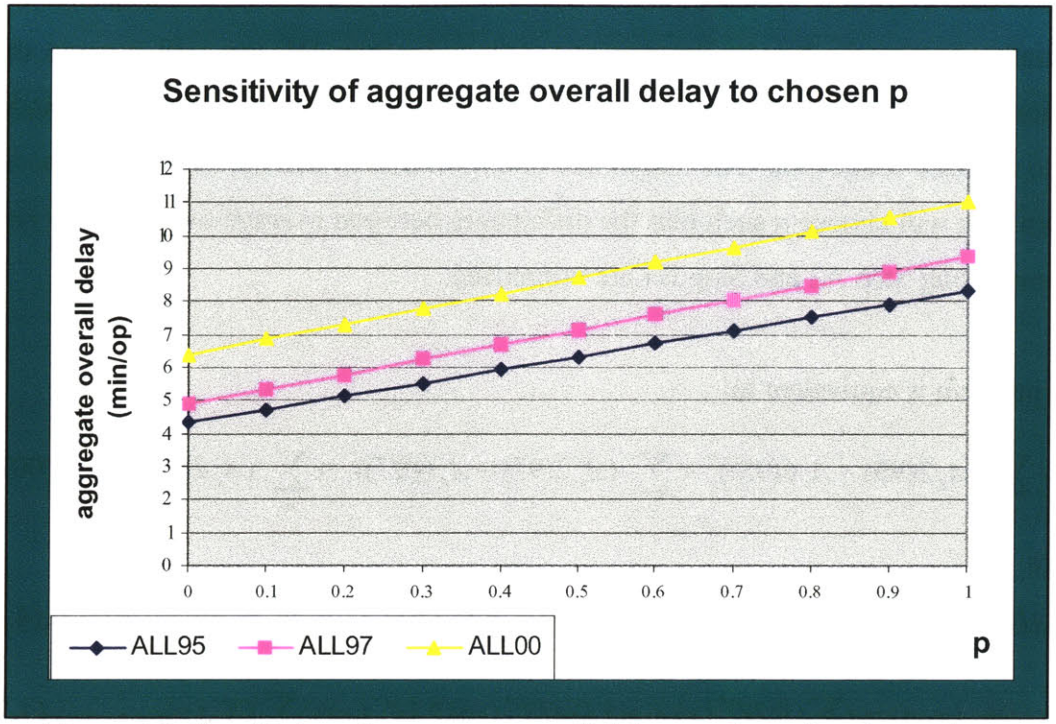

Figure 4.3: Sensitivity of aggregate overall delay results to fraction *p* chosen

The objective function is minimized for p=0.4. The corresponding delay results are shown in Table 4.7.

	METHODB (Step B4)								
	AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
ATL	7.9	5.9	6.9	7.4	7.2	7.3	10.4	7.6	9.0
BOS	5.2	5.4	5.3	6.3	6.4	6.3	10.4	8.8	9.6
BWI	4.1	4.2	4.2	3.6	4.2	3.9	6.3	5.2	5.7
CLE	4.7	4.4	4.6	6.5	4.8	5.7	9.4	5.0	7.2
CLT	5.1	4.8	4.9	5.3	5.4	5.4	8.1	5.4	6.7
CMH	3.4	3.5	3.4	4.2	4.2	4.2	5.4	4.2	4.8
CVG	5.3	3.8	4.6	6.6	5.1	5.8	9.5	5.6	7.5
DCA	5.1	4.6	4.8	5.8	5.0	5.4	8.1	4.7	6.3
DEN	5.4	6.4	5.9	5.9	6.3	6.1	6.5	7.8	7.1
DFW	8.0	8.7	8.4	8.8	9.6	9.2	8.6	8.3	8.4
DTW	7.5	7.1	7.3	8.3	7.6	7.9	10.9	8.1	9.5
EWR	9.2	5.8	7.5	12.8	7.3	10.1	15.5	8.3	11.9
FLL	3.8	4.7	4.3	3.7	5.1	4.3	6.8	5.8	6.4
IAD	4.3	4.1	4.2	5.0	5.2	5.1	9.7	7.1	8.4
IAH	5.5	6.4	6.0	6.6	6.5	6.5	8.8	6.7	7.8
LAX	5.8	7.6	6.7	6.2	7.9	7.0	7.4	8.7	8.1
LGA	7.7	5.0	6.3	9.9	6.0	7.9	15.5	7.4	11.4
MCO	4.0	5.3	4.7	3.7	5.3	4.5	5.5	5.2	5.4
MEM	4.3	4.3	4.3	6.0	5.2	5.6	5.8	4.9	5.4
MIA	8.1	7.1	7.6	7.5	7.4	7.5	8.1	7.0	7.6
MSP	6.5	5.6	6.1	7.8	6.9	7.4	9.9	7.7	8.8
ORD	6.0	6.2	6.1	6.8	7.0	6.9	9.6	8.9	9.3
PHL	4.9	4.5	4.7	7.5	6.3	6.9	14.0	8.1	11.1
PHX	4.0	4.7	4.3	5.1	5.3	5.2	6.7	6.9	6.8
PIT	4.8	4.4	4.6	4.5	4.6	4.5	7.3	5.1	6.3
SFO	6.3	6.6	6.4	7.3	6.4	6.8	7.9	8.2	8.1
TPA	3.4	4.5	4.0	4.3	5.0	4.7	5.2	4.8	5.0
	6.0	5.8	5.9	6.9	6.5	6.7	9.2	7.2	8.2

Table 4.7: Average airport delays (min/op) obtained using Step B4

Results obtained using Step B4 are consistent with those obtained in Step A2. A detailed comparative analysis between the two sets of results is described in the next section.

4.2 Analysis and Interpretation of Results

4.2.1 Comparative Analysis

First, at the aggregate level, we can consider the aggregate average overall delay per airport, obtained as a weighted average of the delays incurred at the 27 individual airports.

		AIRPORT DELAYS 1995			AIRPORT DELAYS 1997			AIRPORT DELAYS 2000		
		ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
Weighted Average	Step A2	5.5	5.6	5.5	5.5	7.7	6.6	8.4	8.4	8.4
	Step B4	6.0	5.8	5.9	6.9	6.5	6.7	9.2	7.2	8.2

Table 4.8: Comparison at the aggregate level of airport delays (min/op) obtained using Step A2 and Step B4

At the aggregate level (Table 4.8), the following observations can be made:

- Both methods show an increase in the aggregate average overall delay per airport from 1995 to 2000. This increase is of about 53% (for Step A2) and 39% (for Step B2) between 1995 and 2000.
- Aggregate average destination delay is greater than or equal to origin delay for Step A2. Aggregate average destination delay is smaller than average origin delay for Step B4.

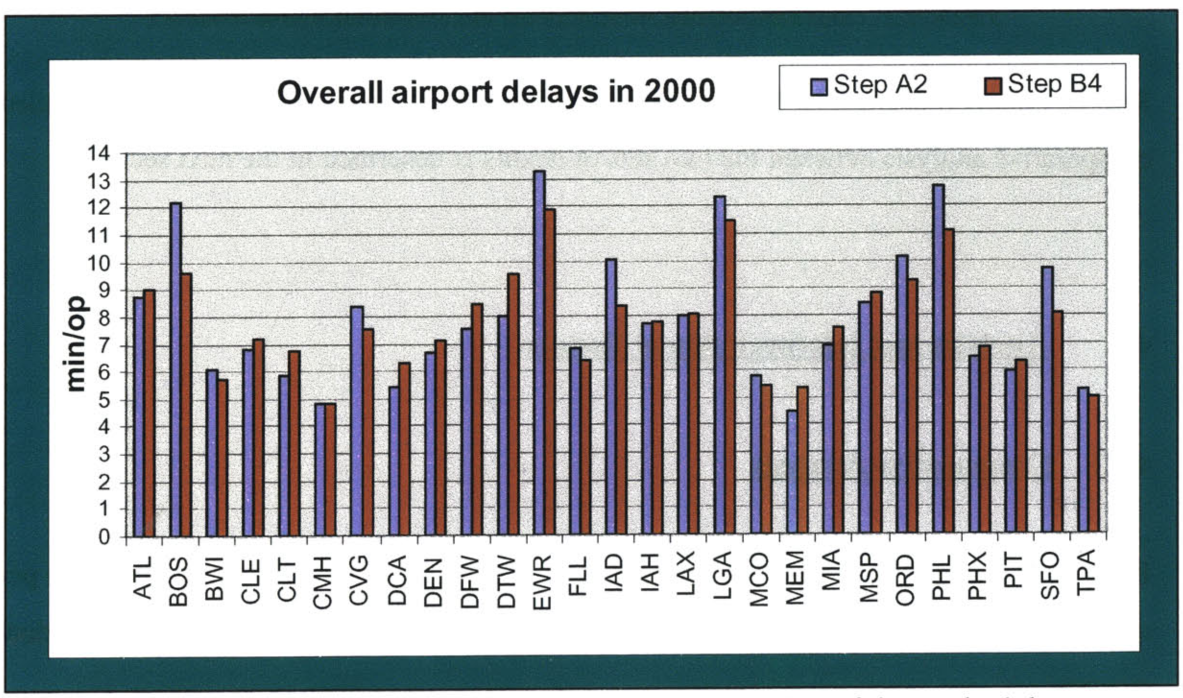

Figure 4.4: Airport delays in 2000 calculated as a function of the methodology

At the individual airport level (Figure 4.4), some of the observations made at the aggregate level no longer hold. Specifically,

- Both methods show increases in the average overall delay from 1995 to 2000, at the individual airports. The only exception is MIA[20].
- There does not seem to be any trend concerning a systematically higher origin or destination delay for either method.
- Airport delays in 2000 range from 4.5 minutes per operation to 13.3 minutes per operation depending on the airport under consideration and the method used to estimate the delay.

		Spread (min/op)								
		ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
Weighted Average	Step A2	5.2	5.7	4.3	8.0	6.2	7.1	10.2	8.5	8.8
	Step B4	5.8	5.2	4.9	9.2	5.4	6.2	10.3	4.7	7.1

Table 4.9: Comparison of spreads for Step A2 and Step B4

Table 4.9 shows that the gap between average delay incurred by the airport with the most and the least delay has increased over the 1995-2000 period, for both methods. For Step A2, the gap has increased from 4.3 to 8.8 minutes per operation, which represents a 105% increase; for Step B4, the gap has increased from 4.9 to 7.1 minutes per operation (45% increase). This shows that over the years, delays have increased significantly more at certain airports than at others. This is due to the fact that delays increase non-linearly when airports operate near their capacity. Airports operating near capacity in 1995 saw their delays increasing at a faster rate than the airports that were not operating near capacity. It is also interesting to note that the greater increase in spread occurs for the origin delay, for both methods.

[20] Average delay at MIA airport decreased by 0.2 minutes per operation from 1995 to 2000,when calculated using Step A2. This can be explained by the fact that traffic growth in MIA was very slow over the years.

4.2.2 Standard Deviations

In addition to providing an estimation of airport delays, Method B yields interesting insights as to the validity of the assumptions it is based on.

Standard deviations of taxi out delays were computed for the airport of origin (4.27) and airport of destination (4.28) for the years 1995, 1997, and 2000.

$$SD_a^{ORG}(TO,y)=\sigma(DTO_{aj}^{15}(y)) \qquad (4.27)$$

$$SD_a^{DEST}(TO,y)=\sigma(DTO_{ia}^{15}(y)) \qquad (4.28)$$

Standard deviations of taxi-in delays were computed for the airport of origin (4.29) and airport of destination (4.30) for the years 1995, 1997, and 2000.

$$SD_a^{ORG}(TI,y)=\sigma(DTI_{aj}^{15}(y)) \qquad (4.29)$$

$$SD_a^{DEST}(TI,y)=\sigma(DTI_{ia}^{15}(y)) \qquad (4.30)$$

Standard deviations of airborne delays were computed for the airport of origin (4.31) and airport of destination (4.32) for the years 1995, 1997, and 2000.

$$SD_a^{ORG}(AIR,y)=\sigma(DAIR_{aj}^{15}(y)) \qquad (4.31)$$

$$SD_a^{DEST}(AIR,y)=\sigma(DAIR_{ia}^{15}(y)) \qquad (4.32)$$

Methodology and detailed results are shown in Appendix D.

Step B1 results show that taxi out delays at a specific origin airport tend to be similar on average, regardless of the destination. This is indicated by the small standard deviations ($SD_a^{ORG}(TO,y)$) shown in Figure 4.5.

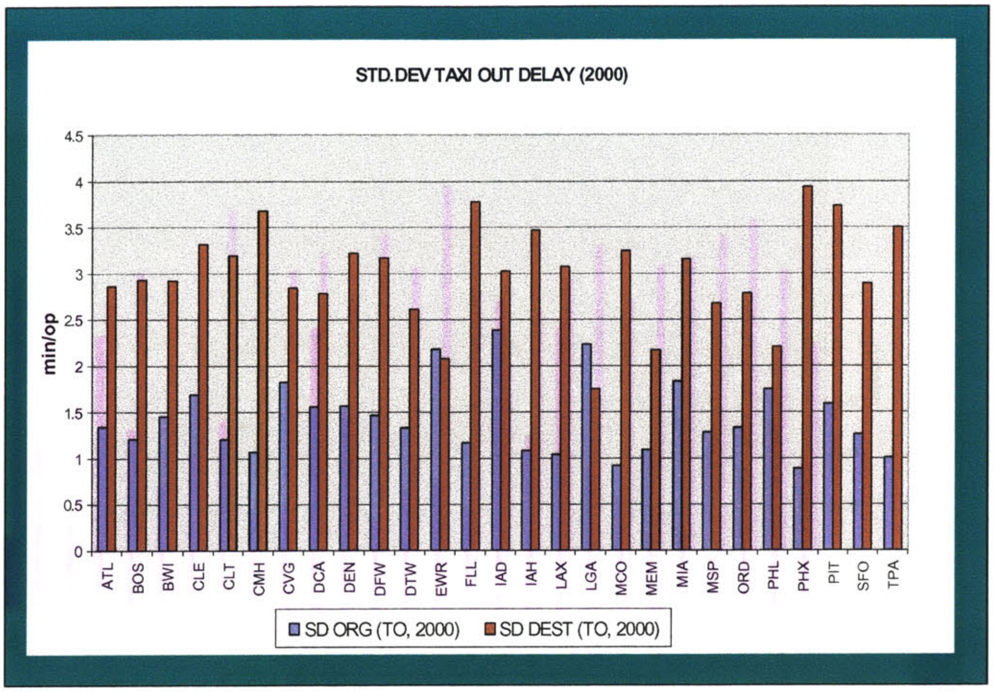

Figure 4.5: Standard deviation of taxi out delays grouped by origin airport vs. destination airport

Figure 4.5 shows that the standard deviation for taxi out delay for all O-D pairs originating at a given airport a - $SD_a^{ORG}(TO,2000)$ -is much smaller than the standard deviation of the taxi out delays for all O-D pairs arriving at that airport, $SD_a^{DEST}(TO,2000)$. The same observation can be made for the years 1995 and 1997.

The values of the standard deviations of taxi out delays $SD_a^{ORG}(TO,y)$ are very small in magnitude. They are mostly in the 0.7-1.5 minutes range, in all years. The coefficients of variation for taxi out delays grouped by origin airport in 2000 range from 0.12 to 0.25, which indicates a tight distribution of taxi out delays at each origin airport. This shows that there is a strong correlation between taxi out delay and airport of origin and justifies the decision to attribute taxi out delay to the origin airport.

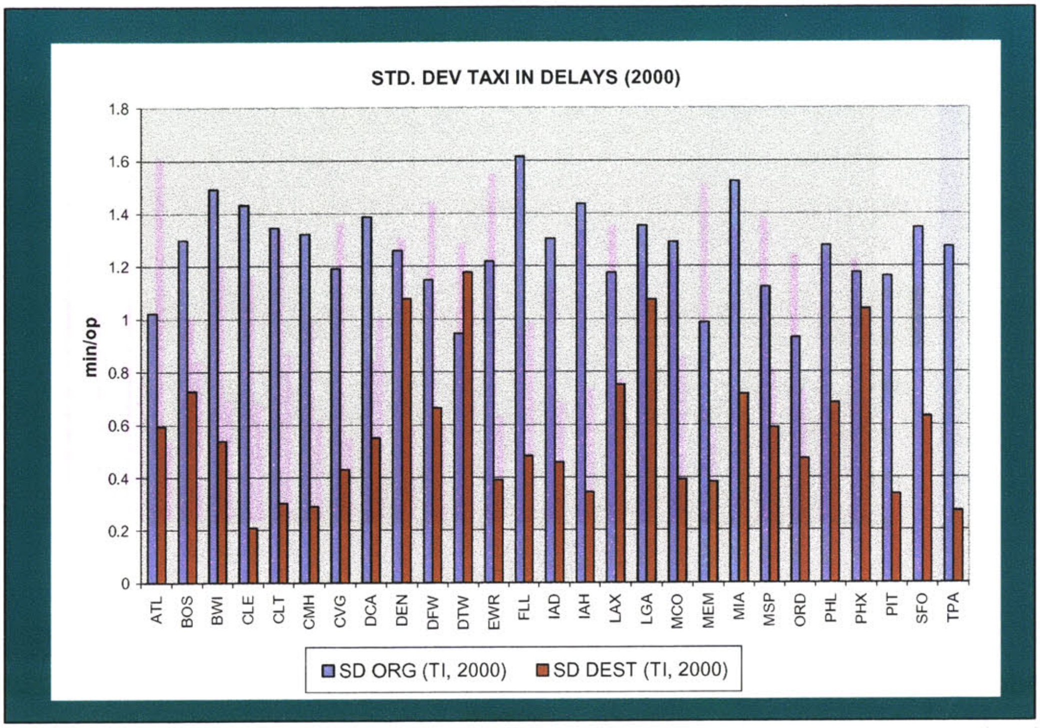

Figure 4.6: Standard deviation of taxi in delays grouped by origin airport vs. destination airport

The standard deviations of taxi in delays occurring on O-D pairs terminating at airport *a* - $SD_a^{DEST}(TI,2000)$ - are much smaller on average [21] than the standard deviations of taxi in delays occurring on O-D pairs originating at airport *a*, $SD_a^{ORG}(TI,2000)$, as shown by Figure 4.6. The values of $SD_a^{DEST}(TI,2000)$ are very small, with most of them in the 0.2-0.7 minute range, in all years. The coefficients of variation of taxi in delays grouped by destination airports in 2000 range from 0.10 to 0.31; this shows a strong correlation between taxi in delay and destination airport and justifies the decision to attribute taxi in to the destination airport.

