EXAMINATION OF AIR TRANSPORTATION

TRIP TIME VARIABILITY

by

Raymond A. Young III

Bachelor of Science in Engineering
Princeton University
1964

Master of Business Administration
Harvard University
1970

A dissertation submitted in partial fulfillment
of the requirements of the

Doctor of Philosophy Degree in Engineering
Department of Civil and Environmental Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
December 2008
This Dissertation prepared by

Raymond Alfred Young III

Entitled

Examination of Air Transportation Trip Time Variability

is approved in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Engineering

Examination Committee CoChair

Examination Committee Chair

Examination Committee Member

Dean of the Graduate College

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Examination of Air Transportation Trip Time Variability

by

Raymond A. Young III

Dr. Shashi S. Nambisan, Examination Committee Chairman
and Research Advisor
Professor of Civil Engineering
Iowa State University

Dr. Mohamed Kaseko, Examination Committee Co-Chairman
Associate Professor of Civil Engineering
University of Nevada, Las Vegas

Scheduled air transportation is required to provide a service that is safe, consistent, and dependable, with reliable trip times and delays managed within acceptable limits. High trip time variability and delay in the current system are driven by multiple factors.

The study objectives were: (1) to develop a comprehensive database for major U.S. airline domestic trips between 1995 and 2005; (2) to explore the central tendency and variability of airline gate-to-gate trip times and delays; (3) to develop values for unconstrained, or unimpeded, trip times, and (4) to develop traveler and airline delay and variability costs relative to unimpeded trip times.

The research used U.S. Department of Transportation (U.S. DOT) data for scheduled domestic airline trips reported by major U.S. air carriers between 1995 and 2005. The study used reported trip times as a primary indicator, unimpeded trip times as a reference, and attached a cost to the excess of reported trip time over unimpeded trip time at the
individual flight level. This approach represents a process for evaluating the time savings and operating cost impacts of measures for increasing capacity and reducing impedance in U.S. domestic scheduled air transportation.

Areas in which trip time variability and delay impose a high penalty on travelers and airlines were identified. The most important study results concerned disproportionately higher delays and costs relative to: (1) arrivals and departures at leading airports (40 percent of flights and 55 percent of costs); (2) flight departures and arrivals between noon and early evening (50 percent of flights and 60 percent of costs); and (3) during the 40 percent of days in which there were heavy system wide delays (55 percent of costs).

Using costs appropriate to time changes on individual trips, penalties incurred by impeded trips were estimated relative to unimpeded trips. These were: 150 million annual excess traveler hours per year; $8 billion annual excess costs (in constant 2005 dollars); with 400 million annual gallons of excess jet fuel consumption. The costs of impeded trips added about 10 percent (or about $3.4 billion annually) to airline variable operating costs during the study period.
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................ iii

TABLE OF CONTENTS ....................................................................................................................... v

LIST OF TABLES ............................................................................................................................ vii

LIST OF FIGURES .......................................................................................................................... viii

ACKNOWLEDGMENTS ................................................................................................................... ix

CHAPTER 1  INTRODUCTION ................................................................................................... 1
  - Research Background ............................................................................................................. 1
  - Trip Time for Scheduled Flights ......................................................................................... 3
  - The Context for the Research ............................................................................................ 7
  - Need for and Purpose of the Study .................................................................................... 11
  - Outline of the Dissertation ............................................................................................... 13

CHAPTER 2  REVIEW OF RELATED LITERATURE ........................................................... 14
  - Introduction ......................................................................................................................... 14
  - Air Traffic Management ..................................................................................................... 15
  - Current System Limitations and the Basis for Change ..................................................... 18
  - System Performance Goals ............................................................................................... 22
  - Airport Surface Traffic Management .............................................................................. 28
  - Airspace System Capacity and Throughput ...................................................................... 32
  - Delay Propagation ............................................................................................................ 34
  - Delay and Disruption Costs to Travelers ......................................................................... 36
  - Delay and Disruption Costs to Air Carriers ..................................................................... 42
  - Value of Reduced Schedule Variability ........................................................................... 51
  - Gaps Addressed by this Research ..................................................................................... 53

CHAPTER 3  METHODOLOGY .............................................................................................. 55
  - Research Methodology ....................................................................................................... 55
  - Data Sources ........................................................................................................................ 56
  - Database Development ....................................................................................................... 61
  - Data Quality ........................................................................................................................ 69
  - Treatment of Data as Pooled Cross-Sectional Data .......................................................... 74
  - Data Analyses and Methods ............................................................................................... 76
  - Criteria for Identifying Unimpeded Times ......................................................................... 78
  - Ground Taxi Time Estimation ............................................................................................ 79
  - Observed Trip Time Estimation ......................................................................................... 84
LIST OF TABLES

Table 2-1  Estimated non-fuel Airbus A320 family variable operating costs ..........46
Table 2-2  Legacy air carrier cost per block hour and seats per departure ...............48
Table 3-1  Validated and recovered chained records by year ........................................67
Table 3-2  BTS published summary by category and year ........................................71
Table 3-3  Research dataset flight records by category and year ................................72
Table 3-4  Percent differences between BTS summary and research data ...................73
Table 3-5  Paired t-test results for fitted Z-distribution for impeded trip time ..........99
Table 3-6  Weighting factors for cost allocation for representative aircraft types ....105
Table 3-7  Confidence intervals for allocating variable cost elements ..................107
Table 4-1  Airline flight time, distance, and arrival delay 1995-2005 ..........................117
Table 4-2  Annual cost of impeded and delayed flights 1995-2005 ............................138
Table 4-3  Average seats per departure by carrier group ........................................139
Table 4-4  Delay distribution by aircraft seat capacity (1995-2005) .........................143
Table 4-5  Delay distribution by airport-pair category (1995-2005) .......................144
Table 4-6  Delay distribution by origin airport group (1995-2005) .........................145
Table 4-7  Delay distribution by destination airport group (1995-2005) .................146
Table 4-8  Delay distribution by flight stage length (1995-2005) .........................147
Table 4-9  Delay distribution by carrier group (1995-2005) ..................................148
Table 4-10 Delay distribution by CRS departure time (1995-2005) .......................149
Table 4-11 Delay distribution by CRS arrival time (1995-2005) ..........................150
Table 4-12 Delay distribution by prior scheduled turn (1995-2005) ......................151
Table 4-13 Delay distribution by prior actual turn (1995-2005) ............................152
Table 4-14 Delay distribution by impeded day deciles (1995-2005) ......................153
Table 4-15 Annual airline impeded trip times .........................................................156
Table 4-16 Annual impeded hours by trip phase .....................................................157
Table 4-17 Added carrier expense above unimpeded operating expense ...............158
Table 4-18 Excess fuel by flight phase for impeded flights ....................................159
Table 4-19 Fuel expense by flight phase .................................................................160
Table 4-20 Scenario 1 delay distribution by day bands .......................................167
Table 4-21 Scenario 2 delay distribution by day bands .......................................168
Table 4-22 Scenario 3 delay distribution by day bands .......................................169
Table 4-23 Overview of scenarios 1 through 3 ......................................................170
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Scheduled, early, on-time, and delayed arrival flights</td>
<td>5</td>
</tr>
<tr>
<td>1-2</td>
<td>Air trip cycle and identification of OOOI times</td>
<td>6</td>
</tr>
<tr>
<td>2-1</td>
<td>Arrival delay utility function</td>
<td>40</td>
</tr>
<tr>
<td>3-1</td>
<td>Dataset development process flowchart</td>
<td>63</td>
</tr>
<tr>
<td>3-2</td>
<td>FAA 2005 chart showing expected capacity change 2001-2013</td>
<td>75</td>
</tr>
<tr>
<td>3-3</td>
<td>Distribution of unimpeded taxi-out time residuals</td>
<td>82</td>
</tr>
<tr>
<td>3-4</td>
<td>Distribution of unimpeded taxi-in time residuals</td>
<td>83</td>
</tr>
<tr>
<td>3-5</td>
<td>Distribution of unimpeded airborne time residuals</td>
<td>84</td>
</tr>
<tr>
<td>3-6</td>
<td>Distribution of unimpeded block time residuals</td>
<td>89</td>
</tr>
<tr>
<td>3-7</td>
<td>Arrival delay distribution 1995-2005</td>
<td>92</td>
</tr>
<tr>
<td>3-8</td>
<td>Impeded trip time Z-values by year</td>
<td>94</td>
</tr>
<tr>
<td>3-9</td>
<td>Distribution of impeded trip time Z residuals</td>
<td>96</td>
</tr>
<tr>
<td>3-10</td>
<td>Cumulative probability distribution of trip time Z residuals</td>
<td>96</td>
</tr>
<tr>
<td>3-11</td>
<td>Probability P-P plot for fitted and empirical trip time distributions</td>
<td>97</td>
</tr>
<tr>
<td>3-12</td>
<td>Cost assignment methodology flow chart</td>
<td>103</td>
</tr>
<tr>
<td>4-1</td>
<td>Box-plot of flight arrival delays 1995-2005</td>
<td>119</td>
</tr>
<tr>
<td>4-2</td>
<td>85-percent arrival punctuality by year and stage length</td>
<td>121</td>
</tr>
<tr>
<td>4-3</td>
<td>85-percent arrival punctuality for 1996 and 2003 by stage length</td>
<td>122</td>
</tr>
<tr>
<td>4-4</td>
<td>Median-adjusted arrival punctuality</td>
<td>124</td>
</tr>
<tr>
<td>4-5</td>
<td>85th percentile less median arrival delay by year and airport</td>
<td>126</td>
</tr>
<tr>
<td>4-6</td>
<td>Flight on-time performance reporting</td>
<td>128</td>
</tr>
<tr>
<td>4-7</td>
<td>85th percentile flight arrival delay with median-adjustment</td>
<td>131</td>
</tr>
<tr>
<td>4-8</td>
<td>Impeded trip time variation for 12 airports by quarter 1995-2005</td>
<td>133</td>
</tr>
<tr>
<td>4-9</td>
<td>Trend in jet fuel gallons per weighted block hour 1995-2005</td>
<td>161</td>
</tr>
<tr>
<td>4-10</td>
<td>Probability density function of mean daily impeded times</td>
<td>163</td>
</tr>
<tr>
<td>4-11</td>
<td>Cumulative distribution function of mean daily impeded times</td>
<td>163</td>
</tr>
<tr>
<td>5-1</td>
<td>Distribution of unimpeded block time residuals</td>
<td>183</td>
</tr>
<tr>
<td>A-1</td>
<td>Capacity coverage chart for New York LaGuardia Airport</td>
<td>191</td>
</tr>
<tr>
<td>A-2</td>
<td>Illustration of runway delay as a function of volume</td>
<td>196</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS

My greatest thanks go to my research advisor and dissertation committee chair, Professor Shashi Nambisan, who is a gifted teacher and an inspiring advisor. My research was far more productive as a result of his insights, encouragement, and support. My thanks also go to my dissertation committee co-chair, Professor Mohamed Kaseko, who helped me discover connections that were important in making sense of the data.

Committee members Professors Edward Neumann, Alan Schlottman, and Hualiang Teng asked the right questions and set high standards in their reviews of my proposal, dissertation drafts, and during my dissertation defense.
CHAPTER 1

INTRODUCTION

Research Background

The scope of the study covers U.S. domestic scheduled passenger air service between commercial service airports. U.S. domestic scheduled air service operates within the National Airspace System (NAS), under an air traffic management (ATM) system operated by the Federal Aviation Administration (FAA), an operating administration of the U.S. Department of Transportation. The United States is one of 190 Contracting States within the International Civil Aviation Organization (ICAO), which coordinates civil aviation standards and recommended practices globally.

Scheduled air transportation has three design attributes relevant to this research: safety, efficiency, and regularity (ICAO, 2005). Trip times that are longer and more variable in duration work against flight efficiency, cost more to operate, burn more fuel, and generate more atmospheric emissions (Kettunen et al., 2005). Travelers must spend more time in travel. Trip times that are too long and too variable add no value to the service provided, and thus meet the definition of waste (Ohno, 1988).

The requirement for scheduled air transportation is to provide a service that is safe, consistent, and dependable, with reliable trip times and delays managed within acceptable limits. High trip time variability and delay in the current system are driven by several factors. Historically, bad weather has been the major cause of flight delays, with the next
main cause the high demand relative to the capacity of the National Airspace System
(Government Accountability Office, 2005).

Flight delays have many causes: limited airspace and airport capacity in bad weather;
a requirement for aircraft to avoid severe weather; concentration of air traffic at airports
serving major metropolitan areas; air traffic demand peaking during certain periods; and
an airspace and air traffic management system that is inefficient in matching air traffic
demand with available capacity (Odoni, 1994). Goals for air traffic management system
modernization include shorter and less variable trip times, less wasted traveler time,
lower operating costs, and less jet fuel wastage (Mohler, 2006; NextGen, 2004). Current
five-year FAA planning emphasizes continuing safety, capacity, and environmental
improvement (FAA, 2008g). An FAA philosophy on delays is that "much delay could be
eliminated if the specific causes of delay were identified and resources applied to develop
the necessary improvements to remove or reduce the deficiency" (FAA, 1995).