[21] Except for DTW

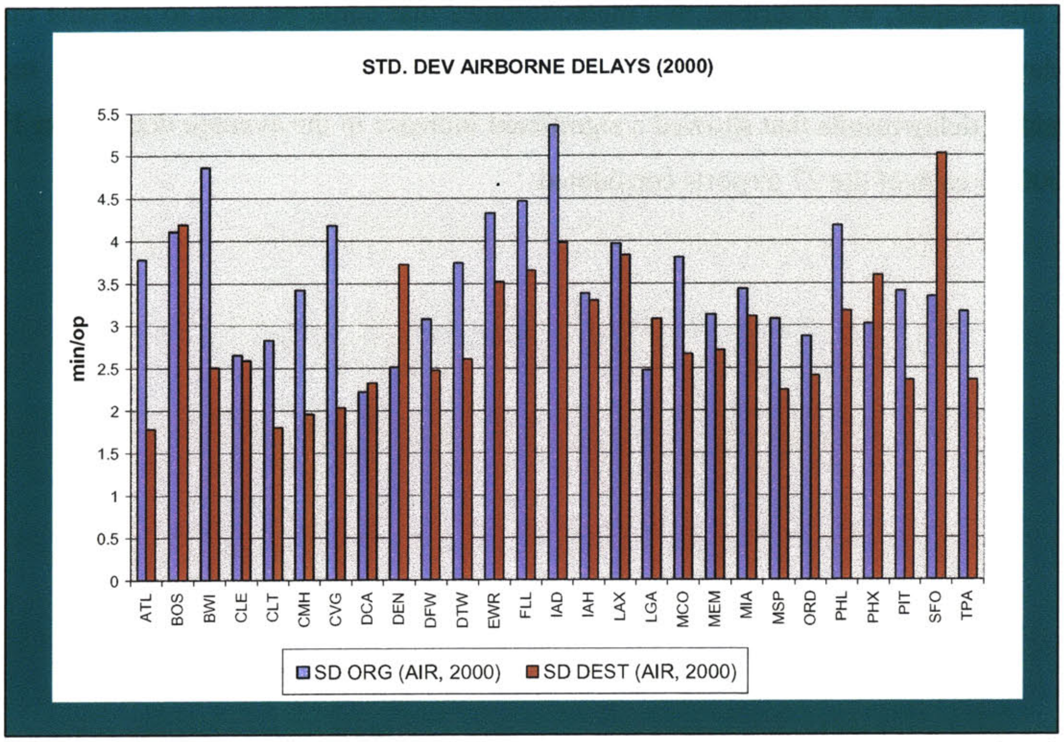

Figure 4.7: Standard deviation of airborne delays grouped by origin airport vs. destination airport

The standard deviations of airborne delays occurring on O-D pairs with the same destination airport ($SD_a^{DEST}(AIR,y)$) are slightly smaller, but comparable in magnitude, to the standard deviations of airborne delays occurring on O-D pairs originating at the same airport ($SD_a^{ORG}(AIR,y)$), as shown in Figure 4.7. The coefficients of variation of airborne delays grouped by destination airports in 2000 range from 0.19 to 0.43; these suggest that airborne delays are not that strongly correlated with the destination airport. This confirms our previous hypothesis that airspace congestion, which cannot be attributed to any specific airport, might be at least partly responsible for the airborne delays. This also explains why destination delay results in Step B1 and B2 were so high. It also suggests that Step B4 is the most appropriate approach, in Method B, to estimate airport delays.

In this chapter, we described two methodologies that could be used to attribute the O-D delays calculated in Chapter 3 to the origin and destination airports. Both methods yielded delay results that showed a significant increase in the average delay from 1995 to 2000, at each of the 27 airports considered.

CHAPTER 5: APPLICATIONS

In Chapter 4, two methodologies were used to estimate the average origin, destination, and overall delay per operation at each of the 27 airports under consideration. Chapter 5 illustrates two applications of the results obtained in Chapter 4. Section 5.1 describes the calculation of total annual delays at Logan airport. Section 5.2 compares airport rankings derived from Chapter 4 with airport rankings published in the 2001 airport capacity benchmark report.

5.1 Logan Airport Annual Delays

5.1.1 Calculations

Logan International Airport (BOS) is the world's 32nd busiest airport in terms of passenger volume. It is serviced by over 55 scheduled airlines (of which 8 are major domestic carriers, 16 are non-US flag carriers, and 13 are regional and commuter airlines)[22]. Operations also include general aviation flights.

[22] Source: Massport website

In Chapter 4, the following results were obtained for Logan airport.

	AIRPORT BOS								
	ORG95	DEST95	ALL95	ORG97	DEST97	ALL97	ORG00	DEST00	ALL00
FLIGHTS (SAMPLE)	25,882	25,933	51,815	28,004	28,105	56,109	22,112	22,107	44,219
AVERAGE DELAY USING STEP A2 (min/op)	5.7	5.5	5.6	7.8	7.4	7.6	11.6	12.8	12.2
AVERAGE DELAY USING STEP B4 (min/op)	5.2	5.4	5.3	6.3	6.4	6.3	10.4	8.8	9.6

Table 5.1: BOS airport delays [23]

Table 5.2 shows the number of total annual operations ($OP(y)$) at BOS airport.

	Airport BOS		
	1995	1997	2000
Annual Operations	476,846	502,187	508,283

Table 5.2: Total number of operations at BOS airport (Source: CODAS database)

Table 5.2 shows that the total number of operations at Logan airport increased by 6.6% over the 1995-2000 period. Using the total number of operations per year, and assuming an equal number of departures and arrivals, total annual delay at BOS airport can be computed. Annual delays were calculated based on the results of Step A2 and Step B4, as shown in equations (5.1) and (5.2).

$$YD2_{BOS}(y) = [\,OrgAD2_a(y)\ *\ OP(y)/2\ +\ DestAD2_a(y) *\ OP(y)/2\,]\ /60 \quad \text{.........(5.1)}$$

$$YD6_{BOS}(y) = [\,OrgAD6_a(y)\ * OP(y)/2\ +\ DestAD6_a(y) * OP(y)/2\,]\ /60 \quad \text{...........(5.2)}$$

The table below shows the sensitivity of the total annual delay at Logan to the methodology used:

[23] Note that the numbers reported in the "FLIGHTS" row of the table indicate the number of scheduled jet flights flown by the 10 major carriers in the months of January, April, July, and October for 1995 and 1997, and January, April, and July for 2000. These only represent a small sample (roughly 8-11% depending on the year) of the total number of flown flights during these years.

	AIRPORT BOS								
	ORG DELAY 95	DEST DELAY 95	TOTAL DELAY 95	ORG DELAY 97	DEST DELAY 97	TOTAL DELAY 97	ORG DELAY 2000	DEST DELAY 2000	TOTAL DELAY 2000
TOTAL ANNUAL DELAYS BOS USING STEP A2 (hrs/year)	22,750	21,952	44,702	32,788	30,803	63,590	49,017	54,191	103,208
TOTAL ANNUAL DELAYS BOS USING STEP B4 (hrs/year)	20,768	21,433	42,201	26,205	26,928	53,133	44,230	37,196	81,426

Table 5.3 Total Annual Delay at Logan airport

Table 5.3 indicates that our best estimate of the annual aircraft delay hours incurred at Logan in 2000 is in the range of 80,000 – 105,000. The delay estimates we obtain from our two methods fall within 6% of each other in 1995, 16% in 1997, and 21% in 2000. Both estimates also show that annual delays at BOS almost doubled from 1995 to 2000.

Analogous estimates to those shown in Table 5.3 can easily be obtained for the other 26 airports in our sample.

5.1.2 Discussion of Results

The delay estimates obtained in Chapter 4 were based on data extracted from the ASQP database. The ASQP database reports information for the 10 major US airlines, and only contains data for scheduled jet operations. However, ASQP carriers' scheduled jet operations only represent about 40% of total annual operations at Logan Airport[24]. Therefore the average delay figures obtained in Chapter 4 are representative of only one category of aircraft operations at Logan.

In order to obtain total annual delay results, we implicitly assumed that all flights, whether general aviation or commercial aircraft flights, experience delays similar to those

[24] Note that as of October 2002, the breakdown per operation type at Logan airport was as follows: 58% air carriers, 35% commuters, and 7% general aviation.

of jets flown by major carriers. The calculation above therefore represents an approximation: it might not be accurate to extrapolate and infer that non-ASQP carriers (in general smaller carriers) and general aviation would incur the same average delay. A future direction of research could be to compute separately delays for regional carriers and general aviation operations. However, data on such operations are hard to come by.

5.2 Airport rankings

Table 5.4 is an extract from the 2001 airport capacity benchmark report and shows the 31 most congested airports in the US. They are ranked according to the proportion of flights delayed according to the FAA's Operations Network (OPSNET) database.

From take-off to landing, each flight travels through different sectors under the supervision of different ATC facilities (en-route control centers, terminal radar approach control, and airport control towers). In OPSNET, statistics are collected independently by each ATC facility in charge of the sector the plane is flying through. A flight is considered delayed in a specific sector or airport if its elapsed flight time in the sector exceeds its flight plan time in the sector by more than 15 minutes. The OPSNET reporting method results in the fact that a single aircraft might incur more than one reportable delay as it progresses through the different sectors.[25] Conversely, and this is a more frequent situation, an aircraft might incur a cumulative delay of more than 15 minutes over the whole flight but might never be reported as being late if the individual delays in each sector do not exceed 15 minutes. For this reason, OPSNET statistics greatly underestimate the extent of true delays.

[25] http://www.faa.gov/apa/jan01del.htm

Airport ranked by delay	Delays per 1000 operations
LGA	155.0
EWR	81.2
ORD	63.3
SFO	56.8
BOS	47.5
PHL	44.5
JFK	38.8
ATL	30.9
IAH	28.1
DFW	23.8
PHX	22.0
LAX	21.9
IAD	19.5
STL	18.2
DTW	17.6
CVG	15.4
MSP	12.7
MIA	11.3
SEA	10.4
LAS	8.0
DCA	8.0
BWI	6.9
MCO	6.3
CLT	6.0
PIT	3.8
SAN	2.5
DEN	2.2
SLC	2.0
TPA	1.6
MEM	0.4
HNL	0.0

Table 5.4: Airport rankings by proportion of flights delayed (OPSNET)
(Source: Airport Capacity Benchmark 2001)

Our analysis has focused on 24 of the airports listed in Table 5.4, namely: LGA, EWR, ORD, SFO, BOS, PHL, ATL, IAH, DFW, PHX, LAX, IAD, DTW, CVG, MSP, MIA, DCA, BWI, MCO, CLT, PIT, DEN, TPA, MEM. In addition to these, we also considered CLE, CMH, and FLL, as they represent large passenger markets as well.

In order to perform a comparison of the airport rankings derived from Chapter 4 results with those obtained from the 2001 benchmark report, we only considered the airports that were common to both data sets: CLE, CMH, FLL in our set of 27 airports were not considered; similarly, JFK, STL, SEA, LAS, SAN, SLC, HNL which are included in the benchmark report were not included.

	Airport rankings in 2000		
	Method A (Step A2)	**Method B (Step B4)**	**OPSNET proportion of delayed flights (based on 2001 benchmark report)**
ATL	8	7	7
BOS	4	4	5
BWI	18	23	18
CLT	20	19	20
CVG	10	15	14
DCA	22	21	17
DEN	16	17	22
DFW	14	9	9
DTW	11	5	13
EWR	1	1	2
IAD	6	10	12
IAH	13	13	8
LAX	12	11	11
LGA	3	2	1
MCO	21	24	19
MEM	24	25	24
MIA	15	14	16
MSP	9	8	15
ORD	5	6	3
PHL	2	3	6
PHX	17	18	10
PIT	19	22	21
SFO	7	12	4
TPA	23	26	23

Table 5.5: Comparison of airport rankings using Step A2, B4, and OPSNET delays

Using Step A2 and B4 results, airports were ranked in decreasing order, from the airport that incurred the highest average overall delay in 2000 to the one that incurred the lowest, as shown in Table 5.5.

We then used the Spearman Rank Correlation test to compare the rankings and test whether they were comparable, using the equation below:

$$r_s = 1 - 6*(d_1^2 + d_2^2 + ...+ d_n^2)/(n*(n^2 - 1)) \quad (5.3)$$

Spearman Rank Correlation Coefficient		
Step A2 & B4	Step A2 & OPSNET ranking	Step B4 & OPSNET ranking
0.92	0.87	0.83

Table 5.6: Correlation between airport rankings

The coefficients obtained (see Table 5.6) are close to 1, indicating a very high correlation between the different rankings. Despite the severe underestimation of total delays by OPSNET, airport *rankings* derived from OPSNET and those obtained using Step A2 and Step B4 are very consistent.

We also compared airport rankings obtained using Step A2 and Step B4 to the following airport rankings:

- OPSNET number of delays: airports are ranked according to total number of flights delayed in 2000. The airport with the greatest number of delayed flights gets the lowest rank.
- ASPM average arrival delay: the Aviation System Performance Metrics (ASPM)[26] system reports arrival delays measured as the actual gate arrival time minus the scheduled gate arrival time. This measure is equivalent to what we referred to as "delays relative to schedule". Airports are ranked according to the

[26] ASPM is the successor of the Consolidated Operations and Delay Analysis System (CODAS) and is operated by the FAA Office of Aviation Policy and Plans. ASPM uses data gathered by Aeronautical Radio Inc. (ARINC) to compile several metrics that describe the traffic, prevailing conditions, and performance (actual vs. scheduled individual flight times, airport efficiency) for the previous day.

average arrival delay in 2000: the airport with the highest average arrival delay gets the lowest rank.

- ASQP on-time arrivals: airports are ranked according to the percentage of on-time flight arrivals in 2000. The airport with the lowest percentage of on-time flights gets the lowest rank.
- Enplaned passengers: airports are ranked according to the number of enplaned passengers in 2000. The airport with the highest number of enplaned passengers in 2000 gets the lowest rank.
- OPSNET Total Operations Rank: the airport with the highest number of annual operations in 2000 gets the lowest rank.
- Optimum Capacity/Total Operations: Airports are ranked according to the ratio of optimum airport capacity divided by total operations in 2000. The airport with the lowest ratio gets the lowest rank.
- Reduced Capacity/Total Operations: Airports are ranked according to the ratio of reduced airport capacity (in bad weather conditions) divided by total operations in 2000. The airport with the lowest ratio gets the lowest rank.

Optimum Capacities and Reduced Capacities are estimates of maximum number of flights per hour an airport can handle under good weather conditions[27] and adverse weather conditions[28], respectively. These figures were obtained from Table 1 of the 2001 FAA benchmark report. Note that we used the lower end of the reported ranges. Total Operations represent the OPSNET Total Operations reported in the benchmark report.

[27]Good weather conditions consist of periods of unlimited ceiling and visibility

[28] Adverse weather conditions may include poor visibility, unfavorable winds, or heavy precipitation.

	RANKINGS OBTAINED USING...									
Airport	Method A (Step B2)	Method B (Step B4)	OPSNET proportion of delayed flights	OPSNET Number of Delays	ASPM Average Arrival Delay	ASQP on-time arrivals	Enplaned Pax.	OPSNET Total Ops.	Optimum Cap./Total Ops.	Reduced Cap./Total Ops
ATL	8	7	7	4	9	7	1	1	4	8
BOS	4	4	5	6	3	8	14	10	11	6
BWI	18	23	18	20	14	20	19	23	20	15
CLT	20	19	20	17	24	24	17	15	17	18
CVG	10	15	14	14	15	23	20	14	15	19
DCA	22	21	17	18	18	16	23	22	9	9
DEN	16	17	22	22	7	5	6	7	23	24
DFW	14	9	9	8	17	6	3	3	18	12
DTW	11	5	13	12	20	19	7	6	16	17
EWR	1	1	2	3	5	11	10	16	10	5
IAD	6	10	12	13	11	18	22	13	13	16
IAH	13	13	8	11	19	21	11	11	12	14
LAX	12	11	11	9	8	1	4	4	2	3
LGA	3	2	1	1	1	9	15	19	3	2
MCO	21	24	19	19	13	14	13	21	22	21
MEM	24	25	24	24	22	17	24	20	21	22
MIA	15	14	16	16	10	15	12	9	14	11
MSP	9	8	15	15	23	12	5	8	7	13
ORD	5	6	3	2	4	4	2	2	5	7
PHL	2	3	6	7	6	10	16	12	6	10
PHX	17	18	10	10	12	3	9	5	1	1
PIT	19	22	21	21	21	22	18	17	19	20
SFO	7	12	4	5	2	2	8	18	8	4
TPA	23	26	23	23	16	13	21	24	24	23

Table 5.7: Airport delay rankings using different criteria (Source for columns 3-10: 2001 Airport Capacity Benchmark Report)

Table 5.7 shows the airport rankings obtained depending on different criteria. Airport rankings were compared using the Spearman Rank Correlation test. Results are shown in Figure 5.1 below. Note that the matrix is symmetric but only the above-diagonal part is shown in Figure 5.1.