Operation of the existing air transportation system in the United States has evolved in
a way that has for a long time tolerated waste and inefficiency in resource utilization
(Curtis, 1957; Thomas, 1963). Delay has been accepted as a tool for rationing capacity
and limiting demand (Howell et al., 2003). Delays in scheduled air service have three
consequences: travelers are inconvenienced, operations are less productive, and excess
fuel is burned (EUROCONTROL, 2008). During the operational day, delays tend to
propagate as late flight arrivals often lead to late departures (Schaefer and Millner, 2001).
Unless a flight can catch up or several flight legs are cancelled, delays are passed on to
the downstream flight legs that follow (Beatty et al., 1998).
The concept of delay used in this research follows from this definition: "Delay is the difference between constrained and unconstrained operating time" (FAA, 1995). However, in today's usage, delay is most commonly measured and reported as the difference between actual and scheduled trip times, rather than between actual and unconstrained trip times. In a system with adequate base capacity, there would be little practical difference between the two ways of measuring delay, since scheduled times would approximate unconstrained or unimpeded times (TRB, 2003). Under conditions of inadequate base capacity, saturation levels are approached more often. Capacity then interacts with sources of variability to produce large changes in delay (TRB, 2003). As delays increase, buffer time must be included in scheduled times to compensate for the higher likelihood of late flights. As a result, the difference between scheduled and actual trip times underreports the true extent of delay.

This dissertation will use the term "unimpeded" to represent unconstrained operating times. "Impeded time" is defined here as the difference between reported (or observed) time and unimpeded time. The use of the term "impeded" incorporates the fundamental concept of delay as the difference between constrained and unconstrained trip times.

Trip Time for Scheduled Flights

Trip time is defined, from a passenger viewpoint, as the elapsed time between the scheduled flight departure time and the actual flight arrival time. Trip time differs from block time, in that trip time includes any departure delay. Block time is defined as the sum of taxi-out, airborne and taxi-in times. Block time starts when the pilot releases the aircraft parking brake after passengers have been loaded and aircraft doors have been
closed; block time ends when the pilot sets the aircraft parking brake after arriving at the airport gate or passenger unloading area (BTS, 2008g).

Major U.S. scheduled airlines report their on-time performance for each scheduled trip operated. Flights that depart or arrive within 15 minutes after the scheduled time are considered to operate on time. A delay of 15 minutes or more for a flight departure or a flight arrival is reported as a delay.

A rule-of-thumb for system-wide on-time performance is 85 percent of arrivals or departures are to be within the 15-minute reporting grace period. An FAA performance target is to achieve an on-time arrival rate of 88 percent at 35 major airports by fiscal year 2011, and to maintain that rate through 2012 (FAA, 2008g). The FAA excludes from its count any delays not related to the operation of the National Airspace System (NAS) (FAA, 2007d).

Figure 1-1 shows graphically the role of schedule buffer time and how delays affect trip time and block time. Figure 1-1 is derived from Institut du Transport Aérien (2000). Scenario 1 illustrates how buffer time and the 15-minute reporting grace period work together to handle operational uncertainty. Scenario 2 shows an early arrival. Scenario 3 shows an on-time arrival within the 15-minute limit. Scenario 4 shows a delayed arrival.

Figure 1-1, Scenario 1 represents the times allocated to a scheduled flight. The three nominal (delay-free) components of block time are shown (taxi-out, airborne, and taxi-in). The sum of the nominal taxi-out, airborne, and taxi-in times can be assumed, for the purpose of this example, to be the expected block time. An airline must decide how much buffer time to add to the expected block time in order to meet its on-time objective. The required buffer time depends on trip time variability. The higher the variability, the more
buffer time must be added to maintain the on-time performance of a schedule.

Pre-taxi-out delays are shown in scenarios 2, 3, and 4 of Figure 1-1. These represent departure delays, and do not count as part of block time. They do, however, have an impact on travel time and airline costs, and are therefore included in the definition of trip time used in this research.

Source: Adapted from Institut du Transport Aérien, (2000)

Figure 1-1. Scheduled, early, on-time, and delayed arrival flights
Figure 1-2 shows the gate-to-gate (or “block-to-block”) cycle. The cycle starts with contracting, or agreement on a flight plan (flight trajectory) from origin to destination airports. This step may involve a "gate-hold" or departure delay, if for any reason, the airport and airspace systems are not ready to accept the flight, or the flight is not ready to leave. An aircraft may be held at the gate before receiving a clearance for pushback, to avoid long runway queues. Gate departure is followed by taxi-out, and takeoff. The aircraft then climbs to en-route altitude. The en-route part of the trip cycle may involve altitude changes. As the aircraft nears its destination, descent is followed by approach and landing. The aircraft then taxies to and arrives at the destination airport gate. “Turn time” or "gate turn" is the time the aircraft spends at the gate before the next cycle begins. An airport gate, in this study, is any location at which an aircraft is stationary and at which passengers embark or disembark the aircraft, at which baggage and cargo are loaded or unloaded, and at which the aircraft may be serviced and refueled for the next flight.

Figure 1-2. Air trip cycle and identification of OOOI times
The Context for the Research

A historical analysis of variability in scheduled air transportation needs to recognize the context in which civil aviation exists. The International Civil Aviation Organization (ICAO) sets standards and recommended practices for global civil aviation. ICAO was formed in Chicago in 1944, when 52 nations signed a Convention on International Civil Aviation. The Chicago Convention laid the foundation for a set of rules and regulations governing air navigation, which paved the way for a common worldwide air navigation system. ICAO today has 190 Contracting States (ICAO, 2008c).

ICAO requires its member nations to establish and monitor performance objectives (ICAO, 2007). In this respect, ICAO has identified 11 performance expectations for the design and operation of the future air navigation system. The 11 performance expectations include safety, security, environment, efficiency, cost-effectiveness, capacity, access, and equity, flexibility, predictability, global interoperability, and participation by the entire aviation community (ICAO, 2005).

Predictability is one of the outcome-based measures of performance of the air transportation system. According to SESAR (2007), predictability is "a flight performance measure which has both tactical and strategic dimensions." "Tactically, any horizontal, vertical, or speed variability, or any combination of these during a flight cycle will lead to low flight time predictability and will also have a negative impact on on-time performance and cost" (SESAR, 2007).

SESAR (2006) referred to predictability as "the ability of the future ATM system to enable the airspace users to deliver consistent and dependable air transport services." Predictability is associated with the ability of the ATM system "to ensure a reliable and
consistent level of 4D trajectory performance" (SESAR, 2006). "In other words, across many flights, the ability to control the variability of the deviation between the actually flown 4D trajectories of aircraft in relation to the Reference Business trajectory" (SESAR, 2006). The 4D trajectory concept, its past development, and requirements for effective 4D trajectory implementation in the future, are reviewed in Wilson (2007).

ICAO (2005) defined predictability as "a measure of delay variance against a performance dependability target." In the ICAO (2005) definition of predictability there is a statement that "conceptually, predictability metrics should be a comparison of the actual flight time to the scheduled flight time, since the scheduled flight time includes the amount of expected delay at a targeted dependability performance."

In this research, the use of the term "predictability" will be limited to flight times (airborne times). In reference to trip times, the term "variability" will be used.

ICAO (2005) introduced concepts of Required Total System Performance and Required ATM Performance. These are defined as criteria that must be met "in order to deliver the approved quality of service specified for a particular environment." The implications are: (a) that variability is a component part of the predictability key performance area; (b) that regulators will set performance criteria for predictability; and that (c) such performance criteria will be set based on an approved quality of service for a particular environment.

Within the ICAO framework, the United States and Europe have been leaders. The performance-based framework defined by the ICAO Global Air Traffic Management Concept (ICAO, 2005) and Global Air Navigation Plan (ICAO, 2007) houses two major research programs: the Next Generation Air Transportation System (NextGen, 2004)
program for the United States; and the Single European Sky ATM Research (SESAR) programme for Europe.

A design and operational objective for the future air traffic management system, according to the SESAR, is "to provide a quality of service which maximizes predictability and minimizes the amount of variability within the constraints of the available infrastructure" (SESAR, 2006). Both on-time performance and cost are related to predictability, in that these can be negatively impacted by "any horizontal, vertical, or speed variability" in an aircraft flight path (SESAR, 2006). Rapid travel, together with consistent and reliable travel times have been design goals throughout the one hundred year history of air transport. Introduction of reliable modern jet transport aircraft, air traffic flow management and system safety management 50 years ago have all helped. However, limited traffic handling capacity of the airspace and airport system has served as a constraint on meeting demand for more consistent air travel times at high safety levels. As delays have become endemic, delay performance measures that may once have been appropriate may no longer be so.

Technology has advanced to a level which has created the opportunity to redesign the global air transportation system for better performance. There is recognition that evolution to new systems requiring global adoption takes at least fifteen to twenty years, and that a performance and level of service orientation is necessary in the designing, planning, implementation, and operation of the future air traffic management (ATM) system.

A fundamental problem today is that the design and manufacture of modern aircraft have produced vehicles that are operationally reliable and efficient, but the system for
managing air traffic, while safe, has not evolved in a manner which supports acceptable levels of schedule performance. The air traffic management system is limited by two capacity-related factors: limits on runway capacity at major airports and the number of aircraft that can be safely handled by air traffic controllers. In the operation of the current system, delay is used as a tool for limiting demand to match available capacity. To the extent that long-term capacity growth is less than long-term demand growth, delays will inevitably increase, and uncertainty and variability in system performance will increase.

The iron law is that as the ratio of demand to capacity increases, delays increase disproportionally. Delay reduction involves a combination of increasing system capacity more rapidly than system demand, managing the system so as to bypass constraining choke-points, and a policy of maintaining the ratio of volume to capacity at levels that support an acceptable level of service. All these require effective performance measurement tools.

The present air traffic control (ATC) system evolved over three quarters of a century from the one that that was put in place in the 1930s. The operational characteristics and organization of the ATC system were determined largely by the technologies available and trusted in the past—radio for navigation, voice radiotelephony for air/ground communication, radar for separation and position fixing, and telephone and teletype networks for distributing information between ATC facilities. New technology—such as transponder beacons, microwave relays, and electronic data processing—was introduced over time, but these did not in any fundamental way change the essential characteristics of earlier generation of air traffic control—a ground-based, human-controlled, and centralized system that uses airspace in an inefficient and wasteful manner (Mills, 1982).
Although this research addresses the broader issue of trip time variability, the benefits of reduced trip time variability and increased flight time predictability are issues that require resolution as part of current ATM transformation programs. ATM transformation exemplifies the difficulties of developing very large, safe and highly reliable transportation systems in a period of technological change. The issues in the aviation system are complex and extend beyond national boundaries. Even though existing technologies are available to precisely locate aircraft positions and flight paths, and to communicate information throughout the system, deploying a new ATM system internationally involves issues of national sovereignty and governance that transcend system and engineering design considerations (Lewis & Witkowsky, 2004).

This research does not directly address the policy and political issues involved in transforming the U.S. aviation system. However, policy issues must be considered to the extent they impact on the economic and technical feasibility of attaining improved performance.

Need for and Purpose of the Study

Three considerations drive the need for this study: the first is that there is a coordinated global effort now underway to design and introduce into operation a new ATM system over the next 10 to 15 years; the second is that the social and economic costs of trip time delay and variability have not been adequately measured; the third derives from a lack of prior multi-year research on the performance of the existing scheduled air transport system with respect to trip time delay and variability.

The benefits of reduced trip times and trip-time variability are not broadly evident nor are they widely understood today. Delay and variability reduction are components of the
initiatives now underway to transform the air transportation and air traffic management systems. Without measurable criteria (such as social and economic costs), the benefits of reduced trip times and trip time variability will neither be evident nor understood. Assigning costs is necessary for setting program priorities for design, development and introduction into service of new concepts for air traffic management.

The study objectives were: (1) to develop a comprehensive database for individual major U.S. airline domestic trips between 1995 and 2005; (2) to explore the central tendency and variability of airline gate-to-gate trip times and delays; (3) to develop values for unconstrained, or unimpeded, trip times, and (4) to develop costs of delay and variability relative to unimpeded trip times, for both travelers and airlines.

The research methodology used reported trip times as a primary indicator, unimpeded trip times as a reference, and attached a cost to the excess of reported trip time over unimpeded trip time at the individual flight level. This approach represents a process for evaluating the time savings and operating cost impacts of initiatives for increasing capacity and reducing impedance in the system.

The U.S. Department of Transportation’s Bureau of Transportation Statistics collects and distributes individual trip on-time performance data for leading U.S. domestic scheduled airlines (BTS, 2008a). The research dataset is built on these BTS data for all scheduled trips performed by major U.S. airlines between 1995 and 2005. To get the most value from this data requires combining the five million annual records with other data, validating the data and cleaning basic data entry errors, and sequencing the data to identify trip chains. The research dataset allows trip time delay and variability to be quantified. The research dataset supports model development for classifying trip time
delay and variability. The study is aimed at identifying trip time delay and variability metrics and setting trip time performance goals.

Outline of the Dissertation

The dissertation continues with a review of related literature, the methodology, results and analysis of results, followed by conclusions and recommendations.

A summary of the literature reviewed is presented in Chapter 2. The literature review begins published research in air traffic management, airport capacity, and the value of reduced schedule variability. The literature review concludes with sections on delay and disruption costs, and airline operating costs.

Chapter 3 describes the methodology, starting with the data used in the research, and will describe the analytical approaches employed in the research. The main models that are developed are ground taxi and airborne unimpeded time and cost models.

Chapter 4 summarizes the results of the study. Chapter 5 presents the conclusions of the research and the recommendations for future study that follow from this research.