Spearman's Rank Correlation	RANKS OBTAINED USING...									
	Method A (Step B2)	Method B (Step B4)	OPSNET proportion of delayed flights	OPSNET Number of Delays	ASPM Average Arrival Delay	ASQP on-time arrivals	Enplaned Pax.	OPSNET Total Ops.	Optimum Cap./Total Ops.	Reduced Cap./Total Ops
RANKS OBTAINED USING... Method A (Step B2)		0.92	0.87	0.85	0.67	0.37	0.39	0.39	0.62	0.59
Method B (Step B4)			0.83	0.84	0.48	0.31	0.46	0.48	0.58	0.56
OPSNET proportion of delayed flights				0.98	0.69	0.50	0.47	0.38	0.75	0.82
OPSNET Number of Delays					0.67	0.54	0.54	0.47	0.77	0.82
ASPM Average Arrival Delay						0.68	0.30	0.16	0.47	0.61
ASQP on-time arrivals							0.65	0.47	0.52	0.61
Enplaned Pax.								0.81	0.41	0.41
OPSNET Total Ops.									0.45	0.33
Optimum Cap./Total Ops.										0.89
Reduced Cap./Total Ops										

Figure 5.1: Correlation of airport rankings using different criteria (Spearman Rank Correlation Test)

It can be observed from Figure 5.1 that:

- The airport rankings obtained using Step A2, Step B4, OPSNET proportion of delayed flights, and OPSNET total number of delayed flights are all strongly correlated.
- There seems to be a very weak relationship between ASQP on-time rank and Step A2 and B4 ranks. This suggests that on-time statistics are a poor indicator of the true severity of airport delays at different airports.
- The relationship between Step A2 and B4 rankings and ASPM average arrival delay ranking is rather weak. This shows that delay relative to schedule is not a good estimator of true delays.
- It is interesting to note that the OPSNET total number of delayed flights ranking is well correlated with the ratio of reduced capacity over total operations ranking. This shows a relationship between the number of flights delayed and the reduction in capacity due to poor weather at an airport.

The above observations suggest that ASQP on-time statistics and average delay relative to schedule are poor indicators of the true extent of air traffic delays. The measures yielding airport rankings closest to those derived from Chapter 4 results are OPSNET proportion of delayed flights and OPSNET total number of delayed flights. This observation is surprising since we pointed out at the beginning of the Chapter that OPSNET delay statistics severely underestimate delays. This suggests that despite the numerous possible criticisms, OPSNET statistics can be useful in determining the relative state of congestion at the different airports.

Chapter 5 provided two applications of the results derived in Chapter 4. In Chapter 6, we will discuss the complexities associated with making optimal scheduling decisions, through the development of a simple probabilistic model.

CHAPTER 6: OPTIMAL SCHEDULING: A SIMPLE CASE STUDY

We showed in the previous chapters that both true delays and delays relative to schedule have been increasing over the past years. True delays are measured against a fixed benchmark, which cannot be adjusted. In contrast, delays relative to schedule can be reduced by adjusting schedules: airlines can schedule their flights and turn times to match anticipated actual transit times as closely as possible, therefore minimizing the probability of incurring delays relative to schedule.

In this Chapter, we change our perspective and try to show why it may be very difficult for airlines to optimize their schedules so as to achieve high schedule compliance records. This analysis also shows some of the interdependences in the schedule that make airline scheduling so complex.

Section 6.1 introduces the example that will be used in the remainder of the Chapter. Section 6.2 explores alternative objective functions aimed at minimizing the cost of delays. Section 6.3 consists of a discussion of the results obtained for each objective function.

6.1 Context

The following case will be analyzed in the remainder of the Chapter.

Assume an aircraft is scheduled to fly from A to B, then fly back from B to A, as shown in Figure 6.1.

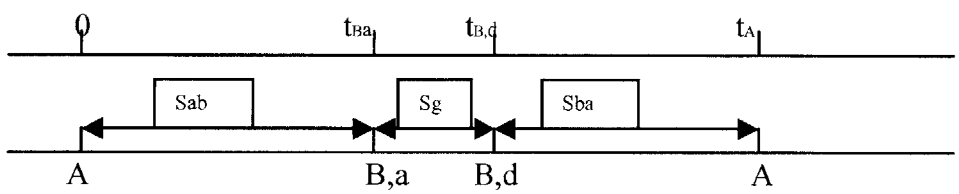

Figure 6.1: Spatial and temporal description of flight path

The probability density functions of actual transit times on O-D pairs (A,B) and (B,A) can be obtained from ASQP data such as those used in Chapters 3 and 4. In this particular case, we will assume for simplicity that the probability distributions are known, and are uniform, as shown in Figure 6.2.

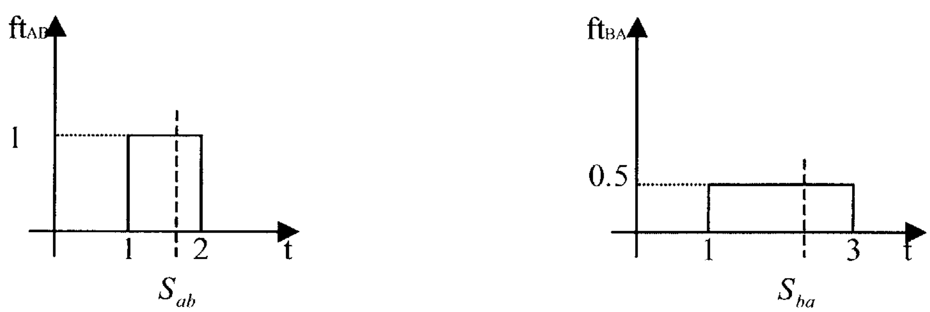

Figure 6.2: Probability distribution functions of actual transit times between A and B[29]

The problem consists in determining the optimal schedule of the aircraft, based on the given probability distributions of transit times on (A,B).

[29] Figure 6.2 assumes that transit times from B to A are larger on average than transit times from A to B. This is a common phenomenon, especially on medium-haul to long-haul flights. It is usually due to the directionality of dominant winds.

The decision variables are:

- S_{ab}: scheduled transit time from A to B
- S_g: scheduled turnaround time at B
- S_{ba}: scheduled transit time from B to A

The constraints are:

- $S_g \geq 0.5$: the minimum turn time is assumed to be 0.5 hours.
- $1 \leq S_{ab} \leq 2$
- $1 \leq S_{ba} \leq 3$

The objective function can take various forms depending on the goals to be achieved and will be examined in more detail in Section 6.2.

6.1.1 Delays

6.1.1.1 Arrival Delay at B

Given the assumption of a uniform actual transit time between A and B, Figure 6.3 illustrates the probability distribution of arrival delay at B, as a function of S_{ab}.

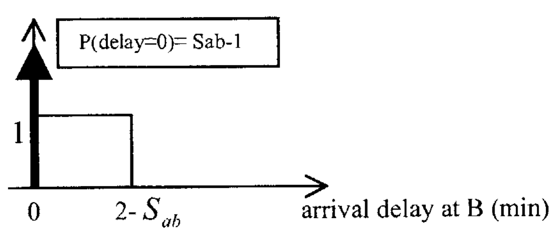

Figure 6.3: Probability distribution of arrival delay at B

6.1.1.2 Departure Delay at B

We can distinguish between 2 cases:

- $S_{ab}+S_g$=2.5: in this case, there will be no departure delay.
- $S_{ab}+S_g$<2.5: in this case, there may be a departure delay.

Since the maximum actual transit time on AB is 2 hours, and the turn time is required to be at least 0.5 hours, the plane is guaranteed to depart on time at B if $S_{ab}+S_g$=2.5[30].

The probability distribution of the departure delay at B is shown below.

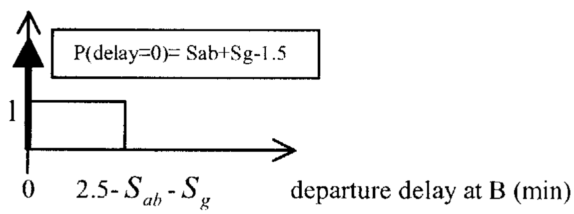

Figure 6.4: Probability distribution of departure delay at B

6.1.1.3 Elapsed time between scheduled departure at B ($t_{b,d}$) and arrival at A

The distribution of the elapsed time between the scheduled departure time at B and the actual arrival time at A is illustrated in Figure 6.5. The distribution is obtained by using a convolution of the probability density functions of departure delay at B and actual transit time from B to A.

[30] Note that it would never make sense to have $S_{ab}+S_g$>2.5.

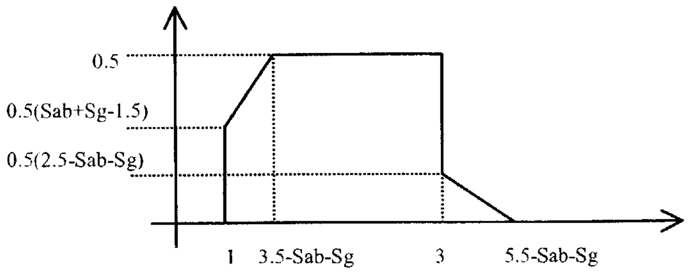

Figure 6.5: Probability distribution of elapsed time between scheduled departure at B ($t_{b,d}$) and arrival at A (Cases 1&2)

6.1.1.4 Arrival Delay at A

In order to compute the probability distribution of arrival delay at A, we distinguish between 3 cases:

- Case 0: $S_{ab}+S_g=2.5$

In this case, the airplane always departs on time from B. Therefore, the probability of an arrival delay at A only depends on the scheduled time from B to A, S_{ba}.

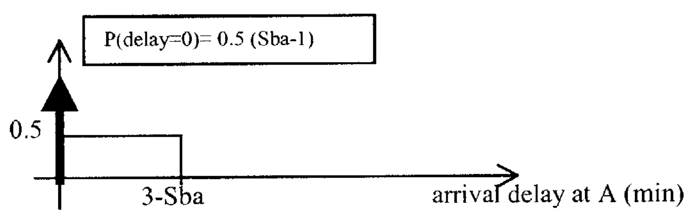

Figure 6.6: Probability distribution of arrival delay at A (Case 0)

- Case 1: $S_{ab}+S_g<2.5$ and $1 \le S_{ba} \le 3.5-S_{ab}-S_g$

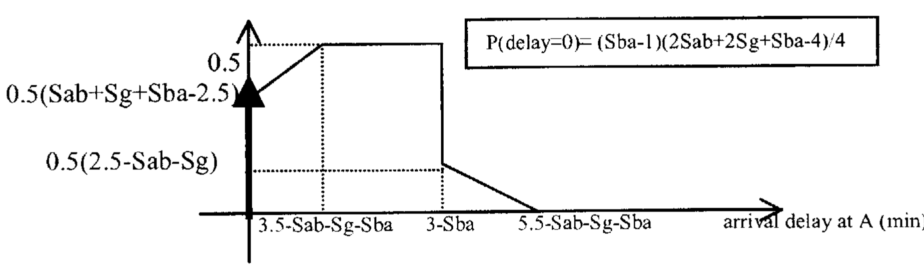

Figure 6.7: Probability distribution of arrival delay at A (Case 1)

- Case 2: $S_{ab}+S_g<2.5$ and $3.5-S_{ab}-S_g \leq S_{ba} \leq 3$

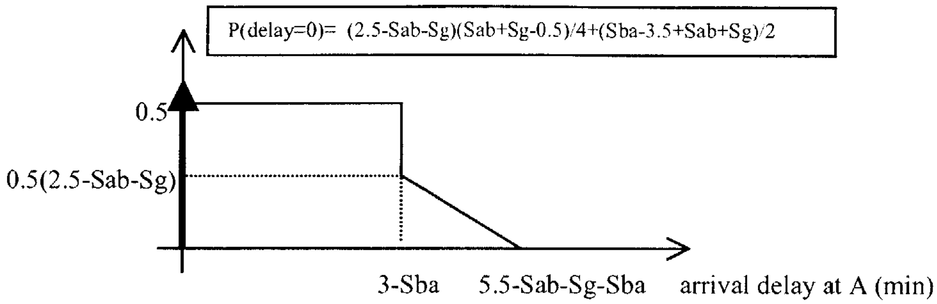

Figure 6.8: Probability distribution of arrival delay at A (Case 2)

6.2 Objective functions

This section discusses important types of objective functions that can be used to minimize delays relative to schedule on the A to B to A route. Four objective functions are examined in detail.

We will define the parameters used in the objective functions as follows:

- K: the penalty cost in \$ incurred if the total scheduled time from A to B to A exceeds a maximum duration, D. This penalty cost would typically exist in order to ensure adequate aircraft utilization, or that a crew will not be over-scheduled. In our particular example, D will be set equal to 4 hours.
- L: the penalty in \$/flight associated with being "late" at A or at B, for some specified amount of "lateness" (0 minutes, 15 minutes, etc.).
- F: the cost in \$/hour of delay at A or at B.
- C_a: the cost in \$/scheduled block hour.
- C_g: the cost in \$/hour of scheduled turn around time.

We shall also introduce a new binary decision variable, δ, which will be used to indicate whether a maximum duration constraint is satisfied or not. The constraint, $S_{ab}+S_g+S_{ba} \leq 4+M.\delta$[31], is useful for enforcing a penalty cost, if the optimal

[31] M here is an infinitely large number.

scheduled times exceed the maximum duration D (4 hours in this example). When the total scheduled time is under 4 hours, $\delta = 0$. When the total scheduled time exceeds 4 hours, $\delta = 1$ and a penalty cost of $K is incurred, as mentioned above.

In this particular example, we chose to use $D = E[S_{ab}] + S_{g,MIN} + E[S_{ba}]$, with $E[S_{ab}]$=1.5 hours, $S_{g,MIN}$=0.5 hours, and $E[S_{ba}]$=2 hours. A maximum duration of 4 hours assumes a relatively efficient utilization of the aircraft. In retrospect, it is conceivable that the maximum duration value chosen (D=4 hours) was not the best choice. Future work could consist of examining how solutions would change with a different cutoff limit (such as 4.5 hours or 5 hours).

6.2.1 Objective Function 1

Objective Function 1 (OF 1) assumes that a late flight at B or at A is penalized by the same amount L, regardless of the amount of delay. In this case, the plane is considered late if its actual arrival time exceeds its scheduled arrival time. This implies the following objective function:

Min $K.\delta$ + L. P(late at B)+ L. P(late at A) ....(OF 1)

where δ=1 if $S_{ab} + S_g + S_{ba} > 4$ and δ=0 otherwise.

The above objective function assumes that delays are undesirable at both locations A and B. Such an objective function encourages robustness and leads to slack building in the schedule on the first leg of the trip or in the ground time, to ensure minimal propagation of delays from B to A.

Table 6.1 shows the case-specific details of the expressions P(late at B) and P(late at A).

	Case Conditions	P(late at B)	P(late at A)
Case 0	$S_{ab} + S_g \geq 2.5$	2- S_{ab}	$(3 - S_{ba})/2$
Case 1	$S_{ab} + S_g \leq 2.5$ $2.5 \leq S_{ab} + S_g + S_{ba} \leq 3.5$	2- S_{ab}	$1-(S_{ba}-1).(2S_{ab}+2S_g+S_{ba}-4)/4$
Case 2	$S_{ab} + S_g \leq 2.5$ $3.5 \leq S_{ab} + S_g + S_{ba}$	2- S_{ab}	$(2.5 - S_{ab} - S_g)^2/4 + (3 - S_{ba})/2$

Table 6.1: Objective Function Terms for Objective Function 1

6.2.2 Objective Function 2

Objective Function 2 (OF 2) again assumes that a late flight, regardless of the amount of delay incurred, is penalized by the same amount L. In objective function 2, however, a plane is considered delayed if its actual arrival time exceeds its scheduled arrival time by more than 15 minutes (0.25 hours). This rule is similar to that used by the US DOT. This is captured by the following objective function:

Min K. δ +L. P(late_{15} at B)+ L. P(late_{15} at A)...(OF 2)

with δ defined in the same way as in (OF 1).

Table 6.2 shows the case-specific details of the expressions P(late_{15} at B) and P(late_{15} at A).

	Case Conditions	P(late$_{15}$ at B)	P(late$_{15}$ at A)
Case 0	$S_{ab}+S_g=2.5$	$MAX(0,1.75-S_{ab})$	$MAX(0,(2.75-S_{ba})/2)$
Case 1a	$S_{ab}+S_g\le 2.5$ $S_{ab}+S_g+S_{ba}\le 3.25$	$MAX(0,1.75-S_{ab})$	$1-(S_{ba}-1).(2S_{ab}+2S_g+S_{ba}-4)/4$ $-(S_{ab}+S_g+S_{ba}-2.375)/8$
Case 1b	$S_{ab}+S_g\le 2.5$ $3.25\le S_{ab}+S_g+S_{ba}\le 3.5$	$MAX(0,1.75-S_{ab})$	$1-(2.5-S_{ab}-S_g).(S_{ab}+S_g-0.5)/4$ $-(S_{ab}+S_g+S_{ba}-3.25)/2$
Case 2a	$S_{ab}+S_g\le 2.5$ $3.5\le S_{ab}+S_g+S_{ba}\le 5.25$ $3-S_{ba}\ge 0.25$	$MAX(0,1.75-S_{ab})$	$(2.5-S_{ab}-S_g)^2/4+(2.75-S_{ba})/2$
Case 2b	$S_{ab}+S_g\le 2.5$ $3.5\le S_{ab}+S_g+S_{ba}\le 5.25$ $3-S_{ba}<0.25$	$MAX(0,1.75-S_{ab})$	$(5.25-S_{ab}-S_g-S_{ba})^2/4$
Case 2c	$S_{ab}+S_g\le 2.5$ $S_{ab}+S_g+S_{ba}\ge 5.25$ $3-S_{ba}<0.25$	$MAX(0,1.75-S_{ab})$	0

Table 6.2: Objective Function Terms for Objective Function 2

6.2.3 Objective Function 3

In Objective Function 3 (OF 3), the cost of delay increases linearly with delay time. F represents a penalty cost in dollars per hour of expected delay. Note that a plane is considered late if its actual arrival time exceeds its scheduled arrival time. This implies:

Min $K.\delta + F$. E[minutes of delay at B]+F. E[minutes of delay at A]............(OF 3)

with δ defined in the same way as in (OF 1).