Appendix A examines patterns of delay and several probability distributions that fit delay patterns. Appendix B provides a description of Airline Service Quality Program (ASQP) data elements reported monthly for individual flights by major air carriers in U.S. domestic scheduled service. Appendix C provides a glossary of air traffic management terms.
CHAPTER 2

REVIEW OF RELATED LITERATURE

Introduction

This research reviewed literature in the following areas:

1. Air traffic management
2. Current system limitations and the basis for change
3. System performance goals
4. Airport surface traffic management
5. Airspace system capacity and throughput
6. Delay propagation
7. Delay and disruption costs to travelers
8. Delay and disruption costs to air carriers
9. Value of reduced schedule variability

Appendix A extends the literature review, examining patterns of delay, the relationship between congestion and capacity, and probability distributions that relate to variability of trip time and its components.

This chapter begins with a review of the literature on air traffic management in general, as context for the research, and continues with a review of the literature in the above areas. In this review of published literature in air traffic management and air
transportation, particular attention was paid to the handling of uncertainty and the application of probability distributions to represent uncertain events and outcomes.

### Air Traffic Management

The air traffic management (ATM) function incorporates the more limited function of air traffic control (ATC). The purpose of ATC is to provide for the safe and efficient use of airspace (Thomas, 1963). Air traffic control: (1) keeps aircraft safely separated while operating in controlled airspace—on the ground, during takeoff and ascent, en-route, and during approach and landing; and (2) provides pre-flight and in-flight assistance to all pilots (Kane & Vose, 1967).

Current FAA doctrine considers a process that will transition from air traffic control to air traffic management (FAA, 2008g; FAA, 2000h). The ATM function is designed for the “safe and expeditious” movement of air traffic (Litchford, 1969).

The objectives of air traffic management services are defined by ICAO as follows (Gilbert, 1973a):

- Prevention of collisions between aircraft in flight
- Prevention of collisions between aircraft in the maneuvering area of an airport and obstructions in that area
- Expedition and maintenance of an orderly flow of air traffic
- Provision of advice and information useful for the safe and efficient conduct of flights
- Notifying appropriate organizations regarding aircraft in need of search and rescue aid, and assisting such organizations as required
Early attempts to provide a semblance of air traffic control were based on simple "rules of the road" resulting from the European sponsored International Convention for Air Navigation in 1919. The United States formulated its first regulations relating to air traffic following the passage of the Air Commerce Act of 1926. By 1930, radio equipped airport traffic control towers were being established by some local (municipal) authorities. In 1933 instrument flying commenced, and by 1935 several airlines jointly established the first Airway Traffic Control centers to safeguard their aircraft against midair collisions. In 1936 this preliminary effort was transferred to the Federal Government, and the first-generation Air Traffic Control (ATC) System was born. This generation pioneered the development of ATC procedures, rules and regulations, the establishment of a nationwide ATC system for both civil and military air traffic, and certain new equipment and facilities. The advent of radar in the early 1950s marked the inauguration of the second-generation system, which carried on, expanded, and improved the accomplishments of the first generation, and brought into operational use radar and direct center/pilot communication capability. In the early 1960s the third generation came into being with the introduction of automation. Recognizing the need to develop a more comprehensive approach to solving the requirements of ever increasing air traffic volume, an upgraded third-generation system was postulated in 1969. The third/upgraded third generations merged during the 1970s. From this base, the ATC System transitioned to a fourth generation, which was defined during the first half of the 1970's, and implemented in the early 1980s (Gilbert, 1973b).

In the current air traffic management system, flight within airspace imposes certain operational and equipment requirements on airspace users. These involve adherence to
established rules and procedures designed to minimize the possibility of collisions. The ATM system functions as an arbiter. If several aircraft plan to fly in the same airspace at the same time, then ATM must make a decision. To prevent a collision, one or more of the aircraft will need to be diverted from its intended or predicted flight trajectory. The air traffic management system must be capable of looking ahead in time and space in order to deal with potential conflicts in advance.

Scheduled airline services operate with defined airport gate departure and gate arrival times. The system in which these services operate can be considered as a system of airport nodes, with links connecting airports. Almost from the time an aircraft leaves an originating airport to the time it arrives at a destination airport, scheduled flights today operate under the control of ground-based radar air traffic management network, with a surveillance system responsible for keeping aircraft separated from each other and from severe weather. Recognizing that the broad scope of the system within which aircraft operate, ICAO uses the term “CNS/ATM” (Communications, Navigation, and Surveillance/Air Traffic Management) to refer to the ATM system.

Historically, ATM and air navigation services (ANS) have been provided by governments or other public sector organizations. Governments have also maintained their responsibility for safety regulation and licensing of individuals and service providers. Scheduled air services, on the other hand, have been provided by airline companies operating as businesses. Direct or indirect user charges are imposed on aircraft operating in the system.

In recent years there has been a trend toward establishment of autonomous entities for national air navigation service providers (ANSPs). ICAO (2008b), in a survey of ANSPs
in 101 countries, reported that 44 percent had ANSPs operating as autonomous entities. There has been movement to separate operation of air navigation services from regulatory functions, with 75 percent of respondents to the ICAO survey reporting that ANSPs were separated from the regulator, "with more States planning to separate these functions" (ICAO, 2008b).

A major challenge in designing and operating the airspace system is the generally applied principle that the price of admission to the system should be reasonable and cost effective in relation to user needs. Flights in airspace fall into one of two basic operational classifications—Visual Flight Rules (VFR) and Instrument Flight Rules (IFR). These rules play a part in system functioning, and in required pilot and aircraft performance (Gilbert, 1973). Aircraft in scheduled airline service today operate under the more restrictive instrument rules. Scheduled flights do not in general have priority access to the airspace and airports, and must share airspace with other users, both IFR and VFR.

When traffic volumes approach capacity anywhere in the U.S. National Airspace System, ground-based air traffic flow management (ATFM) imposes delays on aircraft departures, holds aircraft on the ground at a departure airport, and also reroutes and holds airborne aircraft to balance immediate system link and node demand and capacity (Odoni, 1994; Chang et al., 2001; Pulugurtha & Nambisan, 2001a; Pulugurtha & Nambisan, 2001b; Kotnyek & Richetta, 2006).

Current System Limitations and the Basis for Change

The challenge of introducing new ideas and innovation in a complex high safety system such as the air traffic management (ATM) system is daunting. Coordination of government and industry development and investment in new systems, processes and
technologies represents a complex challenge. Agreement must be reached by consensus from a large number of organizations across the community in both the public and private sectors. Decisions involve interrelated technological, human factors, system performance, political, financial, societal and implementation considerations. Constant technological change makes for a moving platform and thus it is difficult to obtain consensus on implementation. The airline industry tends to resist investing in new technologies without government commitments, and correspondingly, government is reluctant to make long-term commitments under uncertainty and fragile consensus.

Reliance on ground radar as the primary basis for air traffic surveillance and safe separation will be inevitably be reduced over the next twenty years. Radar's main shortcoming is its imprecise ability to locate aircraft positions. Radar has no look-ahead capability. Radar reflects an aircraft's past track and location, and not the intended track and location at some time in the future. Notwithstanding these limitations, ground radar will remain in use for defense and security, and as a fall back sensor.

Promising system and engineering approaches exist for establishing and projecting aircraft location and intent, and for monitoring safe separation between aircraft. It is now technically feasible to reduce gate-to-gate times and trip time variability through more precise management and prediction of aircraft trajectories, with dynamic assignment of conflict-free paths through the network. As this transition occurs, randomness and uncertainty will be reduced, and trip times will become more deterministic.

A consensus of the design and concept of operations of the future system is evolving. Mohleji and Ostwald (2003) described a scenario for the evolution of a harmonized global system through 2020 and beyond. The concept in their paper is to distribute the
responsibility for separation between flight crews and ground-based ATM managers. Mohleji and Ostwald summarized the underlying concepts as: (1) gate-to-gate problem-free flight planning independent of look-ahead times based on aircraft self-delivery within defined time tolerances; and (2) increased delegation to the aircraft of responsibility for maintaining separation, including using “sense and avoid” capabilities to support what today is done under visual “see and avoid” conditions.

Two developments are forcing the pace for the United States. The first is ATM consolidation and modernization in Europe. Europe's airspace is more crowded than in the U.S. and is less efficiently managed. Existing ATM system architecture in Europe uses ground-based technologies and takes a national approach to ATM, as opposed to a Europe-wide approach. Europe is out of necessity moving from fragmented national ATM services to a unified European approach (European Commission, 2008). The European drive is to standardize and harmonize technologies and approaches as a foundation for using technology to build a single European ATM system to replace separate national systems. The second development is Asia's need to upgrade its ATM systems. China and India will make their own decisions about systems and architecture to accommodate air transport demand (Lewis & Witkowski, 2004).

The United States has supported the European imperative for change, as a way to accelerate the transformation of a unified global system to meet the shared requirements of North America, Europe, and Asia (Lewis & Witkowski, 2004).

Under United States law, the United States Government has exclusive sovereignty of airspace of the United States. Airlines operate under a federally-owned and operated ATM system. Separate from the airline operations management decision-making process,
air traffic management is the responsibility of the Federal Aviation Administration (FAA), the government agency responsible for air traffic control. The FAA Administrator is responsible for plans and policy for the use of the navigable airspace, and for issuing regulations or orders for use of the airspace necessary to ensure the safety of aircraft and the efficient use of airspace. The FAA Administrator prescribes air traffic regulations for the flight of aircraft (including regulations on safe altitudes) for: navigating, protecting, and identifying aircraft; protecting individuals and property on the ground; using the navigable airspace efficiently; and, preventing collision between aircraft, between aircraft and land or water vehicles, and between aircraft and airborne objects.

Airline schedules and trip times, however, are not under government control. The FAA has little direct control over airline scheduling. U.S. Legislation (Civil Aeronautics Act, 1938) since the 1930s has prohibited federal imposition of limitations which would restrict “the right of an air carrier to add to or change schedules, equipment, accommodations, and facilities for performing the authorized transportation and service for the development of the business and the demands of the service shall require.” This prohibition has been retained without substantive change in subsequent U.S. legislation.

Individual airlines independently decide on the amount of time to allow for each trip on their schedule, as well as time to allow between trips at each airport, in order to balance desired on-time performance, competitive published trip times, and efficient resource allocation. Given the statistical distribution (variability) of actual trip times, airlines build buffer time into their schedules in order to achieve an on-time performance rating, as measured by the U.S. DOT definition of delay. Under this standard, in effect since 1987, arrivals are “on-time” if they arrive at the destination airport gate within 15
minutes after the time published in the airline's schedule or listed in the computer reservation system (CRS). For departures, the 15-minute on-time definition applies to flights departing within 15 minutes of the published or listed departure time.

The FAA manages the flow of air traffic produced by airline schedules to match the available capacity of the air traffic control system and the airport network. Delays are a tool used by the FAA for managing capacity. The FAA air traffic flow management process trades off ground holding delays prior to takeoff and delays incurred while airborne. The FAA, however, has limited control over airline schedules. When the FAA needs to constrain demand, the boundaries between flight crews, airline operations management and air traffic management are addressed through a collaborative decision-making (CDM) process.

System Performance Goals

The setting of system performance goals is ultimately a matter of political choice. Regulatory agencies choose to set standards for safety in air transportation, just as we choose to accept reduced standards of safety in trade for convenience in other modes of transportation. Regulatory agencies have also chosen not to set standards for quality in schedule performance, allowing delay to become the de facto standard setting mechanism.

For scheduled airline service, DOT’s Bureau of Transportation Statistics (BTS) is the federal agency that tracks and ranks on-time performance of domestic flights operated by large air carriers. DOT’s Air Travel Consumer Report, released about 30 days after the end of the month, provides information on the number of on-time, delayed, canceled and
diverted flights. Airline on-time rankings also appear in tables accessible on the BTS Website (BTS, 2008a).

Leading U.S. airlines file a monthly On-Time Flight Performance (BTS Form 234), as prescribed by Title 14 of the Code of Federal Regulations, Part 234 (BTS, 2008c). Airlines have been required to report on-time trip performance to the BTS since 1987, coincident with the introduction of the 15 minute on-time standard. The reporting requirements were updated in January 1995 to include reporting of mechanical delays and in June 2003 to include details on flight delays by cause of delay.

In the United States, the 2025 vision of the Next Generation Air Transportation System (NextGen, 2004) initiative was originally conceived with goals to improve passenger transit time and trip time variability (domestic airport curb to airport curb time cut by 30 percent), and to reduce the impact of weather and other disruptions on system performance (95 percent [of scheduled aircraft operations] within 15 minutes of timetable) (Next Generation Air Transportation System, 2004). A European Commission goal for 2020 is 99 percent of all flights within 15 minutes of timetable (Knoerzer, 2006). Less variability in scheduled operations, especially in operations on high density routes and at high volume airports, is a recognized as one outcome in concepts now under consideration for modernizing global air transport operations.

Specific performance targets are not included in the ICAO Global Air Traffic Management Operational Concept (ICAO, 2005) or the ICAO Global Air Navigation Plan (ICAO, 2007). ICAO considers that “States and regions will choose initiatives that meet performance objectives, identified through an analytical process, specific to the needs of a State, region, homogeneous ATM area or major traffic flow” (SESAR, 2008).
The SESAR (Single European Sky ATM Research) program is the European air traffic management modernization plan. The SESAR definition phase, completed in April 2008, identified European ATM modernization activities through 2020, together with a detailed work plan for 2008 through 2013. The comparable U.S. program is the Next Generation Air Transportation System (NextGen, 2004) program, managed through a joint U.S. government program development office. NextGen and SESAR are both oriented toward performance-based operations. In defining “performance-based,” ICAO distinguishes between external performance (outcomes which correspond to expectations) and internal system performance (which relates to the functionality of ATM components and their collective contribution to required levels of external performance) (ICAO, 2005). In this dissertation, “performance-based” refers only to those outcome measures which relate to quality of service.

The SESAR program definition phase adopted specific capacity and performance outcome targets for the future European ATM system. Capacity targets were set at the ATM network level, and best-in-class declared airport capacity targets for visual meteorological conditions (VMC) and for instrument meteorological conditions (IMC) (SESAR, 2008).

The SESAR capacity targets envisioned a system capable of handling 3 times more air traffic than the current system, with airport best-in-class VMC capacities 20 better than current levels. For IMC, the best-in-class airport target was to reduce the gap between IMC and VMC capacity from 50 percent in 2008 to 20 percent in 2020.

Performance targets were set in each of the eleven ICAO key performance areas. In so doing, SESAR grouped three of the eleven performance areas as “quality of service”
areas: Efficiency, Flexibility, and Predictability. For these three areas, SESAR developed performance targets for the year 2020 (SESAR, 2007; SESAR, 2008).

The NextGen program has comparable capacity targets, but has not yet adopted a set of schedule efficiency, flexibility and predictability targets and objectives. ICAO considers the setting of specific system performance objectives in these areas to be a regional (European) or national (United States) responsibility.

The SESAR performance targets for 2020 follow:

Efficiency—The initial indicative SESAR Efficiency design targets address the actually flown four-dimensional (4D) trajectories of aircraft in relationship to their Initial Shared Business Trajectory (ISBT):

- At least 98 percent of flights departing on-time, with average departure delay of delayed flights not to exceed 10 minutes. On-time departure performance defined as actual off-block departure less than 3 minutes before or after the departure time of the Initial Shared Business Trajectory; delayed departure is defined as actual departure more than 2 minutes after the departure time of the Initial Shared Business trajectory.

- More than 95 percent of flights with normal block-to-block duration, with average severity of less than 10 minutes for out-of-normal (delayed) flights. Normal flight duration, for the purposes of flight duration efficiency, is defined as actual block-to-block time less than 3 minutes longer than that in the Initial Shared Business Trajectory; extended flight duration is defined as any flight duration 3 minutes or more longer than the Initial Shared Business trajectory block-to-block time.
• The gate-to-gate fuel efficiency occurrence target is less than 5 percent of flights with fuel consumption of more than 2.5 percent above the amount specified in the Initial Shared Business trajectory; for flights suffering additional fuel consumption of more than 2.5 percent, the additional average fuel consumption will not exceed 5 percent.

Flexibility—The initial indicative SESAR Flexibility design targets are:

• Of the scheduled flights requesting a change in departure time, no more than 2 percent (European-wide annual average) will suffer a delay penalty of more than 3 minutes (with respect to their requested time) as a consequence of the request.

• The average delay (European-wide annual average) of such scheduled flights (with a delay penalty of more than 3 minutes) will be less than 5 minutes.

• At least 95 percent (European-wide annual average) of the (valid) requests for full Reference Business trajectory (RBT) redefinition of scheduled and non-scheduled flights will be accommodated, albeit possibly with a time penalty (i.e., departure and/or arrival delay).

• Of the scheduled and non-scheduled flights with a successfully accommodated request for full RBT redefinition, no more than 10 percent (European-wide annual average) will suffer a delay penalty (i.e., departure and/or arrival delay) of more than 3 minutes (with respect to their requested time) as a consequence of the request.
• The average delay of such scheduled and non-scheduled flights with a successfully accommodated request for full RBT redefinition (with a delay penalty of more than 3 minutes) will be less than 5 minutes.

• At least 98 percent (European-wide annual average) of the non-scheduled flight departures will be accommodated with a delay penalty of less than 3 minutes.

• The average delay (European-wide annual average) of such non-scheduled flight departures (with a delay penalty of more than 3 minutes) will be less than 5 minutes.

• At least 98 percent (European-wide annual average) of the VFR-IFR change requests will be accommodated without penalties.

Predictability—The initial SESAR predictability design targets address the 4D aircraft trajectories to actually flown in relationship to their Reference Business Trajectories (RBTs):

• Arrival punctuality: less than 5 percent (European-wide annual average) of flights suffering an arrival delay of more than 3 minutes.

• Arrival delay: the average delay (European-wide annual average) of delayed flights (with a delay measuring more than 3 minutes) will be less than 10 minutes.

• Variability of flight duration (block-to-block): coefficient of variation less than 0.015 (meaning that, for a 100-minute flight duration, more than 95 percent of flights would arrive on-time, consistent with the defined arrival punctuality target of 3 minutes or less).
• Service disruption: reduce cancellation rates by 50 percent by 2020 and reduce diversion rates by 50 percent by 2020 relative to 2010 baselines (European-wide annual average).

• Delay propagation (knock-on effect): reduce reactionary delay by 50 percent by 2020 compared to a 2010 baseline and reduce cancellation rate by 50 percent by 2020 compared to a 2010 baseline (European-wide annual averages).

In setting these targets, SESAR uses the concept of a Shared Business Trajectory (SBT), which has a life-cycle, becoming more precisely defined as a flight approaches its time of departure. For a scheduled flight, the Initial Shared Business trajectory is available 24 hours prior to scheduled departure. The SBT switches to a Reference Business Trajectory (RBT) as soon as the SBT is communicated to the flight crew for execution, or is loaded in the aircraft avionics (SESAR, 2007).

The SESAR performance targets are conditioned on aircraft operator discipline in limiting the frequency of flexibility requests and providing ATM with sufficient lead time to determine how to handle requested changes (SESAR, 2008).

Airport Surface Traffic Management

Much of the variability in scheduled air service trip times is introduced before a flight takes off. Idris et al. (1998) described research efforts to identify the flow constraints that impede departure operations at major airports. They concluded that the runway system was the key constraint and source of delay, and that different airport configurations offered different opportunities to improve how aircraft were sequenced for departure. For
departure planning, Idris et al. (1998) used a short-term time horizon of a few hours, with emphasis on the last 30 minutes prior to takeoff. Their focus was on improving the departure efficiency of the runway and, downstream, of the airport's terminal airspace. Balakrishnan and Chandran (2007) also considered downstream flow constraints imposed by the terminal airspace, while recognizing that there were some constraints, such as ground delay programs (GDPs) at destination airports, that required consideration of constraints even further downstream.

Brooker (2008) compared the benefits and costs of the SESAR and NextGen programs. In evaluating their similarities, Brooker noted that both programs involved change from reactive ATM to anticipatory ATM. The basis for planning and system operations would become the aircraft 4D trajectory "which is the aircraft path, three space dimensions plus time, from gate-to-gate, including the path along the ground at the airport" (Brooker, 2008).

Brinton and Atkins (2008) note that today the gate departure time for a flight is one of the largest sources of uncertainty in the National Airspace System. Brinton and Atkins make the distinction that when gate metering is in effect, the relevant time is when an aircraft is ready to leave the gate and not the actual gate departure time. Gate metering or gate-hold policies attempt to avoid long runway queues by holding aircraft at their gates before clearing them for pushback. In this dissertation, the point made in Brinton and Atkins (2008) is an important one. It means that, while unimpeded taxi-out time can be measured and estimated, reported taxi-out times will underestimate the true time between readiness for gate departure and takeoff.
Andersson et al. (2001) estimated nominal, or unimpeded, taxi times by assigning an index to departing flights. The index was number of aircraft which took off while an observed flight was taxiing out on the aircraft surface. Idris et al. (2002) used a similar approach to estimating the number of departure aircraft present on the airport surface when the observed aircraft pushes back from the gate. These studies noted that there are interactions between surface arrival and departure flows, and that surface congestion and queuing can depend on the imbalance between the arrival and departure demand and capacity of the airport runway configuration.

Carr et al. (2005) used a dataset of $10^4$ airline turn operations to evaluate the accuracy of gate-out or pushback forecasts, concluding that airport surface traffic management must incorporate uncertainty in predicting pushback times. Carr et al. concluded that operational projections could not rely on predicted pushback times for turns. Instead, short term operational planning needed to be sufficiently adaptive to turn time variability. A problem discussed in Carr et al. (2005) was the assumption that random variables followed lognormal, Weibull, or inverse Gaussian distributions. These distributions were all characterized by long tails, but decay rates for these tails differed, yielding parametric predictions sensitive both to the choice of the distribution and the parameters of the model. A similar point is made by Castillo (1988), who emphasized the importance of accurately describing tail behavior in the analysis of extreme value distributions.

Pujet and Feron (1999) developed an approach, based on Pujet (1999), to modeling the departure process at Boston Logan International Airport, Using one year of operational data, Pujet and Feron used an empirical distribution for the travel time on the taxiway system from the terminal to the runway queue. They did not classify the
distribution. Their research accounted for different runway configurations in use, and different airline terminals at the airport, and produced estimates for emissions, fuel and time savings from gate-hold procedures.

Pujet and Feron (1999) expressed concern over two undesirable side effects of gate holding control schemes—gate shortage, and on-time performance statistics. The conclusions were that both issues were manageable, with their model showing that, on average, an airline would run out of gate capacity only 144 minutes over a year, and that only about two percent of pushbacks would be delayed more than five minutes.

Idris et al. (2002) identified taxi-out time as a greater source of uncertainty than airborne time. For a sample of flights at Boston Logan Airport, taxi-out time had a mean of 19 minutes and a standard deviation of 11 minutes, compared to 11 minutes en-route standard deviation and a mean on the order of hours. They showed that downstream restrictions had a larger impact on pushback delay than on taxi time, since affected aircraft were typically held at the gate. Idris et al. attempted to fit Gamma distributions to the distributions of taxi-out times as a function of the number of departure aircraft on the airport surface. However, they found that their model had a lower success rate than a model that mapped the empirical distribution.

In the context of the current research, several conclusions can be drawn from review of the literature. First, the largest source of trip time uncertainty today is the time between a flight's scheduled departure and the flight's takeoff time (Idris et al. 2002; Brinton and Atkins, 2008). Second, reported taxi-out time is an unreliable estimate of system-imposed departure delay when ground delay programs, ground stops, and gate metering or gate-hold policies are imposed (Brinton and Atkins, 2008). Third, in any system operating
with managed 4D gate-to-gate trajectories, there is an implication most delays will be taken prior to takeoff. After takeoff, adjustment will be mainly for spacing and for variation in weather, winds, and temperatures from values predicted at time of takeoff.

Airspace System Capacity and Throughput

Weitz, Hurtado & Bussink (2005) discussed a terminal-area operational concept developed by NASA that might improve system capacity and throughput. The concept, Airborne Precision Spacing (APS), uses an aircraft flight deck system to provide speed guidance to flight crews, as a means to achieve more precise spacing between aircraft at the arrival runway. This supports reduction of buffer space between arriving aircraft and increases runway capacity. According to Weitz et al. (2005), in the APS concept, “the maximum arrival rate is increased by implementing airborne managed spacing, which allows aircraft to space themselves relative to an assigned lead aircraft in the terminal area.” The ultimate goal is accurate self-spacing under low visibility conditions, a process that today can be used only under high visibility conditions. According to Weitz et al., “Accurate self-spacing can reduce the variability of threshold spacing errors, which are defined as the differences in the actual and desired spacing between aircraft pairs.”

One aim of current FAA and NASA research is the development of operational procedures to improve collaboration and decision-making between ground and flight resources for more efficient operations throughout the system.

Fellman and Topiwala (2006) discuss procedures that Air Route Traffic Control Centers (ARTCCs), in collaboration with airspace users, use for rerouting flights around severe weather and congestion. Their paper presents planning and development of systems for eventual incorporation in the Traffic Flow Management System (TFMS)
scheduled for deployment in 2008. Crook et al. (2007) take a longer view of collaborative air traffic flow planning. While optimistic about the long-term deployment potential for multiple-stakeholder and multiple objective flow planning, Crook et al. (2007) point out limitations in the current system that result in poor use of available resources. These limitations include legacy systems and architecture, inflexible airspace, procedural rules, and lack of collaboration among stakeholders. More significant, according to Crook et al. (2007) is the limited system level planning that currently exists for reconciliation of air traffic demand to available ATM, airspace and airport resources.

A recent advance is Automatic Dependent Surveillance-Broadcast (ADS-B) (Hull et al., 2004). ADS-B, now being implemented in the U.S. and other countries, represents a major step in phasing out reliance on ground-based radar, airborne transponders and voice controller-pilot communications for aircraft position tracking and control.

The need for better trip punctuality and an indication of the capability that technology offers for doing this has been expressed in the literature as follows:

“An urgent ATM problem is improved punctuality and delay reduction at congested airports. Gate-to-gate 4D flight planning could be a significant contributor to achieving these results. Improved punctuality should be flexible enough to cope with unexpected events. A significant 4D benefit would be the ability to plan a Required Time of Arrival (RTA), which together with central flow management, would manage capacity for punctual and undisturbed arrivals. The flow management system would receive regular updates from the aircraft 4D Flight Management System” (de Jonge, 2002).
Delay Propagation

Flight delays can be classified in two categories—non propagated delay and propagated delay. Propagated delay is the result of cumulative delay on prior flights which cannot be absorbed through scheduled slack. Lan et al. (2006) found that propagated delay represented 20 to 30 percent of total delay for one major airline. Boswell and Evans (1997) concluded that net delay for an aircraft due to an initial flight delay was about 1.8 times the initial delay.