Table 6.3 shows the case-specific details of the expressions E[min delay at B] and E[min delay at A].

	Case Conditions	E[delay at B]	E[delay at A]
Case 0	$S_{ab}+S_g=2.5$	$(2-S_{ab})^2/2$	$(3-S_{ba})^2/4$
Case 1	$S_{ab}+S_g \le 2.5$ $S_{ab}+S_g+S_{ba} \le 3.5$	$(2-S_{ab})^2/2$	$(3.5-S_{ab}-S_g-S_{ba})^2.(S_{ab}+S_g+S_{ba}-0.5)/12$ $+(6.5-S_{ab}-S_g-2S_{ba}).(S_{ab}+S_g-0.5)/4+$ $(11.5-3S_{ba}-S_{ab}-S_g).(2.5-S_{ab}-S_g)^2/12$
Case 2	$S_{ab}+S_g \le 2.5$ $S_{ab}+S_g+S_{ba} \ge 3.5$	$(2-S_{ab})^2/2$	$(3-S_{ba})^2/4+(11.5-3S_{ba}-S_{ab}-S_g)*$ $(2.5-S_{ab}-S_g)^2/12$

Table 6.3: Objective Function Terms for Objective Function 3

6.2.4 Objective Function 4

In addition to incurring a penalty per delayed flight, Objective Function 4 (OF 4) includes a cost per hour for scheduled time in the air (C_a) and on the ground (C_g). Note that a plane is considered late if its actual arrival time exceeds its scheduled arrival time. This translates into the following objective function:

Min $K.\delta + L.$ **P(late at B)+** $L.$ **P(late at A)+** $C_a.\,(S_{ab}+S_{ba})+C_g.\,S_g$ **..............(OF 4)**

with δ defined in the same way as in (OF 1).

See table 6.1 for case-specific details of the expressions P(late at B) and P(late at A).

All four objective functions described in this section imply that if a flight is late at both A and B, it will get penalized twice for the delay. This type of objective function gives incentives to avoid delays on the first leg of the trip (A to B). Note that it would be possible to use different penalty costs for being late at different locations to account for the fact that some locations are more important than others, for example $\$L_a$ for being late at A and $\$L_b$ for being late at B. However, in our example, we will assume equal costs ($L) for both locations A and B for simplicity.

6.3 Results:

In order to come up with the optimal results corresponding to each objective function, we looked analytically at the different cases and further subdivided them into cases where δ=0 and cases where δ=1. Each sub-case's optimal solution was then derived using a combination of Excel Solver and trial and error.

6.3.1 Objective Function 1

The mathematical programming problem corresponding to objective function 1 is as follows:

Min $K.\delta + L.$ P(late at B)+ $L.$ P(late at A)

s.t

$1 \le S_{ab} \le 2$ ....(i)

$1 \le S_{ba} \le 3$ ....(ii)

$S_g \ge 0.5$ ....(iii)

$S_{ab} + S_g + S_{ba} \le 4 + M.\delta$ ....(iv)

$\delta \in \{0,1\}$ ....(v)

In addition to constraints (i)-(v), case-specific constraints (in the "conditions" column of Table 6.1) are also added, depending on the case considered.

Solutions on a case-by-case basis are shown in Table 6.4.

	Optimal Solutions (OF 1)	
	δ=0	δ=1
Case 0	$S_{ab}=2, S_{ba}=1.5, S_g=0.5$ $Obj=0.75L$	$S_{ab}=2, S_{ba}=3, S_g=0.5$ $Obj=K$
Case 1	$S_{ab}=2, S_{ba}=1, S_g=0.5$ $Obj=L$	Impossible[32]
Case 2	$S_{ab}=2, S_{ba}=1.5, S_g=0.5$ $Obj=0.75L$	$S_{ab}=2, S_{ba}=3, S_g=0.5$ $Obj=K$

Table 6.4: Solutions for Objective Function 1

As expected, for large values of L relative to K (i.e., when the airline strongly favors on-time performance achievement over high aircraft utilization rates), the airline will ensure that schedules are such that delays are minimized. Because the penalty cost for exceeding the maximum duration, D, is a lump sum and does not depend on the magnitude of the duration by which the maximum is exceeded, scheduled times are set to the maximum possible duration of actual transit times, to ensure a null probability of delay. Note that this would not necessarily be the case if the penalty depended on the magnitude of the time by which maximum scheduled duration was exceeded.

As can be seen in Table 6.4, the relative values of K and L will determine which scheduling strategy the airline should choose.

- If $K/L \geq 0.75$, then the optimal solution is S_{ab}=2, S_{ba}=1.5, S_g=0.5. The objective function has the optimal value of 0.75L.
- If $K/L \leq 0.75$, then the optimal solution is S_{ab}=2, S_{ba}=3, S_g=0.5. The objective function has the optimal value of K.

As expected, both optimal strategies consist of scheduling the first leg of the trip (A,B) for the largest possible observed duration. This makes sense, as arriving late at B results in a double-penalty in some cases. When there is not enough slack, arriving late at B implies departing late at B, which results in a higher probability of being delayed arriving at A.

[32] Note that case 1 by definition would never have delta=1, because case 1 is such that
$2.5 \leq S_{ab} + S_g + S_{ba} \leq 3.5$

6.3.2 Objective Function 2

Min $K.\delta + L.$ P(late$_{15}$ at B)+ $L.$ P(late$_{15}$ at A)

s.t

$1 \le S_{ab} \le 2$ ……………………………………………………………………..(i)

$1 \le S_{ba} \le 3$ ……………………………………………………………………..(ii)

$S_g \ge 0.5$ ……………………………………………………………………..(iii)

$S_{ab} + S_g + S_{ba} \le 4 + M.\delta$ ……………………………………………………..(iv)

$\delta \in \{0,1\}$ ……………………………………………………………………..(v)

In addition to constraints (i)-(v), case-specific constraints (in the "conditions" column of Table 6.2) are also added, depending on the case considered.

Solutions are shown in Table 6.5 below.

	Optimal Solutions (OF 2)	
	δ=0	**δ=1**
Case 0	$S_{ab} \ge 1.75, S_{ba} = 1.5, S_g = 2.5 - S_{ab}$ ** $Obj = 0.625L$	$S_{ab} \ge 1.75, S_{ba} \ge 2.75, S_g = 2.5 - S_{ab}$ ** $Obj = K$
Case 1a	$S_{ab} = 1.75, S_{ba} = 1, S_g = 0.5$ $Obj = 0.8906L$	Impossible
Case 1b	$S_{ab} = 1.75, S_{ba} = 1.25, S_g = 0.5$ $Obj = 0.7656L$	Impossible
Case 2a	$S_{ab} = 1.75, S_{ba} = 1.75, S_g = 0.5$ $Obj = 0.5156L$	$S_{ab} \ge 1.75, S_{ba} = 2.75, S_g = 2.5 - S_{ab}$ ** $Obj = K$
Case 2b	Impossible	$S_{ab} \ge 1.75, S_{ba} \ge 2.75, S_g = 5.25 - S_{ab} - S_{ba}$ ** $Obj = K$
Case 2c	Impossible	$S_{ab} \ge 1.75, S_{ba} \ge 2.75, S_g = 2.5 - S_{ab}$ ** $Obj = K$

** multiple solutions

Table 6.5: Solutions for Objective Function 2

The optimal schedule will depend on the relative values of K and L.

- If $K/L \geq 0.5156$, the optimal solution is S_{ab}=1.75, S_{ba}=1.75, S_g=0.5. The objective function's optimal value is then 0.5156L.
- If $K/L \leq 0.5156$, there are multiple optimal solutions. Solutions such that

$S_{ab} \geq 1.75$, S_g=2.5-S_{ab}, and $S_{ba} \geq 2.75$ will all yield an objective function equal to K.

As expected in this case, the optimal solution is such that S_{ab} is always greater or equal to 1.75, ensuring no delay at B. However, it is interesting to note that the optimal solution when $K/L \geq 0.5156$ is such that some departure delay at B may be incurred, potentially causing a propagation of delays.

6.3.3 Objective Function 3

Min $K.\delta + F.$ E[minutes of delay at B]+$F.$ E[minutes of delay at A]

s.t

$1 \leq S_{ab} \leq 2$ ....(i)

$1 \leq S_{ba} \leq 3$ ....(ii)

$S_g \geq 0.5$ ....(iii)

$S_{ab} + S_g + S_{ba} \leq 4 + M.\delta$ ....(iv)

$\delta \in \{0,1\}$ ....(v)

In addition to constraints (i)-(v), case-specific constraints (in the "conditions" column of Table 6.3) are also added, depending on the case considered.

In summary, we have:

	Optimal Solutions (OF 3)	
	δ=0	δ=1
Case 0	$S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = 0.5625F$	$S_{ab} = 2, S_{ba} = 3, S_g = 0.5$ $Obj = K$
Case 1	$S_{ab} = 1.562, S_{ba} = 1.438, S_g = 0.5$ $Obj = 0.7878F$	Impossible
Case 2	$S_{ab} = 1.6375, S_{ba} = 1.8625, S_g = 0.5$ $Obj = 0.4305F$	$S_{ab} = 2, S_{ba} = 3, S_g = 0.5$ $Obj = K$

Table 6.6: Solutions for Objective Function 3

Once again, the optimal schedule will depend on the relative values of K and L.

- If $K / F \geq 0.43$, the optimal solution is S_{ab}=1.64, S_{ba}=1.86, S_g=0.5. The corresponding objective function value is 0.43F.
- If $K / F \leq 0.43$, the optimal solution is S_{ab}=2, S_{ba}=3, S_g=0.5. The corresponding objective function value is K.

Note that in the optimal solution for $K / F \geq 0.43$, S_{ab} is no longer scheduled to its maximum 2 hours duration.

6.3.4 Objective Function 4

Min $K.\ \delta + L.$ P(late at B)+ $L.$ P(late at A)+ $C_a.(S_{ab} + S_{ba})$+ $C_g.\ S_g$

s.t

$1 \leq S_{ab} \leq 2$ ....(i)

$1 \leq S_{ba} \leq 3$ ....(ii)

$S_g \geq 0.5$ ....(iii)

$S_{ab} + S_g + S_{ba} \leq 4 + M.\delta$ ....(iv)

$\delta \in \{0,1\}$..(v)

In addition to constraints (i)-(v), case-specific constraints (in the "conditions" column of Table 6.1) are also added, depending on the case considered.

In this case, optimal solutions will depend on the relative values of L, K, C_a, and C_g.

6.3.4.1 Case 0

Figures 6.9 and 6.10 illustrate the optimal solutions obtained for Case 0. The lines define the boundaries between families of optimal solutions. The lines represent combinations of factors L, C_a and C_g for which there exist multiple optimal solutions.

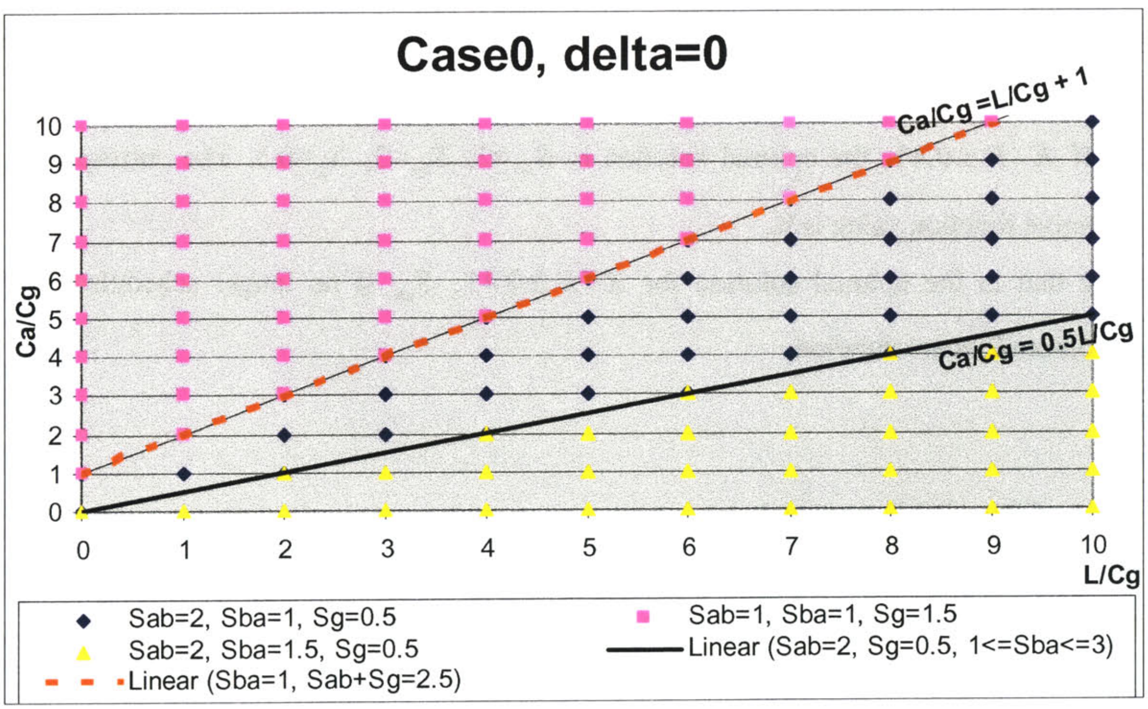

Figure 6.9: Optimal solutions for Case 0, $\delta=0$

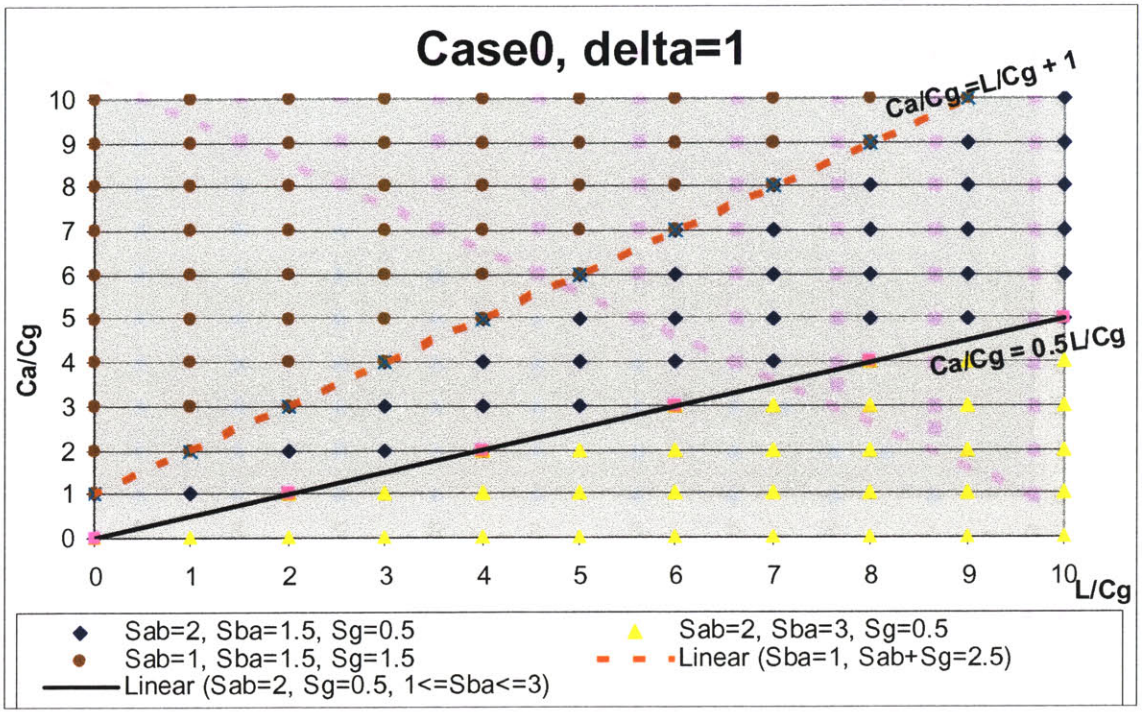

Figure 6.10: Optimal solutions for Case 0, δ=1

Figures 6.9 and 6.10 show that the optimal solutions will depend on the relative values of L, C_a, C_g, and K.

6.3.4.2 Case 1

Given the definition of Case 1 ($S_{ab} + S_g \leq 2.5$ and $2.5 \leq S_{ab} + S_g + S_{ba} \leq 3.5$) δ is always equal to zero. Figure 6.11 shows there are 2 families of optimal solutions, depending on the relative values of C_a/C_g and L/C_g.

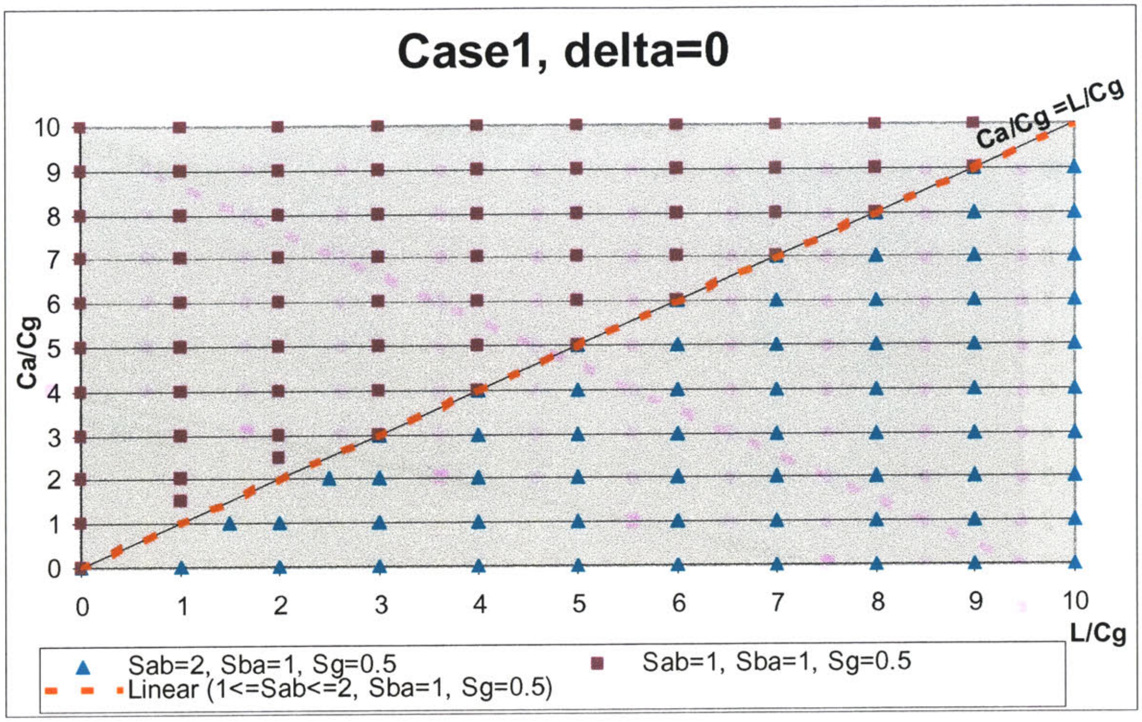

Figure 6.11: Optimal solutions for Case 1, δ =0

6.3.4.3 Case 2

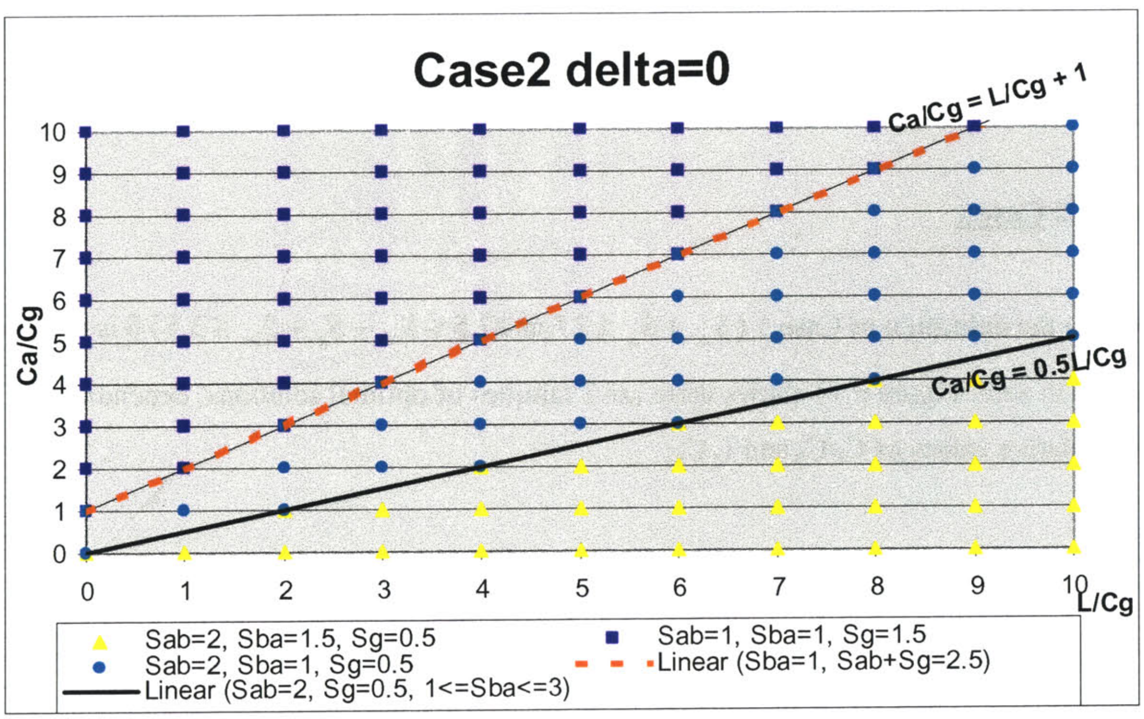

Figure 6.12: Optimal solutions for Case 2, δ =0

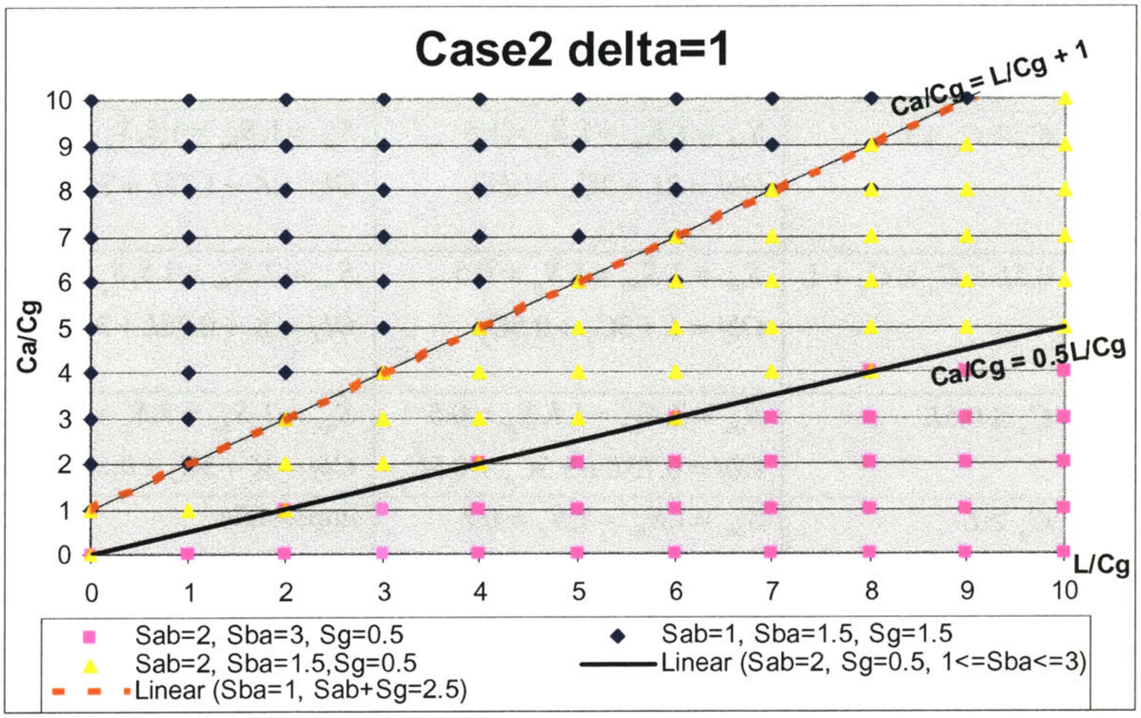

Figure 6.13: Optimal solutions for Case 2, $\delta = 1$

6.3.4.4 Summary

Table 6.7 summarizes the case-specific optimal solutions and corresponding objective function values.

	Additional Conditions	Optimal Solutions (OF 4) δ=0	δ=1
Case 0	$C_a \geq C_g + L$	$S_{ab} = 1, S_{ba} = 1, S_g = 1.5$ $Obj = 2L + 2C_a + 1.5C_g$	$S_{ab} = 1, S_{ba} = 1.5, S_g = 1.5$ $Obj = K + 1.75L + 2.5C_a + 1.5C_g$
	$0.5L \leq C_a \leq C_g + L$	$S_{ab} = 2, S_{ba} = 1, S_g = 0.5$ $Obj = L + 3C_a + 0.5C_g$	$S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = K + 0.75L + 3.5C_a + 0.5C_g$
	$C_a \leq 0.5L$	$S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = 0.75L + 3.5C_a + 0.5C_g$	$S_{ab} = 2, S_{ba} = 3, S_g = 0.5$ $Obj = K + 5C_a + 0.5C_g$
Case 1	$C_a \geq L$	$S_{ab} = 1, S_{ba} = 1, S_g = 0.5$ $Obj = 2L + 2C_a + 0.5C_g$	Impossible
	$C_a \leq L$	$S_{ab} = 2, S_{ba} = 1, S_g = 0.5$ $Obj = L + 3C_a + 0.5C_g$	Impossible
Case 2	$C_a \geq C_g + L$	$S_{ab} = 1, S_{ba} = 1, S_g = 1.5$ $Obj = 2L + 2C_a + 1.5C_g$	$S_{ab} = 1, S_{ba} = 1.5, S_g = 1.5$ $Obj = K + 1.75L + 2.5C_a + 1.5C_g$
	$0.5L \leq C_a \leq C_g + L$	$S_{ab} = 2, S_{ba} = 1, S_g = 0.5$ $Obj = L + 3C_a + 0.5C_g$	$S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = K + 0.75L + 3.5C_a + 0.5C_g$
	$C_a \leq 0.5L$	$S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = 0.75L + 3.5C_a + 0.5C_g$	$S_{ab} = 2, S_{ba} = 3, S_g = 0.5$ $Obj = K + 5C_a + 0.5C_g$

Table 6.7: Detailed case-by-case optimal solutions for Objective Function 4

Table 6.7 can be further reduced to Table 6.8, in which optimal solutions are not case-specific, and only depend on the relative values of K, L, C_a, and C_g (Table 6.8):

	Optimal Solutions (OF 4)
$C_a \geq L$	$S_{ab} = 1, S_{ba} = 1, S_g = 0.5$ $Obj = 2L + 2C_a + 0.5C_g$
$0.5L \leq C_a \leq L$	$S_{ab} = 2, S_{ba} = 1, S_g = 0.5$ $Obj = L + 3C_a + 0.5C_g$
$C_a \leq 0.5L$	If $K \geq 0.75L - 1.5C_a$: $S_{ab} = 2, S_{ba} = 1.5, S_g = 0.5$ $Obj = 0.75L + 3.5C_a + 0.5C_g$
	If $K \leq 0.75L - 1.5C_a$: $S_{ab} = 2, S_{ba} = 3, S_g = 0.5$ $Obj = K + 5C_a + 0.5C_g$

Table 6.8: Optimal solutions for OF 4 as a function of K, L, C_a, and C_g

The objective function was more complex in this case. This resulted in the optimal schedule depending on the relative values of a larger number of parameters. In the optimal solution, S_{ab} is not always set equal to its maximum possible value. It is beneficial to have it equal to this maximum to ensure on-time departure at B and reduce delay propagation. However, when there is a cost associated with flying time, it is not necessarily cost minimizing for the airlines to fix S_{ab} equal to its maximum.

6.4 **Conclusions**

This simple example illustrates the impact of the choice of an objective function on the optimal schedule. There are many more potential objective functions that could be considered, depending on the variables and parameters that the scheduler wishes to capture. Objective functions reflect the priorities schedulers have. Depending on whether they want to reduce expected minutes of delay, or the probability of delays, and depending on how they value time spent in the air as opposed to time spent on the ground, they will make different scheduling decisions.

In our example, scheduling solutions depend on the relative perceived costs of aircraft utilization and cost of delays. As expected, if the perceived cost of delays is much greater than the cost of foregoing efficient aircraft utilization, then optimal scheduled transit times on each leg are set to the corresponding maximum actual times observed on this leg. This observation is only valid for objective functions 1-3, and only valid because the penalty cost incurred for exceeding the maximum scheduled duration does not depend on the amount by which it is surpassed (as noted earlier). Results obtained show the importance of ensuring that the schedule minimizes the delay on the first leg of the trip, in order not to propagate delays on the remaining legs.

Future directions of research could consist of examining the effect of:

- varying the value of the maximum scheduled duration parameter.
- introducing a penalty cost that would increase with the amount by which the maximum scheduled duration is exceeded.
- introducing different delay costs on the different legs of the trip to emphasize the relative importance of being on time at different locations.

In this chapter, we demonstrated the complexity of scheduling an airline route so as to minimize delays relative to schedule. This was done through a very simple example (one airplane making a round trip, and uniform trip time distributions). In reality, airlines deal with extensive networks of routes. Moreover, in most cases, reducing costs is not the airline's only consideration. Schedules are also driven by efforts to coordinate the number of flights in each connecting bank at hub airports, and are also designed with the competitors' schedules in mind. It is also important to point out that the probability distributions of transit times on given O-D pairs are complex and evolve over time (as shown in Chapter 3), making it even more difficult for airlines to determine an optimal schedule.

CHAPTER 7: CONCLUSION

7.1 Summary

In Chapter 1, we argued that schedule adjustments prevent the commonly reported statistics on flight delays relative to schedule (such as the US DOT measure) from being used in a number of contexts. They cannot be used to estimate the true extent of air traffic delays or to gauge the state of the airspace and air traffic control systems, since they do not account for congestion-related delays. This motivated us to develop an alternative delay metric. We determined that the new measure should consist of taking the difference between the actual gate-to-gate time and a consistent benchmark that would approximate the congestion-free time.

In Chapter 2, we discussed appropriate estimates for the benchmark, after considering the factors affecting the variability of gate-to-gate travel times. Given that our primary interest lies in identifying long-term trends and changes in "true" delay, we decided not to concern ourselves with day-to-day fluctuations due to periodic factors (seasonality, day-of-the-week, and time-of-day) or to stochastic factors (weather/winds, runway and gate assignments, and flight path). We also decided not to concern ourselves with the impact of aircraft type on gate-to-gate variability, since all data used referred to jet flights and the substitution of one jet type for another seems to have only a small impact on travel times. We then suggested and discussed alternative measures that could be used to estimate the congestion-free baseline times. After examining several possibilities, it was decided that for our purposes it would be most appropriate to use a percentile of gate-to-gate time in the 5-20% range.

In Chapter 3, we outlined the procedure used to define consistent O-D-specific baseline times. We computed the baseline times for each of the 618 O-D pairs under consideration using the fifteenth percentile of gate-to-gate time, averaged over a four-month period. We then computed "true" O-D delays by taking the difference between actual gate-to-gate time and the baseline, and analyzed their evolution from 1995 to 2000. We found that the average "true" delay on the 618 O-D pairs increased from 11.1 minutes per flight in 1995 to 16.9 minutes in 2000 (52% increase). On 75 of the 618 O-D pairs considered, true delays more than doubled over the 1995-2000 period. When "true" delays were compared to delays relative to schedule, we found that "true" delays were about 40% to 60% greater than delays relative to schedule. Analysis of "delays relative to scheduled transit time" and "delays relative to schedule" suggested that although airlines seem to be able to accurately predict gate-to-gate times, they are not good at predicting departure times, which may be the reason why delays relative to schedule are incurred.

In Chapter 4, we described two different methodologies to attribute O-D delays to the airports of origin and destination. The first method is an iterative method based on the attribution of a variable portion of the overall O-D delay to the airports of origin and destination, depending on the relative congestion at those airports. The second method is based on the decomposition of gate-to-gate time into its three components (taxi out time, airborne time, taxi in time), the calculation of individual component delays, and the attribution of component delays to the relevant airport. Results obtained using both methods showed that airport delays increased over the 1995-2000 period: the average increase in delays at the 27 airports considered was of the order of 2 to 3 minutes per operation, which represents an increase of 40% to 53% depending on the method used. Further analysis on individual component delays suggested that there was a strong correlation between taxi out delay and airport of origin, as well as between taxi in delay and destination airport, confirming our decision to attribute taxi out (taxi in) delay to the origin (destination) airport. The second methodology also suggested that about 60% of the airborne delay on any given O-D route is attributable to airspace congestion whereas the remaining 40% is attributable to the destination airport.

In Chapter 5, we showed two applications of the methodologies outlined in Chapters 3 and 4. In the first application, we estimated total annual delays at Logan airport (BOS) using average delay figures obtained from Chapter 4. Our best estimates showed that annual "true" delays at Logan doubled from 1995 to 2000: "true" delays were on the order of 80,000 to 105,000 hours for the year 2000, up from 40,000-45,000 hours for 1995. This application can be extended to all 27 airports covered in this study. In the second application, we derived delay-rankings of airports based on the individual airport delays obtained in Chapter 4. We then compared our rankings with the FAA's and DOT's airport rankings (such as OPSNET delays, ASPM delays, etc) using the Spearman correlation test. Results suggested that ASQP on-time statistics and average delay relative to schedule are poor indicators of the true extent of air traffic delays. We were surprised to observe that, although OPSNET statistics severely underestimate delays, they yield very similar rankings to those obtained using the methods we derived in Chapter 4. This suggests that OPSNET statistics can be useful in determining the relative extent of congestion at different airports.

In Chapter 6, we focused on delays relative to schedule and showed why it may be very difficult for airlines to optimize their schedules so as to achieve high schedule compliance records. We used a simple case (an aircraft scheduled for a round trip, uniform probability density functions for actual transit times) to point out some of the complexities and interdependences in the schedule that make airline scheduling so complex. We also showed how the choice of the objective function impacted the optimal scheduling solution obtained. In our example, scheduling strategies depended on the relative perceived costs of reduced aircraft utilization, on the one hand, and of delays, on the other. Results obtained in our example showed the importance of ensuring that the schedule minimizes the delay on the first leg of the trip, so as to avoid the propagation of delays on the remaining legs of an aircraft's itinerary.