A number of studies and dissertations are relevant to airline scheduling and air traffic management. Beatty et al. (1998) developed a concept of a delay multiplier (DM), which captured the value of succeeding delays on an aircraft's itinerary as a multiple of an incurred initial delay. Boswell and Evans (1997) analyzed flight routing data for the month of December 1993, employing BTS on-time (ASQP) data, to derive an estimate for the delay multiplier and to estimate the probability of flight cancellation as a result of late flight arrival. Wang et al. (2001) showed how delays along an aircraft itinerary could be analyzed analytically and simulated. Schaefer and Millner (2001) analyzed the effect of flight delays caused by poor weather, which propagated to other airports along an aircraft's itinerary. Wang et al. (2002) analyzed delay propagation at 30 of the busiest U.S. airports, using a good weather day in May 2001 as a standard for comparison.

The contribution of Wang et al. (2001) was a finding that airports along the itinerary operating at volume/capacity ratios of 50 percent or less can absorb delay without propagation. At higher volume/capacity ratios, delay can propagate beyond the ability of an airline's schedule and an airport to absorb it.
Wang et al. (2002) noted that flight departures generally do not leave before their scheduled departure time, and thus departure delays are seldom negative. Flight arrivals, in contrast, can be early or late. Wang et al. (2002) considered airport turn times in their analysis, as well as differences between airline turnaround and scheduling practices at different airports. They concluded that improving capacity at congested airports and “relaxation of flight connections during peak hours to reduce propagated delay” would help reduce arrival delay at airports.

The contribution of Beatty et al. was that the most significant effect on an airline's schedule resulted from control over delays early in the day. This minimized the delay multiplier. The interpretation of this finding is that, while congestion may create delays in the afternoon, the afternoon delays are amplified when the flight has been operating late since early morning.

Taking the findings of Wang et al. (2001) and Beatty et al. (1998) together suggests a need for future research into delay patterns of flights that meet both the following criteria: (1) the aircraft incurs delays early in its itinerary; and (2) the aircraft subsequently transits airports with high volume/capacity ratios.

Wang et al. (2003) developed a recursive model of delay propagation that separated the controllable components from the random components of delay (principally caused by variability in trip time and turn times).

Boswell and Evans (1997) developed a model that showed how operational delays on preceding flights could be partially absorbed along an aircraft's itinerary. Their model, however assumed that operational delays on any leg were independent of carryover delay on the previous leg. Boswell and Evans (1997) recognized that delays experienced at one
airport due to insufficient capacity might interact with delays at another airport with insufficient capacity and that the resultant delay experienced by a flight between the two airports would not be the sum of the individual delays.

Boswell and Evans (1997) considered, as one of their "seed distributions," a delay distribution obtained by combining the distributions of gate-hold delay, taxi-out, airborne, and taxi-in delay. Their data assumed that delays in each of these phases were independent. Boswell and Evans (1997) did not attempt to characterize the distribution, only presenting the shape of probability density function as a small histogram in a figure with three other candidate distributions. The shape of their distribution, however, clearly reflects the patterns of delay evidenced in the current research. Their results were derived on the basis of one month of 1993 traffic under late fall and winter weather conditions.

Delay and Disruption Costs to Travelers

Valuation of travel time has been extensively studied in the literature. Mackie et al. (2001) and Jara-Diaz (2008) provide surveys. Research on travel time reliability is less extensively reported in the literature. Van Lint et al. (2008) provide a critical review of both research and reliability measures. TRB (2003) reports on research on highway travel time reliability.

The value of small travel time savings to travelers has been the subject of a longstanding debate (Welch and Williams, 1997). Gunn (2000) reports on findings of past studies of subjective value of time studies, which appear to indicate that time losses are perceived to be more of a disbenefit than time gains, and that little value is attached to small short-run time savings of up to 3 minutes. Jara-Diaz (2008) distinguishes between subjective value of travel time (SVTT) and the social prices of travel time savings (SPT).
SVTT is defined as the amount an individual is willing to pay to reduce travel time by one unit. SPT is what society is willing to pay for projects financed with public money (Jara-Diaz, 2008).

The accepted standard in the U.S. for evaluating transportation time savings and costs is current U.S. DOT guidance on valuing travel time (DOT, 1997; DOT, 2003a). The DOT specifies value of time and procedures to be used for cost-benefit and cost-effectiveness analyses involving travel time saved or lost. The DOT values are prescribed for government analyses of investment in transportation facilities and transportation infrastructure. The DOT standards include both in-vehicle and out-of-vehicle time savings, with mode-specific values.

The 1997 DOT time values have been updated once (DOT, 2003a). The recommended DOT value of travel time savings for air travel is $28.60 (2000 U.S. dollars) per person-hour. This figure was derived from a 1998 survey of airline passenger incomes for “business” and “other trips,” indexed using U.S. median annual incomes from 1998 to 2000.

FAA (2007b) states that "these values are used by the FAA and are not to be updated for changes in price levels." The controlling authority for valuation of time is the Office of the Secretary of Transportation, which will provide periodic updates "using newly published source data upon which the recommended values are built" (FAA, 2007b). FAA (2007b) prescribes that the recommended values "should be used for all valuations, irrespective of the size of individual increments of time either saved or lost."

The DOT value of $28.60 per hour derives from weighting personal travel time at $23.30 per hour and business travel time at $40.10 per hour. Implicit in this weighting is
a mix of 68.5 percent personal travel and 31.5 percent business travel. FAA (2007b) states that "depending on data availability, the separate values for business and personal travel can be applied for travel time savings or losses experienced. Composite averages can be developed using weights characteristic of the specific application, or the air carrier value for all purposes may be used." The recommended values should be used "when considering investments and regulations that impact aviation from an overall perspective" (FAA, 2007b).

In addition to passenger delay costs, schedule unreliability and delay creates disrupted passengers. Disrupted passengers are those passengers whose scheduled flights are cancelled or who miss their connecting flights because of prior flight leg delays.

An airline view of schedule disruption follows:

“It seemed obvious to those that operate airline schedules that reducing a 60 minute delay to 30 minutes is much more valuable than reducing a 30 minute delay to zero. The question is: how does the value of initial delay reduction vary based on both the length of the initial delay and the time of day at which it occurs? It is important to note that, for an airline, the ‘value’ of delay is not just its effect on an individual airframe but its effect on the operating schedule. It is this schedule that is the primary product offered to the traveling public. Passengers do not go out to the airport to fly on a specific airplane or with a specific crew. They go to catch the two o’clock flight to Chicago which is promised in the airline’s published schedule. A significant part of the airline’s day-to-day operational effort is expended in the attempt to keep that promise” (Beatty et al., 1998)
The approach taken by U.S. DOT and prescribed for FAA use in cost-benefit analyses can be criticized when applied to flight delays. Hansen et al. (2001) point out:

“These approaches to delay cost estimation are based on strong assumptions that are rarely scrutinized or even acknowledged. These include that the cost of delay is an additive function of the cost of individual delay events, and that the cost of each event is a linear function of the duration of the delay (perhaps taking into account the phase of flight in which it occurs). Such assumptions ignore the possibility that delay cost is nonlinearly related to duration, subject to combinatorial effects, and includes sizeable indirect components.” (Quoted in Cook et al., 2004).

The literature contains approaches to delay evaluation which answer the criticisms put forward of Hansen et al. (2001). For example, Grignon (2002), proposed an arrival delay utility function similar to that shown in Figure 2-1.

The utility function, which Grignon credits to researchers at Boeing, produces small value losses for short delays. With increasing arrival delay, value initially decreases more rapidly. Once delay reaches a certain value, the utility value of a flight begins to decrease asymptotically. As Grignon writes, “Long delays may result in loss of customer goodwill and may lead to additional airline operational problems such as missed connections for passengers, crews and aircraft” (Grignon, 2002).
A nonlinear value-of-time component needs to be considered for evaluating the cost of long delays. This is beyond the scope of the current research, which uses a value of time appropriate to short delays, and for this purpose adopts the flat rate prescribed by U.S. DOT for use in regulatory analyses.

Disruption costs affect both travelers and airlines. Bratu and Barnhart (2006) concluded that flight leg delays do not accurately reflect delays for travelers on hub-and-spoke airlines. The authors used two different airline disruption models. The first model takes into account airline operating costs and disrupted passenger costs, while the second model takes into account airline operating costs and total passenger delay costs. In testing their model, the authors use an example an actual day for one airline in August 2000 with average levels of disruption. With an average delay per flight operated of 14 minutes, undisrupted travelers had an average delay of 14 minutes. However, passengers who missed their connecting flights (disrupted passengers) experienced an average delay of
262 minutes. Lan et al. (2006) performed a similar analysis and found that, on a day with adverse weather conditions, disrupted passengers were delayed an average of 419 minutes, compared to an average of 14 minutes for nondisrupted passengers.

While Bratu and Barnhart (2006) deal primarily with airline schedule recovery optimization in the event of crew absences, mechanical failures or bad weather, the insights are relevant to an appreciation of the costs that unreliable schedules impose on disrupted travelers.

Bratu (2003) compared the experience of 1995 (a year with BTS-reported 7.0 minutes average flight delay, a flight cancellation rate of 1.7 percent, and an average load factor of 66 percent) with that of 2000 (a year with BTS-reported 10.5 minutes average flight delay, a flight cancellation rate of 3.3 percent, and an average load factor of 71 percent), concluding that:

- There was a substantial increase in 2000 relative to 1995 in the number of disrupted passengers affected by flight cancellations or missed connections due to severe arrival delays
- There was degradation in airline recovery capability in 2000 as a result of the higher number of disrupted passengers and reduction in seats available due higher load factors

Schedule disruption can result from flight cancellations or from delayed operation of flights. Flight delays can be classified in two categories—propagated delay and nonpropagated delay. Propagated delay is the result of cumulative delay on prior flights which cannot be absorbed through scheduled slack. Lan et al. (2006) found that propagated delay represented 20 to 30 percent of total delay for one major airline.
Delay and Disruption Costs to Air Carriers

The structure of airline operating costs is well understood. This research values delay in terms of the short-term variable cost of aircraft operation. This section reviews the literature on airline costs, and introduces the "cost index," which applies an airline's estimate of its variable costs to aircraft in-flight operation.

From the early days of aviation, technological innovation has been rapid, and as more efficient aircraft designs have been introduced, a detailed knowledge of costs has been important to manufacturers, operators, and regulators. Phelps Brown (1936) reported on an engineering approach to the costs of air transport by M. Louis Bréguet, an early engineer and designer. Mentzer and Nourse (1940) published a pioneering study of air transport operating costs from an airline engineering point of view. Both these early studies were based on engineering cost equations. The U.S. Civil Aeronautics Board conducted the Domestic Passenger Fare Investigation, an extensive evidentiary proceeding (Civil Aeronautics Board, 1974) between 1970 and 1974 to determine the proper structure and level for cost-based schedule airline fares. NASA commissioned a detailed study of transport aircraft operating costs, performed by American Airlines with the support of the Boeing Company (American Airlines, 1978).

Later studies built on the earlier ones. Mentzer and Nourse (1940) was updated five times through 1967, when the U.S. Air Transport Association published its Standard Method of Estimating Comparative Direct Operating Costs of Turbine Transport Airplanes (ATA, 1967). When the ATA decided not to continue updating its study, the Boeing Company continued into the 1970s with updates (Van Bodegraven, 1990). Civil
Aeronautics Board (1980) represents an update of the standard costing methodology developed in the Domestic Passenger Fare Investigation.

Torenbeek (1982) and Isikveren (2002) questioned the ability of standard costing methodologies to reflect differences in airlines and aircraft sector mission criteria. Torenbeek (1982) noted that standardized methods "do not take into account of factors such as fleet size, fleet mix, route structure, actual winds encountered, variations in labor rate and fuel costs with time, etc., all of which can have a significant effect on costs and will vary from one airline to another." Isikveren (2002) investigated the effect of different flight speed and on direct operating costs, total operating costs and profit or return on investment generated. Isikveren also questioned the value of standardized costing methods that compared direct operating costs of aircraft with different productivity characteristics. Criticism by Torenbeek (1982) and Isikveren (2002) of total operating cost models, does not extend to consideration of the variable costs associated with different flight times and flight speeds. Both authors reach similar conclusions, however, about variation of costs with time. Torenbeek (1982) notes that fuel costs are minimum for the airspeed for maximum distance traveled per pound of fuel, and that increasing the airspeed results in increased fuel cost. Isikveren (2002) derives a cost function with three components–time dependent costs, fuel dependent costs, and ancillary parts.

The costing formulas in prior studies show that the variable costs of air transport operation are primarily flight crew, fuel, and maintenance expense. An element of confusion, however, in airline costing is created by the distinction that variable costs do not equate to the received definition of direct costs. Van Bodegraven (1990) points out that the convention of classifying airline costs as direct and indirect does not imply
variable and fixed costs. Airline direct costs, as historically defined, are those associated with operating an aircraft, and indirect costs are those of handling people and goods transported. Under this definition, flight crews are considered to be direct costs, and flight attendants are considered to be indirect costs. However, both flight crews and flight attendants represent variable costs of operation. Historically this distinction derived from the role of aircraft manufacturers in engineering costing. From a manufacturer's standpoint, any cost not involved in technical operation of an aircraft was not a direct cost of operating the aircraft.