7.2 Future Research Directions

The work described in this thesis can be refined and extended in many different ways. Further research directions are discussed below.

7.2.1 Derivation of the baseline

In this thesis, we chose to use the fifteenth percentile of gate-to-gate time in order to compute the baseline. However, as indicated in Chapters 2 and 3, any percentile in the 5-20 range might be equally appropriate. Although it was argued that the exact value of the baseline is not especially critical to our measure of the evolution of true delays, it would be interesting in the future to refine our choice of percentile and examine the sensitivity of the delay results computed to the percentile chosen.

The choice of the sample over which the baseline time is estimated could also be refined. In this thesis, we chose to use a sample of flights that covered the whole day (24 hours) to derive the baseline. Another approach could have been to take a sample of flights operating at times that are believed to be congestion-free, since our goal is precisely to estimate congestion-free times. One could explore the use of a "restricted" sample of flights operating on days that are least traveled (Saturdays) or during off-peak (after 9 PM), to ensure that the baseline derived does not encompass any congestion delay.

More detailed analysis on the impacts of the various factors affecting gate-to-gate variability (as identified in Chapter 2) could be performed. Derivation of seasonal baselines to account for the variability in gate-to-gate time due to seasonality could be explored. The effect of aircraft type substitution could also be investigated more closely, since the impacts of the introduction of large numbers of regional jets may, in the future, prove to be significant, on routes where these jets replace non-jets.

7.2.2 Extension of the analysis

In this thesis, all analysis and computations have been performed for flights operating on a sub-network of 618 O-D pairs between 27 major airports. Analysis could be refined and extended by including more airports, for example, the 50 busiest airports in the US, or even every airport on which airlines regularly report data. Extending the analysis could allow one to monitor the approximate size of delays nationally or at additional individual airports. This would be useful in assessing whether the airport system and the air traffic management system (ATM) are keeping up with traffic growth on aggregate.

Currently the bulk of the analysis was performed for years 1995, 1997, and 2000. It would be very interesting to extend the time horizon and estimate delays after September 11, 2001 to test the validity of the methodologies. One would expect to see a decrease in "true" delays, as traffic levels and congestion decreased nationally after this date.

Finally, the application described in Chapter 5, which consists of calculating total annual delays at Logan airport, should be extended to all airports. Note that total annual delay estimates are based on the untested assumption that all flights, whether general aviation or commercial, experience delays similar to those of jets flown by major carriers. This assumption needs to be validated and a future direction of research could consist of computing separately delays for regional carriers and general aviation operations.

7.2.3 Scheduling to minimize delays relative to schedule

As discussed in Chapter 6, the probabilistic model derived could become more insightful if the following directions of research were explored:

- using probability density functions based on historical data for actual trip time instead of using uniformly distributed trip times;
- varying the value of the maximum scheduled duration parameter (which is currently set to 4 hours) to values of 4.5 hours or 5 hours and examine the impact on the solutions obtained;
- introducing a penalty cost that would increase with the amount by which the maximum scheduled duration is exceeded;
- introducing different delay costs on the different legs of the trip to emphasize the relative importance of being on time at different locations.

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APPENDIX A: NOTATION

Notation used: i: origin airport; j: destination airport.

PERCENTILES		
$P_{ij}^{x}(m,y)$	x^{th} percentile of gate-to-gate time on (i,j) in a given month *m* for year *y*	
AP_{ij}^{x}(y)	Average x^{th} percentile of gate-to-gate time on O-D pair (i,j) in year *y*	$AP_{ij}^{x}(95) = (P_{ij}^{x}(1,95) + P_{ij}^{x}(4,95) + P_{ij}^{x}(7,95) + P_{ij}^{x}(10,95))/4$ $AP_{ij}^{x}(97) = (P_{ij}^{x}(1,97) + P_{ij}^{x}(4,97) + P_{ij}^{x}(7,97) + P_{ij}^{x}(10,97))/4$ $AP_{ij}^{x}(00) = (P_{ij}^{x}(1,00) + P_{ij}^{x}(4,00) + P_{ij}^{x}(7,00))/3$
BASELINE		
B_{ij}^{x}:	Baseline time for O-D pair (i,j) using the x^{th} percentile	$B_{ij}^{x} = \text{MIN}(AP_{ij}^{x}(95),\ AP_{ij}^{x}(97),\ AP_{ij}^{x}(00))$
WB_{i}^{x}:	Weighted baseline per airport of origin using the x^{th} percentile for all O-D pairs originating at *I*	$WB_{i}^{x} = (\sum_{j} B_{ij}^{x} * TF_{ij}(00)) / (\sum_{j} TF_{ij}(00))$
WB_{ALL}^{x}	Overall weighted baseline using the xth percentile for ALL 618 O-D pairs	$WB_{ALL}^{x} = (\sum_{i}\sum_{j \neq i} B_{ij}^{x} * TF_{ij}(00)) / (\sum_{i}\sum_{j \neq i} TF_{ij}(00))$
FLOWN FLIGHTS		
F_{ij} (m,y)	number of flown flights in month *m* of year *y*	
TF_{ij} (y)	number of flown flights in year *y* for the months considered	$TF_{ij}(95) = F_{ij}(1,95) + F_{ij}(4,95) + F_{ij}(7,95) + F_{ij}(10,95)$ $TF_{ij}(97) = F_{ij}(1,97) + F_{ij}(4,97) + F_{ij}(7,97) + F_{ij}(10,97)$ $TF_{ij}(00) = F_{ij}(1,00) + F_{ij}(4,00) + F_{ij}(7,00)$
GATE-TO-GATE TIMES		
G_{ij} (m,y)	average of actual ASQP gate-to-gate time from origin *i* to destination *j* during month *m* of year *y*.	
AG_{ij} (y)	weighted average of actual ASQP gate-to-gate time during year *y*	$AG_{ij}(00) = (G_{ij}(1,00) * F_{ij}(1,00)$ $+ G_{ij}(4,00) * F_{ij}(4,00) + G_{ij}(7,00) * F_{ij}(7,00)) / TF_{ij}(00)$
O-D DELAYS		
$D_{ij}^{x}(y)$	Average O-D delay on O-D pair (i,j) in year *y*.	$D_{ij}^{x}(y) = AG_{ij}(y) - B_{ij}^{x}$

$WD_i^x(y)$	Weighted average per airport of origin using the x[th] percentile for all O-D pairs originating at *I*	$WD_i^x(y) = \sum_j TF_{ij}(y) * D_{ij}^x(y) / (\sum_j TF_{ij}(y))$
$WD_{ALL}^x(y)$	Overall weighted average of delay using the x[th] percentile for ALL 618 O-D pairs	$WD_{ALL}^x(y) =$ $(\sum_i \sum_{j \neq i} TF_{ij}(y) * D_{ij}^x(y)) / (\sum_i \sum_{j \neq i} TF_{ij}(y))$
ATTRIBUTION TO AIRPORTS		
$OrgAD_a^x(y)$	Average origin delay per aircraft at airport *a* computed using the x[th] percentile of gate-to-gate time	$OrgAD_a^x(y) = (\sum_j D_{aj}^x * TF_{aj}(00)) / (\sum_j TF_{aj}(00))$
$DestAD_a^x(y)$	Average destination delay per aircraft at airport *a* computed using the x[th] percentile of gate-to-gate time	$DestAD_a^x(y) = (\sum_i D_{ia}^x * TF_{ia}(00)) / (\sum_i TF_{ia}(00))$
$A_a^x(y)$	Average delay (whether origin or destination) per aircraft at airport *a* computed using the x[th] percentile of gate-to-gate time	$A_a^x(y) = (\sum_{i=a,j} D_{ij}^x * TF_{ij}(00) + \sum_{j=a,i} D_{ij}^x * TF_{ij}(00)) / (\sum_{i=a,j} \sum_{i,j=a} TF_{ij}(00))$

APPENDIX B: DETAILED RESULTS

B.1. SENSITIVITY OF THE BASELINE TO THE PERCENTILE CHOSEN

	Baseline estimation using...						
	5th percentile	7th percentile	10th percentile	13th percentile	15th percentile	17th percentile	20th percentile
BOS-ATL	142.5	144.4	145.7	146.8	147.5	148.0	148.8
BOS-BWI	71.5	72.0	73.7	74.3	74.8	75.3	76.0
BOS-CLE	100.3	101.7	102.8	104.1	104.5	105.2	106.4
BOS-CLT	116.2	117.0	119.0	120.1	120.5	121.5	122.4
BOS-CMH	109.3	110.6	112.0	112.8	113.9	114.6	115.0
BOS-CVG	121.5	122.3	123.5	124.0	124.8	125.3	126.0
BOS-DCA	81.1	82.3	83.4	84.5	85.3	85.8	86.8
BOS-DEN	245.8	248.1	250.0	250.3	252.2	253.0	255.2
BOS-DFW	221.8	224.0	226.3	227.8	228.9	229.8	231.3
BOS-DTW	111.5	112.8	114.4	115.5	116.9	117.2	118.3
BOS-EWR	63.8	64.9	66.0	67.0	67.8	68.5	69.5
BOS-FLL	172.9	173.6	174.7	176.7	177.4	178.3	179.3
BOS-IAD	79.7	80.7	81.8	82.5	83.3	83.5	84.0
BOS-IAH	226.1	228.0	230.4	230.4	232.2	233.3	234.7
BOS-LAX	344.4	347.0	348.8	350.0	352.4	353.8	355.1
BOS-LGA	49.5	50.0	50.9	51.5	52.0	52.5	53.3
BOS-MCO	160.7	162.0	163.6	165.5	166.0	166.9	167.8
BOS-MEM	167.7	168.6	170.2	171.9	172.4	172.8	173.9
BOS-MIA	175.5	176.7	178.7	178.7	181.9	183.9	185.0
BOS-MSP	165.0	166.6	168.9	171.3	172.3	173.0	174.4
BOS-ORD	137.0	138.6	140.3	141.3	142.0	143.0	144.0
BOS-PHL	67.0	67.5	68.5	69.1	69.8	70.3	71.0
BOS-PHX	310.0	312.7	314.9	316.2	318.7	319.8	321.3
BOS-PIT	89.5	90.5	91.8	92.6	93.3	93.5	94.5
BOS-SFO	355.9	357.7	360.0	361.4	362.7	363.6	365.0
BOS-TPA	175.0	176.0	177.8	179.0	179.3	180.3	181.0
	140.4	**141.7**	**143.1**	**144.2**	**145.1**	**145.8**	**146.8**

B.2. EVOLUTION OF "TRUE" DELAYS PER AIRPORT OF ORIGIN

Airport of Origin	"True" Delay 95 (min/op)	"True" Delay 97 (min/op)	"True" Delay 2000 (min/op)	Delay Increase over 95-2000 period
ATL	11.3	11.8	16.7	47.0%
BOS	11.1	14.3	19.9	78.6%
BWI	9.9	9.9	14.2	44.1%
CLE	10.0	12.1	15.5	55.4%
CLT	9.3	10.8	14.6	56.6%
CMH	8.8	10.8	12.8	45.4%
CVG	9.4	12.4	17.3	84.6%
DCA	10.4	12.5	15.5	49.2%
DEN	11.2	12.5	14.1	25.9%
DFW	11.8	14.9	16.5	39.2%
DTW	11.9	12.9	16.8	41.9%
EWR	14.2	18.1	22.9	60.7%
FLL	9.6	10.7	16.1	68.1%
IAD	11.1	13.0	20.5	85.2%
IAH	10.9	12.3	16.7	52.3%
LAX	11.3	14.5	15.8	39.1%
LGA	12.3	15.3	22.0	78.6%
MCO	9.5	11.1	14.7	54.0%
MEM	9.3	11.7	12.8	37.3%
MIA	12.9	13.6	16.0	23.6%
MSP	11.8	13.1	16.2	37.5%
ORD	11.1	13.0	16.9	52.6%
PHL	10.9	14.3	22.3	105.1%
PHX	9.9	12.7	14.7	48.4%
PIT	10.4	10.7	14.9	43.3%
SFO	11.8	14.6	15.5	31.6%
TPA	9.3	11.5	14.7	57.4%
ALL O-D	**11.1**	**13.2**	**16.9**	**51.9%**

B.3. COMPARISON "TRUE" DELAYS VERSUS DELAYS RELATIVE TO SCHEDULE FROM 1995 TO 2000

Airport of Origin	Ave. Sched. Delay 95	Ave. Sched. Delay 97	Ave. Sched. Delay 2000	"True" Delay 95	"True" Delay 97	"True" Delay 2000	Diff. Sched/True 95	Diff Sched/True 97	Diff. Sched/True 2000
ATL	9.5	11.7	12.9	11.3	11.8	16.7	18.9%	0.3%	29.4%
BOS	5.1	6.3	14.8	11.1	14.3	19.9	116.3%	125.1%	34.2%
BWI	5.4	5.1	11.7	9.9	9.9	14.2	82.2%	94.1%	21.9%
CLE	5.9	6.8	7.4	10.0	12.1	15.5	68.0%	76.6%	110.7%
CLT	9.7	8.1	12.7	9.3	10.8	14.6	-3.5%	33.6%	14.8%
CMH	7.0	7.6	7.6	8.8	10.8	12.8	26.4%	42.0%	68.7%
CVG	7.5	8.7	9.3	9.4	12.4	17.3	24.3%	42.6%	85.6%
DCA	2.5	4.3	7.1	10.4	12.5	15.5	322.5%	189.7%	118.7%
DEN	6.8	11.2	14.9	11.2	12.5	14.1	64.9%	11.7%	-5.5%
DFW	8.1	9.8	7.4	11.8	14.9	16.5	45.4%	52.2%	122.2%
DTW	10.0	12.2	11.0	11.9	12.9	16.8	18.3%	6.5%	52.5%
EWR	6.0	11.1	12.8	14.2	18.1	22.9	136.0%	63.2%	79.2%
FLL	6.5	8.7	13.6	9.6	10.7	16.1	47.5%	23.6%	17.6%
IAD	5.8	7.0	15.7	11.1	13.0	20.5	90.9%	85.3%	30.5%
IAH	6.9	8.5	7.6	10.9	12.3	16.7	58.8%	45.7%	118.5%
LAX	8.0	9.4	11.1	11.3	14.5	15.8	41.6%	53.8%	42.3%
LGA	2.8	6.2	12.0	12.3	15.3	22.0	339.3%	145.1%	83.4%
MCO	5.2	7.2	11.7	9.5	11.1	14.7	83.8%	53.8%	25.4%
MEM	3.8	8.5	6.7	9.3	11.7	12.8	145.3%	37.4%	91.0%
MIA	8.5	7.6	12.5	12.9	13.6	16.0	52.4%	77.5%	28.2%
MSP	6.1	8.7	8.5	11.8	13.1	16.2	94.7%	50.1%	90.4%
ORD	7.9	9.6	17.1	11.1	13.0	16.9	40.6%	35.6%	-0.9%
PHL	4.8	7.5	17.8	10.9	14.3	22.3	127.1%	91.9%	25.3%
PHX	9.1	10.3	11.2	9.9	12.7	14.7	8.6%	24.3%	31.6%
PIT	7.7	5.3	12.8	10.4	10.7	14.9	35.6%	103.0%	16.0%
SFO	7.9	10.1	11.2	11.8	14.6	15.5	49.1%	44.7%	38.2%
TPA	4.7	8.8	11.5	9.3	11.5	14.7	99.7%	30.9%	27.3%
ALL O-D	6.9	8.8	11.9	11.1	13.2	16.9	60.3%	50.1%	41.5%

B.4. SENSITIVITY OF ON-TIME PERFORMANCE STATISTICS TO DELAY DEFINITION USED

Airport of Origin	DOT %on-time 95	DOT %on-time 97	DOT %on-time 2000	"true" %on-time 95	"true"% on-time 97	"true"% on-time 2000	Diff. DOT/ "true" 95	Diff. DOT/ "true" 97	Diff. DOT/ "true" 2000
ATL	74%	72%	73%	68%	67%	54%	-5%	-5%	-19%
BOS	81%	80%	70%	70%	60%	44%	-11%	-19%	-26%
BWI	83%	83%	74%	75%	74%	63%	-8%	-8%	-12%
CLE	83%	80%	79%	75%	69%	57%	-8%	-11%	-21%
CLT	75%	77%	71%	77%	72%	61%	2%	-6%	-11%
CMH	82%	80%	80%	79%	73%	66%	-3%	-7%	-14%
CVG	80%	77%	77%	78%	67%	51%	-2%	-11%	-26%
DCA	85%	83%	80%	74%	67%	59%	-12%	-16%	-21%
DEN	80%	74%	69%	71%	67%	61%	-8%	-7%	-8%
DFW	78%	75%	78%	68%	61%	55%	-9%	-14%	-23%
DTW	76%	72%	72%	70%	68%	55%	-6%	-4%	-17%
EWR	79%	73%	71%	60%	51%	43%	-18%	-22%	-28%
FLL	81%	79%	75%	77%	72%	56%	-4%	-6%	-19%
IAD	81%	79%	69%	70%	65%	49%	-11%	-14%	-20%
IAH	80%	80%	79%	71%	66%	51%	-9%	-14%	-28%
LAX	76%	75%	73%	68%	59%	56%	-8%	-15%	-17%
LGA	83%	79%	70%	66%	58%	41%	-17%	-21%	-29%
MCO	84%	81%	76%	75%	70%	58%	-9%	-11%	-18%
MEM	84%	76%	81%	76%	69%	64%	-8%	-7%	-17%
MIA	77%	78%	74%	63%	61%	55%	-14%	-17%	-19%
MSP	80%	75%	75%	68%	65%	54%	-13%	-11%	-21%
ORD	78%	76%	67%	72%	68%	56%	-6%	-9%	-11%
PHL	81%	77%	65%	70%	60%	43%	-11%	-17%	-22%
PHX	76%	75%	73%	73%	64%	57%	-2%	-11%	-16%
PIT	77%	81%	72%	74%	73%	60%	-4%	-8%	-12%
SFO	77%	73%	72%	66%	58%	55%	-11%	-15%	-17%
TPA	84%	79%	77%	77%	69%	59%	-7%	-10%	-18%
All O-D	79%	77%	73%	71%	65%	54%	-8%	-12%	-19%

AIRPORT OF ORIGIN	Ave Scheduled transit time 95	Ave Scheduled transit time 97	Ave Scheduled transit time 2000	Ave. Delay actual vs. Scheduled transit time 95	Ave. Delay actual vs. Scheduled transit time 97	Ave. Delay actual vs. Scheduled transit time 2000	Ave. %late (15 min rule) 95	Ave. %late (15 min rule) 97	Ave. %late (15 min rule) 2000
ATL	123.0	122.8	129.4	-1.0	0.1	-0.1	8.4%	8.7%	10.6%
BOS	148.2	154.7	163.7	-2.8	-0.9	1.3	7.5%	10.6%	15.8%
BWI	118.2	124.4	129.3	-1.7	-1.3	0.8	5.7%	6.7%	10.4%
CLE	110.1	117.6	125.9	-0.8	0.6	-0.5	7.1%	10.6%	11.2%
CLT	108.8	112.2	116.9	-0.2	-0.1	1.6	7.4%	7.9%	11.9%
CMH	100.3	102.1	107.5	-1.1	0.6	-0.6	5.5%	8.7%	8.5%
CVG	107.6	114.5	123.6	-0.8	1.0	0.0	7.3%	10.4%	10.8%
DCA	111.5	112.3	112.6	-2.1	-0.1	0.1	6.8%	9.6%	10.9%
DEN	153.1	151.3	154.8	-1.8	0.8	0.1	8.2%	11.2%	11.9%
DFW	148.8	153.7	162.9	-1.1	-1.3	-2.7	9.1%	10.3%	8.9%
DTW	119.2	122.3	131.2	-0.9	-0.9	-1.0	8.7%	10.6%	12.5%
EWR	165.2	170.1	184.2	-2.2	0.4	-1.1	11.0%	15.2%	16.0%
FLL	138.8	135.8	145.3	-1.5	-0.2	-0.1	5.9%	8.2%	9.8%
IAD	167.4	165.8	155.4	-3.4	-0.8	1.7	6.5%	9.5%	15.3%
IAH	147.1	150.9	158.7	-1.0	-0.3	-1.2	8.2%	9.0%	9.3%
LAX	176.2	182.8	191.3	-1.7	0.0	-1.3	7.7%	10.1%	9.9%
LGA	142.0	140.3	144.0	-3.1	0.8	0.4	8.5%	13.4%	17.0%
MCO	138.1	138.1	147.0	-1.8	-0.8	-0.3	5.4%	7.3%	9.8%
MEM	114.8	115.6	120.3	-2.3	-0.1	-1.1	5.7%	9.1%	8.2%
MIA	172.4	176.6	175.3	-0.3	-1.6	-1.3	10.5%	9.9%	11.3%
MSP	131.3	134.8	142.1	-0.6	-0.8	-0.9	9.1%	10.4%	12.9%
ORD	133.9	136.8	140.0	-1.8	-0.9	-0.1	8.0%	9.4%	13.0%
PHL	136.9	140.8	155.2	-1.9	0.2	3.1	7.9%	11.5%	18.8%
PHX	142.3	149.7	160.5	-0.3	0.5	-1.5	7.6%	9.1%	8.4%
PIT	113.9	114.9	120.8	-0.9	-1.1	1.4	7.2%	8.1%	12.6%
SFO	187.3	193.9	206.4	-1.4	0.4	-2.7	8.1%	11.1%	9.9%
TPA	138.5	140.0	145.6	-2.1	-1.2	-0.4	5.2%	7.3%	8.9%
ALL O-D	139.1	142.3	149.7	-1.5	-0.3	-0.4	7.9%	10.0%	11.8%

APPENDIX C: AIRPORT DELAY ATTRIBUTION

Notation used: i: origin airport; j: destination airport.

ATTRIBUTION TO AIRPORTS- METHODOLOGY A (Step A1)		
$OrgAD1_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step A1	$OrgAD1_a(y) = 0.5*(\sum_j D^{15}_{aj}(y) * TF_{aj}(y)) / (\sum_j TF_{aj}(y))$
$DestAD1_a(y)$	Average destination delay per aircraft at airport *a*, calculated using Step A1	$DestAD1_a(y) = 0.5*(\sum_i D^{15}_{ia}(y) * TF_{ia}(y)) / (\sum_i TF_{ia}(y))$
$A_a1(y)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step A1	$A_a1(y) = [OrgAD1_a(y) * (\sum_j TF_{aj}(y)) + DestAD1_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{ia}(y) + \sum_i TF_{ia}(y))]$
ATTRIBUTION TO AIRPORTS- METHODOLOGY A (Step A2)		
$CORG_{ij,iter=k}(y)$	Coefficient of origin correction	$CORG_{ij,iter=0}(y) = OrgAD1_i(y) / (DestAD1_j(y) + OrgAD1_i(y))$ $CORG_{ij,iter=k+1}(y) = OrgAD2_{i,iter=k}(y) / (DestAD2_{j,iter=k}(y) + OrgAD2_{i,iter=k}(y))$
$CDES_{ij,iter=k}(y)$	Coefficient of destination correction	$CDES_{ij,iter=0}(y) = DestAD1_j(y) / (OrgAD1_i(y) + DestAD1_j(y))$ $CDES_{ij,iter=k+1}(y) = DestAD2_{j,iter=k}(y) / (OrgAD2_{i,iter=k}(y) + DestAD2_{j,iter=k}(y))$
$DepD_{ij,iter=k}(y)$	Departure delay on O-D pair (i,j) using Step A2	$DepD_{ij,iter=k}(y) = CORG_{ij,iter=k}(y) * D^{15}_{ij}$
$ArrD_{ij,iter=k}(y)$	Arrival delay on O-D pair (i,j) using Step A2	$ArrD_{ij,iter=k}(y) = CDES_{ij,iter=k}(y) * D^{15}_{ij}$
$OrgAD2_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step A2	BY ITERATION : ITER k: $OrgAD2_{a,iter=k}(y) = (\sum_j DepD_{aj,iter=k}(y) * TF_{aj}(y)) / (\sum_j TF_{aj}(y))$

$DestAD2_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step A2	BY ITERATION : ITER k: $DestAD2_{a,iter=k}(y) = (\sum_i ArrD_{aj,iter=k}(y) * TF_{aj}(y)) / (\sum_i TF_{ia}(y))$
$A_a 2(y)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step A2	$A_a 2(y) = [OrgAD2_a(y) * (\sum_j TF_{aj}(y)) + DestAD2_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$
ATTRIBUTION TO AIRPORTS- METHODOLOGY B (Step B1)		
$PTO_{ij}^{15}(m,y)$	15th percentile of taxi out time on (i,j) in a given month *m* for year *y*	
$PTI_{ij}^{15}(m,y)$	15th percentile of taxi in time on (i,j) in a given month *m* for year *y*	
$PAIR_{ij}^{15}(m,y)$	15th percentile of airborne time on (i,j) in a given month *m* for year *y*	
$APTO_{ij}^{15}(y)$	Average 15th percentile of taxi out time on O-D pair (i,j) in year *y*	$APTO_{ij}^{15}(95) = (PTO_{ij}^{15}(1,95) + PTO_{ij}^{15}(4,95) + PTO_{ij}^{15}(7,95) + PTO_{ij}^{15}(10,95))/4$ $APTO_{ij}^{15}(97) = (PTO_{ij}^{15}(1,97) + PTO_{ij}^{15}(4,97) + PTO_{ij}^{15}(7,97) + PTO_{ij}^{15}(10,97))/4$ $APTO_{ij}^{15}(00) = (PTO_{ij}^{15}(1,00) + PTO_{ij}^{15}(4,00) + PTO_{ij}^{15}(7,00))/3$
$APTI_{ij}^{15}(y)$	Average 15th percentile of taxi in time on O-D pair (i,j) in year *y*	$APTI_{ij}^{15}(95) = (PTI_{ij}^{15}(1,95) + PTI_{ij}^{15}(4,95) + PTI_{ij}^{15}(7,95) + PTI_{ij}^{15}(10,95))/4$ $APTI_{ij}^{15}(97) = (PTI_{ij}^{15}(1,97) + PTI_{ij}^{15}(4,97) + PTI_{ij}^{15}(7,97) + PTI_{ij}^{15}(10,97))/4$ $APTI_{ij}^{15}(00) = (PTI_{ij}^{15}(1,00) + PTI_{ij}^{15}(4,00) + PTI_{ij}^{15}(7,00))/3$
$APAIR_{ij}^{15}(y)$	Average 15th percentile of airborne time on O-D pair (i,j) in year *y*	$APAIR_{ij}^{15}(95) = (PAIR_{ij}^{15}(1,95) + PAIR_{ij}^{15}(4,95) + PAIR_{ij}^{15}(7,95) + PAIR_{ij}^{15}(10,95))/4$ $APAIR_{ij}^{15}(97) = (PAIR_{ij}^{15}(1,97) + PAIR_{ij}^{15}(4,97) + PAIR_{ij}^{15}(7,97) + PAIR_{ij}^{15}(10,97))/4$

		$APAIR_{ij}^{15}(00) = (PAIR_{ij}^{15}(1,00) + PAIR_{ij}^{15}(4,00) + PAIR_{ij}^{15}(7,00))/3$
BTO_{ij}^{15} :	Taxi out baseline time for OD pair (i,j) using the 15th percentile	$BTO_{ij}^{15} = \text{MIN}(APTO_{ij}^{15}(95), APTO_{ij}^{15}(97), APTO_{ij}^{15}(00))$
BTI_{ij}^{15} :	Taxi in baseline time for OD pair (i,j) using the 15th percentile	$BTI_{ij}^{15} = \text{MIN}(APTI_{ij}^{15}(95), APTI_{ij}^{15}(97), APTI_{ij}^{15}(00))$
$BAIR_{ij}^{15}$:	Airborne baseline time for OD pair (i,j) using the 15th percentile	$BAIR_{ij}^{15} = \text{MIN}(APAIR_{ij}^{15}(95), APAIR_{ij}^{15}(97), APAIR_{ij}^{15}(00))$
$TO_{ij}(m,y)$	average of actual ASQP taxi out time on O-D pair (i,j) during month *m* of year *y*.	
TI_{ij} (m,y)	average of actual ASQP taxi in time on O-D pair (i,j) during month *m* of year *y*.	
AIR_{ij} (m,y)	average of actual ASQP airborne time on O-D pair (i,j) during month *m* of year *y*.	
ATO_{ij} (y)	weighted average of actual ASQP taxi out time during year *y*	$ATO_{ij}(00) = (TO_{ij}(1,00) * F_{ij}(1,00) + TO_{ij}(4,00) * F_{ij}(4,00) + TO_{ij}(7,00) * F_{ij}(7,00)) / TF_{ij}(00)$
ATI_{ij} (y)	weighted average of actual ASQP taxi in time during year *y*	$ATI_{ij}(00) = (TI_{ij}(1,00) * F_{ij}(1,00) + TI_{ij}(4,00) * F_{ij}(4,00) + TI_{ij}(7,00) * F_{ij}(7,00)) / TF_{ij}(00)$
$AAIR_{ij}$ (y)	weighted average of actual ASQP airborne time during year *y*	$AAIR_{ij}(00) = (AIR_{ij}(1,00) * F_{ij}(1,00) + AIR_{ij}(4,00) * F_{ij}(4,00) + AIR_{ij}(7,00) * F_{ij}(7,00)) / TF_{ij}(00)$
$DTO_{ij}^{15}(y)$	Average taxi out delay on O-D pair (i,j) in year *y*.	$DTO_{ij}^{15} = ATO_{ij}(y) - BTO_{ij}^{15}$
$DTI_{ij}^{15}(y)$	Average taxi in delay on O-D pair (i,j) in year *y*.	$DTI_{ij}^{15} = ATI_{ij}(y) - BTI_{ij}^{15}$
$DAIR_{ij}^{15}(y)$	Average airborne delay on O-D pair (i,j) in year *y*.	$DAIR_{ij}^{15} = AAIR_{ij}(y) - BAIR_{ij}^{15}$
$OrgAD3_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step B1	$OrgAD3_a(y) = (\sum_j DTO_{aj}^{15}(y) * TF_{aj}(y)) / \sum_j TF_{aj}(y)$

$DestAD3_a(y)$	Average destination delay per aircraft at airport *a*, calculated using Step B1	$DestAD3_a(y) = (\sum_i (DTI_{ia}^{15}(y) + DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / (\sum_i TF_{ia}(y))$
$A_a 3(y)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step B1	$A_a 3(y) = [OrgAD3_a(y) * (\sum_j TF_{aj}(y)) + DestAD3_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$
ATTRIBUTION TO AIRPORTS- METHODOLOGY B (Step B2)		
$CORR_{ij}(y)$	Correction coefficient that takes into account the correlation between taxi out, taxi in, and airborne times.	$CORR_{ij}(y) = (BTO_{ij}^{15} + BTI_{ij}^{15} + BAIR_{ij}^{15}) / B_{ij}^{15}$
$OrgAD4_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step B2	$OrgAD4_a(y) = (\sum_j CORR_{aj}(y) * DTO_{aj}^{15}(y) * TF_{aj}(y))) / \sum_j TF_{aj}(y)$
$DestAD4_a(y)$	Average destination delay per aircraft at airport *a*, calculated using Step B2	$DestAD4_a(y) = (\sum_i CORR_{ia}(y) * (DTI_{ia}^{15}(y) + DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y)$
$A_a 4(y)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step B2	$A_a 4(y) = [OrgAD4_a(y) * (\sum_j TF_{aj}(y)) + DestAD4_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$
ATTRIBUTION TO AIRPORTS- METHODOLOGY B (Step B3)		
$DTO_{ij}^{15}(y)$	Average taxi out delay on O-D pair (i,j) in year *y*.	$DTO_{ij}^{15} = ATO_{ij}(y) - BTO_{ij}^{15}$
$DTI_{ij}^{15}(y)$	Average taxi in delay on O-D pair (i,j) in year *y*.	$DTI_{ij}^{15} = ATI_{ij}(y) - BTI_{ij}^{15}$
$OrgAD5_a(y)$	Average origin delay per aircraft at airport *a*, calculated using Step B3	$OrgAD5_a(y) = OrgAD3_a(y)$
$DestAD5_a(y)$	Average destination delay per aircraft at airport *a*, calculated using Step B3	$DestAD5_a(y) = (\sum (DTI_{ia}^{15}(y)) * TF_{ia}(y)) / \sum TF_{ia}(y)$

		$(\sum_i (DTI_{ia}^{15}(y)) * TF_{ia}(y)) / \sum_i TF_{ia}(y)$
$A_a 5(y)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step B3	$A_a 5(y) = [OrgAD5_a(y) * (\sum_j TF_{aj}(y)) + DestAD5_a(y) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$
ATTRIBUTION TO AIRPORTS- METHODOLOGY B (Step B4)		
$DTO_{ij}^{15}(y)$	Average taxi out delay on O-D pair (i,j) in year *y*.	$DTO_{ij}^{15} = ATO_{ij}(y) - BTO_{ij}^{15}$
$DTI_{ij}^{15}(y)$	Average taxi in delay on O-D pair (i,j) in year *y*.	$DTI_{ij}^{15} = ATI_{ij}(y) - BTI_{ij}^{15}$
$DAIR_{ij}^{15}(y)$	Average airborne delay on O-D pair (i,j) in year *y*.	$DAIR_{ij}^{15} = AAIR_{ij}(y) - BAIR_{ij}^{15}$
p	Fraction of airborne delay attributed to the destination airport	
$OrgAD6_a(y, p)$	Average origin delay per aircraft at airport *a*, calculated using Step B4	$OrgAD6_a(y, p) = (\sum_j DTO_{aj}^{15}(y) * TF_{aj}(y)) / \sum_j TF_{aj}(y)$
$DestAD6_a(y, p)$	Average destination delay per aircraft at airport *a*, calculated using Step B4	$DestAD6_a(y, p) = (\sum_i (DTI_{ia}^{15}(y) + p * DAIR_{ia}^{15}(y)) * TF_{ia}(y)) / (\sum_i TF_{ia}(y))$
$A_a 6(y, p)$	Average delay (origin and destination) per aircraft at airport *a*, calculated using Step B4	$A_a 6(y, p) = [OrgAD6_a(y, p) * (\sum_j TF_{aj}(y)) + DestAD6_a(y, p) * (\sum_i TF_{ia}(y))] / [\sum_j TF_{aj}(y) + \sum_i TF_{ia}(y))]$

APPENDIX D: STANDARD DEVIATIONS

Notation used: i: origin airport; j: destination airport.