This historical definition of direct and indirect costs is codified in the current U.S. DOT Uniform System of Accounts and Reports for airline traffic and financial reporting (BTS, 2008d). The misunderstanding that can be caused by this definition is evident in current FAA guidance on use of reported airline costs (FAA, 2007b), which lists direct costs derived from airline financial reports, then goes on to interpret these as variable operating costs.

Swan and Adler (2006) published an approach to estimating aircraft operating costs as a function of trip distance and seat capacity, based on engineering data, and using separate models for short- and long-haul aircraft. The authors, in agreement with earlier studies, concluded that a linear relationship exists between trip cost and distance. Swan and Adler used the concept of a cost frontier, which serves to drive the value of used aircraft values down to the level of the operating costs of the most efficient aircraft. Aircraft whose costs are even slightly above the cost frontier are economically uncompetitive. One of the implications of this observation is that there is constant and
intense pressure on aircraft designers, manufacturers and operators to innovate to reduce costs. This, in turn, requires operating costs to be well understood.

The integration of computers into modern aircraft has also driven the need to better understand the variable cost of aircraft operation. Liden (1992a; 1992b) defined a selectable "cost index" used in aircraft flight management system (FMS).

Liden (1992a) defines the cost index:

\[
Cost \text{ Index} = \frac{Non \text{ Fuel Variable Cost per minute}}{100 \times Fuel \text{ Cost per pound}} \quad \text{(in units of 100 lb/hr)}
\]

The CI is the ratio of non-fuel variable cost of operating an aircraft to the cost of fuel consumed. Flying faster burns more fuel, but reduces the time and nonfuel cost of traveling any given distance. Torenbeek (1982) suggests that for long-range aircraft the cost-economical cruise speed is close to the long-range cruise condition, while for short-haul aircraft it is close to the high-speed cruise condition.

Isikveren (2002) provides a theoretical derivation of a cost index (CI), citing an earlier study by Boeing (1990), showing that the CI is "independent of sector distance, the mission characteristics of payload, and ambient conditions." The aircraft FMS can solve this as a nonlinear optimization problem, given as input a variable cost for operating the aircraft and the unit cost of fuel. Additional information on the airline cost index is reported in Burrows et al. (2001), Airbus Industrie (1998), Fuller (2004), and Roberson (2008).
In the numerator of the cost index, Burrows et al. (2001) conclude that only direct costs which relate to either speed or time are relevant to the CI. These include the variable component of flight crew, flight attendants, and maintenance.

Airbus Industrie (1998) provided a study for its customers on the application of the cost index. The non-fuel variable cost components included flight crew, flight attendants, hourly maintenance cost, plus marginal depreciation or leasing costs. The Airbus Industrie study also noted that "extra cost may arise from overtime, passenger dissatisfaction, hubbing or missed connections," and that the cost index could incorporate such costs. Airbus Industrie (1998) cited 12 cases of airline cost index application. From these, the following cost ranges were suggested for Airbus A320 aircraft:

| Table 2-1 Estimated non-fuel Airbus A320 family variable operating costs |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Hourly maintenance              | $3              | $7              | $4              | $8              |
| Crew cost                       | 5               | 10              | 6               | 12              |
| Time-related cost               | $8              | $17             | $10             | $20             |

Source: Airbus Industrie (1998), with costs escalated to 2005 levels using GDP deflator

Fuller et al. (2004) note that airline operating cost drivers are mainly a function of fuel burn per unit of time, affected by "wind, speed, altitude, aircraft weight, and vertical profile." Time is a function of "distance, speed, air traffic flow management constraints, and the value of operating costs varying with time" (Fuller et al., 2004). The parameters
involved in airline flight efficiency "can be summarized into a relatively simple indicator," the cost index (Fuller et al., 2004).

Cook et al. (2008) presented an analysis of the airline cost index. "The cost index is a parameter set in the cockpit, which determines how the flight management system (FMS) will direct the aircraft" (Cook et al., 2008). The cost index incorporates an airline's own assumptions about the valuation of one minute of incremental trip time, and thus data on in-use cost indices for different aircraft types an airlines would be useful as cost reference data in the current research. Airline cost indices, however, are proprietary. Cook et al. (2008) provide some discussion as to how cost indices are set for specific aircraft.

Roberson (2007) presents an evaluation of the optimal cost index for B-737 and MD-80 aircraft at a U.S. airline. The optimal cost index was calculated by the airline to be 12 for the B-737 and 22 for the MD-80, with the cost index equation expressed as the ratio of non-fuel cost per hour divided by fuel cost in cents per pound. Assuming that the evaluation was performed in 2006, when domestic fuel cost was about 30 cents per pound, Roberson's figures represent a variable cost of $6 per minute for a B-737 and $11 per minute for an MD-80.

Examining delay costs in general in a European context, Cook et al. (2004) evaluated costs borne by airlines for each minute of ground or air delay. Their study used European and U.S. experience to conclude that a network marginal cost of €72 per minute should be applied to delays of over 15 minutes, for a 100-seat reference aircraft. The authors selected 15 minutes as the value to be modeled for short delays, and 65 minutes as the corresponding value for long delays. The study included consideration of schedule
variability (variance), schedule buffer times for delay absorption, and different treatment of airborne and ground delays.

FAA (2005a) used an average airline non-fuel variable operating cost of $1,364 per block hour (in 2005 dollars) to evaluate the regulatory impact of a rulemaking procedure for congestion management and delay reduction at Chicago O'Hare International Airport. This cost exclude fuel costs of airborne operations, and assumed an average aircraft seat capacity of 104 (FAA, 2005a). Adjusting the $1,364 cost for the larger reference aircraft size in the current research (132 seats) yields an estimate of between $1,600 and $1,700 per block hour for non-fuel variable operating costs.

Table 2-2 shows values used in two regulatory evaluations performed in 2008 (FAA, 2008c; FAA, 2008d), gave average variable costs per block hour for standard jet operations by "legacy" air carriers. The regulatory evaluations did not state how these values were derived.

<table>
<thead>
<tr>
<th>Legacy air carrier cost per block hour and seats per departure</th>
<th>Cost per block hour $2007</th>
<th>Average Seats per departure</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFK Airport</td>
<td>$4,465</td>
<td>168</td>
</tr>
<tr>
<td>LaGuardia Airport</td>
<td>3,428</td>
<td>141</td>
</tr>
<tr>
<td>Newark Airport</td>
<td>3,462</td>
<td>141</td>
</tr>
</tbody>
</table>

Source: FAA (2008c) and FAA (2008d)

Schedule disruption can result from delayed operation of flights or from flight cancellations or diversions. Shavell (2000) estimated that total disruption costs were $1.83 billion in 1998 for the domestic operations of the 10 major U.S. airlines, about half
attributable to flight cancellations and half to flight delays. For those airline flights diverted in flight to a different airport, Jenkins and Cotton (2002) found that airline costs per diverted flight ranged from $20,700 to $29,100 for narrow-body aircraft, and $89,400 to $181,800 for wide-body aircraft (Jenkins & Cotton, 2002).

DOT (2000) quoted air carrier estimates of the cost of a cancelled flight ranging from $3,500 to $6,684. This estimate includes direct costs such as flight crew salaries, but exclude costs associated with: (a) lost revenue; (b) paying passenger hotel costs or meals; (c) reimbursement and travel certificates for future travel, (d) the cost of paying other carriers to take stranded passengers; and (e) the potential for future lost revenue (DOT, 2000).

EUROCONTROL (2005b) developed recommended standard values for cancelled and delayed flights of €6,380 and €4,552 respectively. The equivalent cost in 2005 dollars would be $5,500 and $3,900, after applying an exchange rate of 0.82884 dollars per Euro (EUROCONTROL, 2005b) and a GDP deflator of 95.79. The EUROCONTROL costs for cancelled flights "should be treated only as a rough estimate" (EUROCONTROL, 2005b).

The cost of a diverted flight assumes that 50 minutes of time are lost, and were derived by adding the cost of 50 minutes additional flying to the cost of 50 minutes lost time for 43 passengers (EUROCONTROL, 2005b). Diversion costs were updated in EUROCONTROL (2007a), with average diversion costs for continental flights valued between €1,000 and €7,000, and intercontinental flight diversion costs valued between €5,000 and €55,000 (EUROCONTROL, 2007a).
EUROCONTROL (2007a) developed standard inputs for cost benefit analyses, using 2006 data. Typical values for cancelled flights were increased to €15,000 for 120-seat narrow body aircraft, and to €70,000 for 400-seat wide body aircraft on intercontinental flights. These costs are were supplied by airline members of the SESAR evaluation team, and apply to cancellation on the day of operation. They include service recovery costs (telephone, hotel passenger vouchers, drinks), interline (passenger rebooking costs), passenger delay value, and differences in operational costs. Not included are: ground handling costs; missed connection compensation; and baggage delivery costs (EUROCONTROL, 2007a).

Scholz (1998) developed estimates for delay and cancellation costs using methodology developed by American Airlines (1978), updated with data from Airbus Industrie and Lufthansa. His methodology calculated delay costs (restated here in 2005 dollars for an aircraft with 132 seats) of $160 for 16 to 29 minute delays, $405 for 30-59 minute delays, and $1,882 for delays exceeding one hour.

Cook et al. (2004) used European airline data to estimate the cost of delayed passengers to airlines. Their estimate was €0.30 per passenger per delay minute per flight. Included in this figure are both the hard costs of passenger compensation and rebooking and the soft costs of potential lost revenue. Data provided by one airline estimated that potential lost revenue comprised 60 percent of the total passenger delay cost.

Odoni (2000) provides a different perspective on the costs of delays. In response to delays, airlines lengthen their scheduled block times on congested routes. "They have been forced to do this in order to maintain schedule reliability and reasonable 'on-time'
performance, but they are paying a high price, in return, in terms of reduced productivity of their equipment and human resources" (Odoni, 2000).

Value of Reduced Schedule Variability

In this area, the literature was surveyed to discover research results identifying cost savings and productivity gains from reduction in excess time and trip time variability.

Cook et al. (2004) estimated the opportunity cost of buffer time as broadly comparable to per-minute cost of short (15 minute) at-gate delays. They estimated this to be €15 per minute for a Boeing 737-300 aircraft.

The EUROCONTROL performance review report for 2005 provides an estimate of €49 for each additional minute of "strategic" schedule buffer time for an A320 aircraft (EUROCONTROL, 2005a). A strategic buffer, in this usage, is defined as the additional time that an airline builds into its schedule in anticipation of uncertainty. The higher the expected trip time variation, the more buffer time is needed and the more costly it becomes as more resources are required to maintain flight schedule integrity (EUROCONTROL, 2005a). For European operations, an estimated saving of €1 billion annually would be produced through a five-minute reduction for 50 percent of airline schedules (EUROCONTROL, 2005a).

Wu and Caves (2000) investigated the relationship between flight schedule punctuality and aircraft turnaround efficiency at airports, without assigning any specific cost per minute of buffer time. They used data collected from a single European airline in 1999 to study the effect of buffer time in the tradeoff between airport turnaround time and schedule punctuality. Based on estimates aircraft operational costs, passenger delay costs and airline opportunity costs, using a model to simulate aircraft turnaround
performance, Wu and Caves derived estimates of optimal buffer times. Broad costs estimates were used by Wu and Caves (2000) in their turnaround model, "due to the unavailability of detailed cost break-downs with respect to aircraft types and sizes from published information."

Marginal delay costs for aircraft and passengers were assumed to be constant with respect to time. Starting with aircraft delay cost values found in the literature, Wu and Caves (2000) considered hourly aircraft operating cost, along with opportunity cost. A linear marginal opportunity cost function was used to assign a cost to buffer time, representing the "marginal hourly operating profit of an airline." Wu and Caves recognized that when schedule time savings become sufficient for an aircraft to perform additional revenue flying, the opportunity cost of schedule buffer time would be higher. Wu and Caves, however, confined their analysis to short buffer times, and did not explore the tradeoff between buffer time and aircraft revenue flying.

The research by Wu and Caves (2000) required development of probability distributions for aircraft arrivals, ground handling times and departure times. Wu and Caves selected the Beta distribution to model arrival punctuality against scheduled arrival times, partly for reasons of analytical tractability.

Howell et al. (2003) reviewed prior studies, and analyzed en route inefficiency changes for different traffic levels. They describe several models to calculate inefficiency estimates. In their paper, they describe limitations in airspace system models, and express a need for improving the cross-comparability of benefit estimates, together with the need for a framework that provides the ability to validate models by comparing calculated values with actual data under actual conditions.
Wu (2005) analyzed airport turnaround operations and used two simulation models, an en route model and an airport turnaround model, to develop an understanding of delay propagation and its impact on schedule reliability. Wu used an approach combining a Markov Chain algorithm and discrete event simulation in his turnaround model, using statistical data from an unspecified European airline to calibrate the model. Wu considered uncertainty in trip times and turnaround times, but did not specify the probability models that he used.

Shorter travel times and reduced travel time variability both have value. In economic justification of transportation projects, the value of time savings often has the same order of magnitude as the value of estimated direct economic benefits. Review of the literature in this area suggests that the main value of reduced trip time uncertainty derives from reduced buffer times and the consequent availability of aircraft for other revenue service. However, buffer times are determined both by trip time variability and the probability distribution of trip times. The little research that can be found in the literature connecting buffer times with trip time distributions has not sustained additional research.