REMINDER		
$DTO_{ij}^{15}(y)$	Average taxi out delay on O-D pair (i,j) in year *y*.	$DTO_{ij}^{15} = ATO_{ij}(y) - BTO_{ij}^{15}$
$DTI_{ij}^{15}(y)$	Average taxi in delay on O-D pair (i,j) in year *y*.	$DTI_{ij}^{15} = ATI_{ij}(y) - BTI_{ij}^{15}$
$DAIR_{ij}^{15}(y)$	Average airborne delay on O-D pair (i,j) in year *y*.	$DAIR_{ij}^{15} = AAIR_{ij}(y) - BAIR_{ij}^{15}$
STANDARD DEVIATIONS		
$SD_a^{ORG}(TO,y)$	Standard deviation of taxi out delays occurring on O-D pairs departing at airport *a*	$SD_a^{ORG}(TO,y) = \sigma(DTO_{aj}^{15}(y))$
$SD_a^{DEST}(TO,y)$	Standard deviation of taxi out delays occurring on O-D pairs arriving at airport *a*	$SD_a^{DEST}(TO,y) = \sigma(DTO_{ia}^{15}(y))$
$SD_a^{ORG}(TI,y)$	Standard deviation of taxi in delays occurring on O-D pairs departing at airport *a*	$SD_a^{ORG}(TI,y) = \sigma(DTI_{aj}^{15}(y))$
$SD_a^{DEST}(TI,y)$	Standard deviation of taxi in delays occurring on O-D pairs arriving at airport *a*	$SD_a^{DEST}(TI,y) = \sigma(DTI_{ia}^{15}(y))$
$SD_a^{ORG}(AIR,y)$	Standard deviation of airborne delays occurring on O-D pairs departing at airport *a*	$SD_a^{ORG}(AIR,y) = \sigma(DAIR_{aj}^{15}(y))$
$SD_a^{DEST}(AIR,y)$	Standard deviation of airborne delays occurring on O-D pairs arriving at airport *a*	$SD_a^{DEST}(AIR,y) = \sigma(DAIR_{ia}^{15}(y))$
COEFFICIENTS OF VARIATION		
$CV_a^{ORG}(TO,y)$	Coefficient of variation of taxi out delays occurring on O-D pairs originating at airport *a*	$CV_a^{ORG}(TO,y) = SD_a^{ORG}(TO,y) /$ AVE($DTO_{aj}^{15}(y)$)
$CV_a^{DEST}(TO,y)$	Coefficient of variation of taxi out delays occurring on O-D pairs arriving at airport *a*	$CV_a^{DEST}(TO,y) = SD_a^{DEST}(TO,y) /$AVE($DTO_{ia}^{15}(y)$)
$CV_a^{ORG}(TI,y)$	Coefficient of variation of taxi in delays occurring on O-D pairs originating at airport *a*	$CV_a^{ORG}(TI,y) = SD_a^{ORG}(TI,y) /$ AVE($DTI_{aj}^{15}(y)$)

$CV_a^{DEST}(TI,y)$	Coefficient of variation of taxi in delays occurring on O-D pairs arriving at airport *a*	$CV_a^{DEST}(TI,y) = SD_a^{DEST}(TI,y)$ / AVE($DTI_{ia}^{15}(y)$)
$CV_a^{ORG}(AIR,y)$	Coefficient of variation of airborne delays occurring on O-D pairs originating at airport *a*	$CV_a^{ORG}(AIR,y) = SD_a^{ORG}(AIR,y)$ / AVE($DAIR_{aj}^{15}(y)$)
$CV_a^{DEST}(AIR,y)$	Coefficient of variation of airborne delays occurring on O-D pairs arriving at airport *a*	$CV_a^{DEST}(AIR,y) = SD_a^{DEST}(AIR,y)$ / AVE($DAIR_{ia}^{15}(y)$)

ORIGIN AIRPORT	STDEV Taxi Out Delay 1995	1997	2000
ATL	1.2	0.9	1.3
BOS	0.7	0.7	1.2
BWI	0.8	0.5	1.5
CLE	0.8	1.0	1.7
CLT	0.6	0.8	1.2
CMH	0.8	1.1	1.1
CVG	0.9	1.5	1.8
DCA	0.8	1.0	1.6
DEN	1.1	0.7	1.6
DFW	1.3	1.3	1.5
DTW	1.3	1.4	1.3
EWR	1.3	1.6	2.2
FLL	0.8	0.7	1.2
IAD	0.9	0.8	2.4
IAH	1.0	1.0	1.1
LAX	0.9	0.9	1.0
LGA	0.9	1.1	2.2
MCO	0.6	0.5	0.9
MEM	1.4	1.3	1.1
MIA	2.0	1.9	1.8
MSP	0.9	1.3	1.3
ORD	0.8	0.7	1.3
PHL	1.1	1.6	1.7
PHX	0.9	1.0	0.9
PIT	0.8	0.8	1.6
SFO	1.4	1.7	1.3
TPA	0.8	0.6	1.0
ALL	**1.9**	**2.2**	**3.0**

DESTINATION AIRPORT	STDEV Taxi Out Delay 1995	1997	2000
ATL	1.6	2.1	2.9
BOS	2.1	2.3	2.9
BWI	2.0	1.9	2.9
CLE	2.0	2.5	3.3
CLT	1.7	2.1	3.2
CMH	2.1	2.5	3.7
CVG	1.8	1.8	2.8
DCA	2.2	2.5	2.8
DEN	1.8	2.4	3.2
DFW	1.5	2.2	3.2
DTW	1.6	2.1	2.6
EWR	1.7	1.5	2.1
FLL	1.9	2.5	3.8
IAD	2.8	2.2	3.0
IAH	1.5	2.5	3.5
LAX	2.1	2.9	3.1
LGA	1.8	1.6	1.8
MCO	1.9	2.5	3.2
MEM	1.5	1.8	2.2
MIA	1.4	2.2	3.2
MSP	1.5	2.1	2.7
ORD	1.7	2.3	2.8
PHL	1.7	1.9	2.2
PHX	2.3	2.4	3.9
PIT	1.7	2.2	3.7
SFO	2.0	2.6	2.9
TPA	1.9	2.3	3.5
ALL	**1.9**	**2.2**	**3.0**

ORIGIN AIRPORT	STDEV Taxi In Delay 1995	1997	2000
ATL	0.7	0.8	1.0
BOS	1.3	1.5	1.3
BWI	1.1	1.3	1.5
CLE	1.1	1.2	1.4
CLT	0.9	1.0	1.3
CMH	0.7	1.4	1.3
CVG	0.6	1.1	1.2
DCA	1.0	1.4	1.4
DEN	1.0	1.1	1.3
DFW	0.9	1.0	1.1
DTW	0.7	1.0	0.9
EWR	0.9	1.3	1.2
FLL	1.1	1.5	1.6
IAD	1.1	1.3	1.3
IAH	0.8	0.9	1.4
LAX	1.5	1.3	1.2
LGA	1.3	1.2	1.4
MCO	1.1	1.3	1.3
MEM	0.8	1.1	1.0
MIA	1.2	1.4	1.5
MSP	1.0	1.0	1.1
ORD	0.8	1.1	0.9
PHL	0.9	1.1	1.3
PHX	1.6	1.1	1.2
PIT	0.8	0.8	1.2
SFO	1.1	1.2	1.3
TPA	1.2	1.4	1.3
ALL	**1.0**	**1.2**	**1.3**

DESTINATION AIRPORT	STDEV Taxi In Delay 1995	1997	2000
ATL	0.4	0.5	0.6
BOS	0.3	0.4	0.7
BWI	0.6	0.5	0.5
CLE	0.4	0.3	0.2
CLT	0.5	0.4	0.3
CMH	0.4	0.3	0.3
CVG	0.3	0.4	0.4
DCA	0.8	0.7	0.5
DEN	1.0	0.6	1.1
DFW	0.9	0.8	0.7
DTW	1.3	1.2	1.2
EWR	0.5	0.5	0.4
FLL	0.3	0.4	0.5
IAD	0.3	0.3	0.5
IAH	0.6	0.4	0.3
LAX	0.7	1.0	0.8
LGA	0.5	0.9	1.1
MCO	0.6	0.3	0.4
MEM	0.3	0.4	0.4
MIA	0.7	1.0	0.7
MSP	0.6	0.6	0.6
ORD	0.7	0.6	0.5
PHL	0.3	0.7	0.7
PHX	0.4	0.7	1.0
PIT	0.3	0.4	0.3
SFO	0.3	0.4	0.6
TPA	0.3	0.4	0.3
ALL	**1.0**	**1.2**	**1.3**

ORIGIN AIRPORT	STDEV Airborne Delay 1995	1997	2000
ATL	3.7	2.6	3.8
BOS	3.9	4.1	4.1
BWI	4.1	2.8	4.9
CLE	4.7	3.2	2.7
CLT	3.5	3.1	2.8
CMH	4.5	3.1	3.4
CVG	3.0	2.6	4.2
DCA	3.0	2.9	2.2
DEN	1.7	2.6	2.5
DFW	1.6	2.1	3.1
DTW	4.4	3.2	3.7
EWR	3.9	3.0	4.3
FLL	2.0	3.3	4.5
IAD	3.4	2.9	5.4
IAH	1.9	2.3	3.4
LAX	3.4	4.2	4.0
LGA	3.8	3.5	2.5
MCO	2.5	3.0	3.8
MEM	3.3	1.5	3.1
MIA	3.1	2.5	3.4
MSP	3.1	2.7	3.1
ORD	2.8	2.5	2.9
PHL	4.8	4.1	4.2
PHX	2.6	3.9	3.0
PIT	5.1	3.3	3.4
SFO	4.0	4.0	3.3
TPA	2.6	2.6	3.2
ALL	3.6	3.4	3.6

DESTINATION AIRPORT	STDEV Airborne Delay 1995	1997	2000
ATL	2.0	2.7	1.8
BOS	2.1	3.2	4.2
BWI	2.9	3.3	2.5
CLE	4.3	4.3	2.6
CLT	2.6	3.1	1.8
CMH	3.7	4.5	2.0
CVG	1.6	2.6	2.0
DCA	1.4	2.1	2.3
DEN	2.9	3.0	3.7
DFW	3.7	2.7	2.5
DTW	2.5	2.9	2.6
EWR	2.2	3.0	3.5
FLL	2.8	3.7	3.7
IAD	1.9	3.8	4.0
IAH	3.0	2.3	3.3
LAX	4.0	3.2	3.8
LGA	1.9	2.6	3.1
MCO	3.0	3.3	2.7
MEM	2.4	2.8	2.7
MIA	3.5	3.0	3.1
MSP	2.4	2.4	2.2
ORD	1.9	2.5	2.4
PHL	2.3	3.2	3.2
PHX	4.6	3.4	3.6
PIT	3.6	4.0	2.4
SFO	3.2	2.3	5.0
TPA	3.2	2.7	2.4
ALL	3.6	3.4	3.6

ORIGIN AIRPORT	COEFF VAR. Taxi Out Delay 1995	1997	2000
ATL	0.14	0.12	0.13
BOS	0.14	0.10	0.12
BWI	0.20	0.14	0.22
CLE	0.17	0.15	0.18
CLT	0.12	0.15	0.16
CMH	0.25	0.26	0.20
CVG	0.16	0.22	0.19
DCA	0.17	0.18	0.20
DEN	0.21	0.13	0.25
DFW	0.15	0.15	0.17
DTW	0.17	0.17	0.12
EWR	0.14	0.13	0.14
FLL	0.22	0.18	0.17
IAD	0.19	0.16	0.24
IAH	0.17	0.15	0.12
LAX	0.16	0.15	0.15
LGA	0.12	0.12	0.15
MCO	0.16	0.13	0.17
MEM	0.29	0.21	0.19
MIA	0.24	0.26	0.23
MSP	0.13	0.17	0.13
ORD	0.14	0.10	0.14
PHL	0.22	0.22	0.13
PHX	0.23	0.19	0.13
PIT	0.18	0.17	0.23
SFO	0.21	0.22	0.17
TPA	0.25	0.14	0.20
ALL	0.33	0.35	0.35

DESTINATION AIRPORT	COEFF VAR. Taxi Out Delay 1995	1997	2000
ATL	0.32	0.32	0.31
BOS	0.35	0.36	0.31
BWI	0.33	0.30	0.34
CLE	0.33	0.38	0.39
CLT	0.36	0.39	0.42
CMH	0.36	0.36	0.40
CVG	0.36	0.30	0.32
DCA	0.39	0.40	0.33
DEN	0.32	0.39	0.39
DFW	0.27	0.34	0.37
DTW	0.31	0.31	0.32
EWR	0.28	0.23	0.23
FLL	0.32	0.37	0.41
IAD	0.49	0.37	0.37
IAH	0.27	0.42	0.41
LAX	0.34	0.42	0.36
LGA	0.34	0.27	0.18
MCO	0.32	0.36	0.37
MEM	0.28	0.30	0.28
MIA	0.23	0.32	0.36
MSP	0.29	0.35	0.34
ORD	0.28	0.34	0.28
PHL	0.31	0.33	0.26
PHX	0.36	0.35	0.45
PIT	0.34	0.37	0.42
SFO	0.29	0.36	0.30
TPA	0.32	0.34	0.38
ALL	0.33	0.35	0.35

ORIGIN AIRPORT

	COEFF VAR. Taxi In Delay		
	1995	1997	2000
ATL	0.35	0.30	0.32
BOS	0.49	0.49	0.39
BWI	0.44	0.47	0.43
CLE	0.46	0.49	0.46
CLT	0.41	0.45	0.45
CMH	0.32	0.45	0.35
CVG	0.34	0.40	0.35
DCA	0.41	0.49	0.42
DEN	0.40	0.45	0.41
DFW	0.38	0.38	0.38
DTW	0.36	0.40	0.32
EWR	0.33	0.48	0.40
FLL	0.37	0.52	0.50
IAD	0.51	0.46	0.40
IAH	0.34	0.42	0.48
LAX	0.55	0.47	0.38
LGA	0.52	0.46	0.42
MCO	0.43	0.45	0.39
MEM	0.37	0.45	0.31
MIA	0.47	0.48	0.43
MSP	0.43	0.39	0.38
ORD	0.37	0.42	0.30
PHL	0.40	0.42	0.42
PHX	0.60	0.40	0.38
PIT	0.34	0.35	0.36
SFO	0.42	0.39	0.39
TPA	0.44	0.45	0.38
ALL	**0.43**	**0.44**	**0.39**

DESTINATION AIRPORT

	COEFF VAR. Taxi In Delay		
	1995	1997	2000
ATL	0.18	0.16	0.15
BOS	0.13	0.15	0.18
BWI	0.33	0.26	0.23
CLE	0.19	0.17	0.14
CLT	0.23	0.18	0.12
CMH	0.26	0.20	0.17
CVG	0.20	0.22	0.18
DCA	0.33	0.25	0.29
DEN	0.30	0.21	0.28
DFW	0.20	0.14	0.13
DTW	0.30	0.25	0.22
EWR	0.19	0.16	0.10
FLL	0.27	0.25	0.22
IAD	0.18	0.15	0.17
IAH	0.25	0.18	0.12
LAX	0.20	0.23	0.16
LGA	0.25	0.34	0.28
MCO	0.27	0.17	0.19
MEM	0.20	0.18	0.19
MIA	0.24	0.30	0.21
MSP	0.25	0.22	0.17
ORD	0.23	0.17	0.10
PHL	0.14	0.26	0.18
PHX	0.27	0.32	0.31
PIT	0.17	0.22	0.14
SFO	0.16	0.19	0.24
TPA	0.24	0.21	0.13
ALL	**0.43**	**0.44**	**0.39**

ORIGIN AIRPORT

	COEFF VAR. Airborne Delay		
	1995	1997	2000
ATL	0.51	0.35	0.44
BOS	0.39	0.36	0.36
BWI	0.46	0.33	0.48
CLE	0.50	0.37	0.34
CLT	0.47	0.39	0.36
CMH	0.53	0.36	0.41
CVG	0.42	0.34	0.50
DCA	0.39	0.33	0.28
DEN	0.21	0.28	0.28
DFW	0.21	0.22	0.30
DTW	0.51	0.39	0.45
EWR	0.40	0.30	0.40
FLL	0.27	0.35	0.45
IAD	0.40	0.31	0.52
IAH	0.23	0.25	0.34
LAX	0.32	0.30	0.35
LGA	0.43	0.38	0.27
MCO	0.34	0.35	0.41
MEM	0.42	0.18	0.36
MIA	0.36	0.27	0.34
MSP	0.33	0.29	0.34
ORD	0.36	0.31	0.34
PHL	0.48	0.43	0.43
PHX	0.27	0.32	0.28
PIT	0.58	0.39	0.40
SFO	0.36	0.30	0.32
TPA	0.35	0.32	0.33
ALL	**0.41**	**0.37**	**0.39**

DESTINATION AIRPORT

	COEFF VAR. Airborne Delay		
	1995	1997	2000
ATL	0.23	0.24	0.19
BOS	0.26	0.33	0.35
BWI	0.41	0.50	0.34
CLE	0.59	0.47	0.29
CLT	0.38	0.35	0.23
CMH	0.61	0.63	0.30
CVG	0.26	0.31	0.25
DCA	0.27	0.35	0.36
DEN	0.29	0.30	0.33
DFW	0.33	0.25	0.28
DTW	0.31	0.37	0.33
EWR	0.25	0.26	0.34
FLL	0.31	0.37	0.43
IAD	0.31	0.48	0.36
IAH	0.28	0.22	0.33
LAX	0.31	0.27	0.31
LGA	0.29	0.34	0.36
MCO	0.39	0.37	0.35
MEM	0.30	0.33	0.35
MIA	0.33	0.29	0.34
MSP	0.25	0.22	0.19
ORD	0.25	0.29	0.24
PHL	0.32	0.35	0.31
PHX	0.39	0.32	0.32
PIT	0.50	0.49	0.34
SFO	0.23	0.19	0.31
TPA	0.37	0.31	0.33
ALL	**0.41**	**0.37**	**0.39**