Gaps Addressed by this Research

The result of this literature review has shown that the value of reducing trip time uncertainty is often mentioned but little studied in published research. There are four foundation elements missing in prior research:

1. Delay has not been measured with reference to uncongested or delay-free times. Delay measured with reference to scheduled times is appropriate for consumer reporting, but is not a very useful measure for monitoring system performance.
2. Available data have not been presented in a form that supports analysis of trip time variability and uncertainty. As a consequence, the variability and statistical distribution of airline delays in scheduled service have not been adequately explored.

3. Lacking elements 1 and 2 above, objective and quantitative criteria have not been applied to value the travel time and cost impact of delays.

4. Without a body of work in the literature on delay variability, delay distributions, and the cost impact of delays, published research on the costs and value of reducing trip time variability has been limited.

The current research presents a way to describe trip time delays compared to uncongested times, to represent trip time variability in the form of probability distributions, and to assign values for traveler time and airline delay costs of delay. This provides a foundation for future research on: (1) the relationship between reduced schedule variability on the one hand, and quality of service and productivity on the other; and (2) evaluation and prioritization of alternative methods for reducing trip-time variability.
CHAPTER 3

METHODOLOGY

Research Methodology

This chapter presents the methodology for development of the research dataset, determining the elements of unimpeded trip time, estimating of the distribution of delays, and applying a costing methodology appropriate to valuation of trip time variability. This research examined three areas: (1) patterns of trip time variability in the U.S. domestic air transportation system between 1995 and 2005; (2) an approach to determining unconstrained, or unimpeded, trip times; and (3) costs of delay and variability relative to unimpeded trip times, for both travelers and airlines.

The research used U.S. Department of Transportation (U.S. DOT) data for scheduled domestic airline trips reported by major U.S. air carriers between 1995 and 2005. For valuing air carrier cost savings, this research estimated variable costs for individual trips based on individual carrier financial reports to U.S. DOT.

The methodology used in this research covered seven main steps:

1. sourcing ASQP data
2. developing and validating the initial ASQP database
3. combining airline ASQP data with other data into a research dataset,
4. estimation of unimpeded trip times for individual flights and routes,
5. estimation of impeded trip time, comparing reported trip times to unimpeded times,
6. evaluation of probability distributions that could characterize delays and impeded trip times, and,
7. assignment of costs to delays.

Data Sources

The dataset in this research consists of airport-to-airport times for all scheduled trips by major airlines (those with more than one percent of U.S. domestic scheduled passenger revenues) between U.S. airports over the most recent eleven-year period for which consistent data were currently available (1995-2005) when this research was initiated. Development of the data set in this research has represented a significant part of the time and effort spent in the overall research.

Part 234 of U.S. Department of Transportation (U.S. DOT) regulations requires major U.S. airlines to submit scheduled flight performance data to DOT, as Airline Service Quality Performance (ASQP) reports (BTS, 2008c). These data are used to monitor each carrier's on-time performance and to provide information to consumers. The scheduled flight performance data are filed electronically (BTS, 2008g).

Major U.S. domestic airlines have been required to report flight delays to U.S. DOT since 1987. In 2000, federal legislation (AIR-21, 2000) was enacted, expanding the reporting requirement. Under this and earlier legislation, the purpose for collecting this data is “to explain more fully to the public the nature and source of airline delays and cancellations.” Since the passage of AIR-21 (2000), Congress has continued to express concern that the U.S. DOT needs more accurate data to better understand gate, tarmac,
and airborne delays. The current research is an example of the advanced uses which this data can serve.

ASQP reporting requirements are defined in the Code of Federal Regulations, Title 14, Part 234 (BTS, 2008c). The Office of Airline Information in the Bureau of Transportation Statistics maintains and publishes ASQP reports. Airlines with one percent or more of total domestic scheduled service passenger revenues are required to report individual flight data at any airport in the 48 contiguous United States which accounts for one percent or more of U.S. domestic scheduled service passenger enplanements. The reporting airlines have all elected to report their total domestic system operations. The data elements include flight times and (starting in 2003) causes of delays.

BTS collects ASQP information and publishes information summary monthly tables and detailed individual flight data online. Airlines report within 15 days and BTS generally releases the data within 30 days after the end of the reporting month. The basic table format has been stable since 1995. Flights are counted as delayed for departures when they leave the airport gate 15 minutes or more after scheduled departure time, and for arrivals when they arrive at the airport gate 15 or more minutes after scheduled arrival time.

Between 1995 and 1999 there were ten reporting carriers. With the growth in partnerships between major airlines and regional airlines, the number of reporting carriers grew to 20 by 2005 and remained at 20 in 2006 and 2007. Together the reporting airlines accounted for about 90 percent of U.S. domestic passenger revenues. ASQP data do not contain any information on the operations of smaller air carriers, commuters, air taxis, or on general aviation, cargo, military and international flights.
The fields in individual records in the BTS tables include origin and destination airports, flight number, tail number of the aircraft performing the flight, scheduled and actual gate departure and arrival times, whether the flight was cancelled or diverted, taxi-out and taxi-in times, actual takeoff and landing times, air time, and non-stop distance. Although ASQP data include aircraft tail numbers, they do not directly provide any information on the aircraft type used for a flight.

The primary ASQP data elements are the airline-reported actual ground and flight movement times for each flight: gate departure ("out"); takeoff (wheels-off or "off"); landing (wheels-on or "on"); and gate arrival ("in"). These are often called "OOOI" times. Gate departure and gate arrival times are defined by the time of release or setting of the aircraft parking brake. Most large airlines use a common service provided by Aeronautical Radio, Inc. (ARINC) to automatically report these times. This service is the Aircraft Communication Addressing and Reporting System (ACARS), which automatically transmits OOOI information to the airline.

In the Year 2000, 10 carriers met the reporting requirement threshold. In 2000, according to Tu et al. (2008), “American, Northwest, United, and US Airways used ACARS exclusively; Continental, Delta, and Trans World Airlines used a combination of ACARS and manual reporting systems; and America West, Southwest, and Alaska Airlines relied solely on their pilots, gate agents and/or ground crews to record arrival times manually.”

Since the ASQP data tables contain scheduled ground and flight movement times for each flight, ASQP is able track performance and delays by phase of flight. The most
important individual information elements currently reported in the ASQP database for individual scheduled flights are:

1. Airline and flight number
2. Date and day of week
3. Flight origin and destination and origin-destination great-circle statute mileage
4. Tail number assigned to the aircraft performing the flight
5. Computer Reservation System (CRS) scheduled arrival and departure time for each scheduled operation of the flight.
6. Actual airport gate departure and arrival times.
7. Actual wheels-off and wheels-on times.
8. Minutes of departure delay.
9. Minutes of arrival delay.
10. Whether the flight was canceled or diverted
11. Causal code for cancellation.
12. Minutes of delay attributed to the air carrier.
13. Minutes of delay attributed to extreme weather.
14. Minutes of delay attributed to the National Airspace System (NAS).
15. Minutes of delay attributed to security.
16. Minutes of delay attributed to a prior late arriving aircraft.

The most recent significant change in ASQP reporting in the 1995-2005 period occurred in June 2003, when airlines began reporting information on causes of delays in five categories, and cancellations in four categories:
- Air Carrier: The cause of the cancellation or delay was due to circumstances within the airline's control (e.g. maintenance or crew problems, aircraft cleaning, baggage loading, fueling, etc.).

- Extreme Weather: Significant meteorological conditions (actual or forecasted) that, in the judgment of the carrier, delayed or prevented the operation of a flight (e.g. tornado, blizzard, hurricane, etc.).

- National Aviation System (NAS): Delays and cancellations attributable to the national aviation system that refer to a broad set of conditions: non-extreme weather conditions, airport operations, heavy traffic volume, air traffic control, etc.

- Late-arriving aircraft: An aircraft arrived late, causing that aircraft’s subsequent flight to depart late. (This cause is reported for delays, but not for cancellations).

- Security: Delays or cancellations caused by evacuation of a terminal or concourse, re-boarding of aircraft because of security breach, inoperative screening equipment and/or long lines in excess of 29 minutes at screening areas.

The ASQP tables also include secondary information, such as airport names, state codes, world area codes, time of day codes, calendar quarter, and whether a flight departed and arrived “on-time” or not.

Although older ASQP information is available, data prior to 1995 are inconsistent with later data. Between September 1987 and December 1994, flight delays or cancellations resulting from mechanical problems were treated differently in airline reporting. If a mechanical problem caused a flight to be late or canceled, the flight was not reported. Thus, prior to 1995, some flights shown as CRS scheduled flights were
missing in ASQP. This means that the proportion of pre-1995 flights operated on time cannot be determined from ASQP data.

Since January 1995, all flights shown in the airlines' CRS have been listed in ASQP. This includes canceled and diverted operations, as well as flights affected by mechanical delays. BTS computation treats canceled and diverted operations as late flights, although they are not counted in the calculation of average or median minutes late. ASQP counts gate arrival as "on-time" if it occurs less than 15 minutes after the scheduled arrival time. However, since canceled and diverted flights have no arrival time benchmark, they do not count in the calculation of "on-time average minutes late."

For the purposes of this research, there is no need to classify flights as either “on-time” or “late.” Delay time in minutes (the difference between actual departure or arrival time and scheduled departure or arrival time) is a better indicator, since ASQP reports both scheduled and actual departure and arrival times, and since the main interest in this research is the ability to analyze the statistical distribution of trip time components.

Database Development

There were three areas in which value was added through creation of the research dataset: (1) validation of data accuracy; (2) linking consecutive flights into trip chains (“flight strings”) by tail number, with the associated aircraft model number, version and date of manufacture; and (3) database design and construction allowing relatively straightforward relational joins (cross-references) with other airport, airline, aircraft specific, and derived data.

In this research, seven steps were needed to process the raw BTS data and to develop a consolidated research dataset:
• Downloading and extracting BTS ASQP on-time data
• Conversion of local times to UTC times
• Merging aircraft make, model and date of manufacture into the dataset
• Merging airline T100 data from BTS into the dataset
• Resolving inconsistencies and validating data
• Developing trip chains and gate turn times
• Building dataset files for analysis

These steps are shown in Figure 3-1. To support these steps, aircraft type and model database was developed for aircraft tail numbers identified in ASQP reports. BTS T100 airline traffic reports were used to develop monthly traffic data for the all ASQP origin-destination pairs by airline and aircraft type.

As part of the comparison of ASQP data with T100 data, a check was made of the relationship of ASQP data to T100 data. For the 11-year period, total passengers in the ASQP dataset represented 78.2 percent of U.S. domestic and international passenger arrivals in T100 reports (including passengers traveling on both U.S. flag and foreign flag international carriers). ASQP weighted arrivals represented 75.7 percent of T100 weighted arrivals (including both U.S. carrier and foreign carrier weighted arrivals).

BTS ASQP data were reviewed for consistency and accuracy, and data from other databases, including T100 data, were incorporated in the research dataset. The amount of raw data and the reliance on self-reporting and airline own-data validation led to concerns about data quality and errors and omissions in reporting. This research did not conduct an independent validation of the accuracy of ASQP data. Andersson et al. (2001) reported on an earlier study (Delcaire & Feron, 1998), based on visual observations at Boston
Logan airport, which confirmed the accuracy of ASQP recorded push back times.

Andersson et al., in their study, also validated ASQP takeoff and landing times against high resolution timed radar tracks at DFW International Airport, finding that the ASQP records closely matched the radar-generated takeoff and landing times.

Figure 3-1. Dataset development process flowchart

Studies using ASQP data during the 1995-2000 period were based on a 10 reporting major airlines. With the expansion of regional airlines in 2000-2005, the reporting airline
population doubled to 20 by 2004 and remained at 20 reporting airlines in 2005. The introduction of new reporting airlines introduced problems of misreported data. A requirement in this research was to support trip chaining and airport turn times. The complete 1995-2005 dataset was therefore analyzed for internal consistency.

Before BTS data was extracted, a program (written in C/C++) was used to review raw BTS data for consistency and accuracy. Missing data fields (mainly schedule times) were imputed from reported actual departure and arrival times and reported departure and arrival delay values. Some missing data, such as airport-to-airport mileages, were obtained from other publicly-available BTS, FAA, or other federal government databases. Validity checks were applied in downloading and extracting data in step 1, and also after merging aircraft data and T100 data.

The second step shown in Figure 3-1 involved conversion of local times to UTC, and verification that calculated elapsed times matched those reported. The BTS report contains redundant data. In most cases, elapsed times between events are reported, in addition to the time of each event. For example, elapsed airborne time in minutes is a data field for a flight, but the times associated with the events of wheels-off and wheels-on are also included in the flight data record. Elapsed times were considered to be temporary variables necessary for data validation. After validating the data, when the size of the dataset became a problem, elapsed times did not need to be stored, since these could be calculated directly from UTC event times.

The third step and fourth steps shown in Figure 3-1 involved merging of aircraft data associated with the registration numbers reported in the ASQP data, and in associating
the average monthly passengers and seats per segment with ASQP flights operated on a specific segment during the same month.

In step 3, airline-reported tail numbers in ASQP (for the individual aircraft assigned to specific flights in the database) were matched with FAA aircraft registry numbers and with other sources of aircraft registration data. In some cases, airlines reported their own assigned aircraft numbers rather than the aircraft registration number. There are between 3,000 and 4,000 active aircraft identification numbers (tail numbers) in the database at any time, with over 10,000 unique numbers reported over the 1995-2005 period. The research dataset identifies specific aircraft types and model numbers, and also, from the FAA aircraft registry and other sources, identifies the an estimate of the date of manufacture or initial entry into service of each aircraft.

Step 5 in Figure 3-1 represents additional testing for validity checks. New tables were developed for inspection and analysis of rejected data. The validity checks included flights with time discrepancies (e.g. a reported wheels-off time prior to the gate departure time), times that appeared unreasonable (e.g. outlying airborne times or taxi times). Some missing data fields were imputed. For example, missing aircraft numbers on some flights were identified by tracking flight sequences by aircraft number, and matching flights with missing numbers to gaps in the sequence and location of known flights.

ASQP data in some cases had data elements missing. For example, BTS data might show actual departure and arrival times for a flight, and also report the length of delays for the departure and arrival, but CRS scheduled departure and arrival times would be missing. In such cases, missing times could be imputed. Other cases, such as airline-
reported data with transposed data elements required logic-based rules for correcting the raw BTS data. Seven main rules were applied:

1. Wheels off time must be later than actual departure time
2. Actual arrival time must be later than wheels-on time
3. Reported departure delay must be equal to actual departure time minus scheduled departure time
4. Reported arrival delay must be equal to actual arrival time minus scheduled arrival time
5. Actual departure time must be greater than prior flight arrival time
6. Reported departure date for any aircraft tail number must be consistent with any prior or subsequent flight leg
7. The airborne time taken to travel between the reported origin and destination airports must be within reason

Records which did not meet one or more of these criteria were reviewed, and were either corrected or rejected. Any record which was corrected was coded to show that a correction had been made to the original BTS data.

Problem records were identified and processed in order to classify and understand data errors and to discover cases where there was enough redundancy to correct reporting errors. Since this research was concerned with aircraft routing sequences (“flight strings”) and flow of aircraft through airports, the need was to recover information to maintain string continuity, rather than discard information from “poor data quality” links. This required judgmental estimates and the imputation of some missing (or unlikely) reported data values. An attempt was made to recover as many records as possible. Table 3-4
shows, by year, the number of reported records (flight segments) that could not be validated and chained.

For purposes not dependent on flight strings, some individual flight segments were rejected summarily rather than analyzed to determine whether there was some plausible value which could be imputed. Given the size of the database and the relative robustness of the data, imputation of a relatively small number of missing or unlikely values was not considered to be productive.

Table 3-1 Validated and recovered chained records by year

<table>
<thead>
<tr>
<th>Year</th>
<th>Records Validated</th>
<th>Records Recovered</th>
<th>Total Records Chained</th>
<th>Records Recovered as Percent of Total Chained Records</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>5,270,213</td>
<td>32,918</td>
<td>5,303,131</td>
<td>0.62</td>
</tr>
<tr>
<td>1996</td>
<td>5,297,034</td>
<td>36,041</td>
<td>5,333,075</td>
<td>0.68</td>
</tr>
<tr>
<td>1997</td>
<td>5,365,528</td>
<td>31,745</td>
<td>5,397,273</td>
<td>0.59</td>
</tr>
<tr>
<td>1998</td>
<td>5,334,813</td>
<td>34,100</td>
<td>5,368,913</td>
<td>0.64</td>
</tr>
<tr>
<td>1999</td>
<td>5,483,541</td>
<td>30,450</td>
<td>5,513,991</td>
<td>0.55</td>
</tr>
<tr>
<td>2000</td>
<td>5,646,619</td>
<td>26,377</td>
<td>5,672,996</td>
<td>0.46</td>
</tr>
<tr>
<td>2001</td>
<td>5,896,016</td>
<td>23,033</td>
<td>5,919,049</td>
<td>0.39</td>
</tr>
<tr>
<td>2002</td>
<td>5,236,321</td>
<td>19,037</td>
<td>5,255,358</td>
<td>0.36</td>
</tr>
<tr>
<td>2003</td>
<td>6,454,232</td>
<td>15,016</td>
<td>6,469,248</td>
<td>0.23</td>
</tr>
<tr>
<td>2004</td>
<td>7,089,853</td>
<td>17,327</td>
<td>7,107,180</td>
<td>0.24</td>
</tr>
<tr>
<td>2005</td>
<td>7,114,609</td>
<td>11,859</td>
<td>7,126,468</td>
<td>0.17</td>
</tr>
<tr>
<td>Total</td>
<td>64,188,749</td>
<td>277,903</td>
<td>64,466,652</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Source: Research dataset

It was reassuring to find that the BTS ASQP data was relatively robust. Over half the recovered records (143,000 out of 278,000) involved date changes. This was not
surprising. Modifying the data with date shift was considered whenever a flight could be slotted to match with a prior and following flight by shifting one the reported date forward or back. This caught not only misreporting of the flight date, but also corrected a problem mentioned earlier, reporting all legs of a multi-leg flight using the local date at the flight origin airport. When subsequent flight legs crossed midnight the reported flight date was not changed. (This follows historical railroad and steamship practices.)

In submitting on-time disclosure reports to BTS, an official of the air carrier is required to sign a certification statement that the report is true, correct, and complete for the period reported.

Inconsistencies in the data often related to the way in which airlines reported data. For example, several carriers kept the same date for second or third segments of flights with the same flight number, even if the multiple flight segments spanned midnight. Others used the date on which each individual segment originated. Since this research developed trip chains for individual aircraft, it was important to assign the correct date to the operation of each flight segment.

The sixth step involved itinerary development in order to associate times of arrival at an airport gate with the times of departure on the following flight. The seventh step in Figure 3-1 was to build datasets for analysis. The primary dataset consisted of annual 221-character files. Once these were in a validated and stable form, special purpose files could be generated to support data analysis.
Data Quality

From the start of this research the intent was to develop a large set of clean and consistent data spanning an extended period, and to be able to use the data for analysis in ways that would extend beyond this dissertation.

In a self-reporting system, airline reporting errors are not unexpected in a database as large as the airline on-time database. Airline reports to BTS are not subject to rigorous data integrity validation. Errors ran the gamut from misreporting of dates, misreporting of times, even misreporting of origins and destinations. The integrity of the reported data was a notable problem whenever a new carrier began reporting data to BTS.

Out of nearly 65 million records in the dataset, about 220,000 records (0.34 percent) posed problems—missing data fields, inconsistencies between fields, negative values reported for fields that should contain positive values, zero minute taxi times, transposed entries, ambiguous or missing aircraft tail numbers, incorrect dates, confusion between UTC and local times, or incorrect or garbled formats. BTS (2008e) describes similar problems in compiling a special report on taxi times. Records that could not be chained were rejected.

Table 3-2 reproduces the BTS 1995-2005 summary report. Table 3-3 shows total number of records in the research dataset, reported in the same format as the BTS annual summary report. Table 3-4 shows differences between BTS data and the research dataset.

For 2001, 48,731 operating records were rejected (5,967,780 BTS records compared to 5,919,049 accepted in the research dataset, a difference of 0.82 percent). BTS data miscoded aircraft identification and dropped the last character in the 6-character alphanumeric field. Thus, when an airline operated different aircraft with the same initial
five characters (for example, Delta Air Lines in 2001 operated a Boeing 737-800 with registration number N376DA, when Delta also operated a Boeing 737-200 with registration number N376DL), BTS coded both tail numbers as N376D, so it was difficult to identify the aircraft, and the flight record was rejected. This data problem occurred in 2001 and in the first two months of 2002. Most other aircraft could be uniquely identified, even without the last character in this field.

The number of chained flight records includes 101,000 flights which were accepted after review and adjustment for misreporting of times, dates and aircraft tail numbers.
### Table 3-2  BTS published summary by category and year

<table>
<thead>
<tr>
<th>Year</th>
<th>Operations</th>
<th>Late Arrivals</th>
<th>Late Departures</th>
<th>Cancelled</th>
<th>Diverted</th>
<th>Percent On-Time Arrivals</th>
<th>Percent Late Arrivals</th>
<th>Percent Late Departures</th>
<th>Percent Cancelled</th>
<th>Percent Diverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>5,327,435</td>
<td>1,039,250</td>
<td>827,934</td>
<td>91,905</td>
<td>10,492</td>
<td>78.57</td>
<td>19.51</td>
<td>15.54</td>
<td>1.73</td>
<td>0.20</td>
</tr>
<tr>
<td>1996</td>
<td>5,351,983</td>
<td>1,220,045</td>
<td>973,948</td>
<td>128,536</td>
<td>14,121</td>
<td>74.54</td>
<td>22.80</td>
<td>18.20</td>
<td>2.40</td>
<td>0.26</td>
</tr>
<tr>
<td>1997</td>
<td>5,411,843</td>
<td>1,083,834</td>
<td>846,870</td>
<td>97,763</td>
<td>12,081</td>
<td>77.94</td>
<td>20.03</td>
<td>15.65</td>
<td>1.81</td>
<td>0.22</td>
</tr>
<tr>
<td>1998</td>
<td>5,384,721</td>
<td>1,070,071</td>
<td>870,395</td>
<td>144,509</td>
<td>13,161</td>
<td>77.20</td>
<td>19.87</td>
<td>16.16</td>
<td>2.68</td>
<td>0.24</td>
</tr>
<tr>
<td>1999</td>
<td>5,527,884</td>
<td>1,152,725</td>
<td>937,273</td>
<td>154,311</td>
<td>13,555</td>
<td>76.11</td>
<td>20.85</td>
<td>16.96</td>
<td>2.79</td>
<td>0.25</td>
</tr>
<tr>
<td>2000</td>
<td>5,683,047</td>
<td>1,356,040</td>
<td>1,131,663</td>
<td>187,490</td>
<td>14,254</td>
<td>72.59</td>
<td>23.86</td>
<td>19.91</td>
<td>3.30</td>
<td>0.25</td>
</tr>
<tr>
<td>2001</td>
<td>5,967,780</td>
<td>1,104,439</td>
<td>953,808</td>
<td>231,198</td>
<td>12,909</td>
<td>77.40</td>
<td>18.51</td>
<td>15.98</td>
<td>3.87</td>
<td>0.22</td>
</tr>
<tr>
<td>2002</td>
<td>5,271,359</td>
<td>868,225</td>
<td>717,368</td>
<td>65,143</td>
<td>8,356</td>
<td>82.14</td>
<td>16.47</td>
<td>13.61</td>
<td>1.24</td>
<td>0.16</td>
</tr>
<tr>
<td>2003</td>
<td>6,488,540</td>
<td>1,057,804</td>
<td>834,390</td>
<td>101,469</td>
<td>11,381</td>
<td>81.96</td>
<td>16.30</td>
<td>12.86</td>
<td>1.56</td>
<td>0.18</td>
</tr>
<tr>
<td>2004</td>
<td>7,129,270</td>
<td>1,421,391</td>
<td>1,187,594</td>
<td>127,757</td>
<td>13,784</td>
<td>78.08</td>
<td>19.94</td>
<td>16.66</td>
<td>1.79</td>
<td>0.19</td>
</tr>
<tr>
<td>2005</td>
<td>7,140,596</td>
<td>1,466,065</td>
<td>1,279,404</td>
<td>133,730</td>
<td>14,028</td>
<td>77.40</td>
<td>20.53</td>
<td>17.92</td>
<td>1.87</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>64,684,458</td>
<td>12,839,889</td>
<td>10,560,647</td>
<td>1,463,811</td>
<td>138,122</td>
<td>77.67</td>
<td>19.85</td>
<td>16.33</td>
<td>2.26</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Source: BTS (2008)
Table 3-3  Research dataset flight records by category and year

<table>
<thead>
<tr>
<th>Year</th>
<th>Operations</th>
<th>Late Arrivals</th>
<th>Late Departures</th>
<th>Cancelled</th>
<th>Diverted</th>
<th>Percent On-Time Arrivals</th>
<th>Percent Late Arrivals</th>
<th>Percent Late Departures</th>
<th>Percent Cancelled</th>
<th>Percent Diverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>5,303,131</td>
<td>1,034,014</td>
<td>819,300</td>
<td>91,894</td>
<td>10,492</td>
<td>78.57</td>
<td>19.50</td>
<td>15.45</td>
<td>1.73</td>
<td>0.20</td>
</tr>
<tr>
<td>1996</td>
<td>5,333,075</td>
<td>1,215,326</td>
<td>963,890</td>
<td>128,532</td>
<td>14,121</td>
<td>74.54</td>
<td>22.79</td>
<td>18.07</td>
<td>2.41</td>
<td>0.26</td>
</tr>
<tr>
<td>1997</td>
<td>5,397,273</td>
<td>1,080,825</td>
<td>839,759</td>
<td>97,765</td>
<td>12,081</td>
<td>77.94</td>
<td>20.03</td>
<td>15.56</td>
<td>1.81</td>
<td>0.22</td>
</tr>
<tr>
<td>1998</td>
<td>5,368,913</td>
<td>1,067,255</td>
<td>862,609</td>
<td>144,503</td>
<td>13,161</td>
<td>77.18</td>
<td>19.88</td>
<td>16.07</td>
<td>2.69</td>
<td>0.25</td>
</tr>
<tr>
<td>1999</td>
<td>5,513,991</td>
<td>1,149,787</td>
<td>929,335</td>
<td>154,282</td>
<td>13,555</td>
<td>76.10</td>
<td>20.85</td>
<td>16.85</td>
<td>2.80</td>
<td>0.25</td>
</tr>
<tr>
<td>2000</td>
<td>5,672,996</td>
<td>1,353,705</td>
<td>1,123,414</td>
<td>187,487</td>
<td>14,254</td>
<td>72.58</td>
<td>23.86</td>
<td>19.80</td>
<td>3.30</td>
<td>0.25</td>
</tr>
<tr>
<td>2001</td>
<td>5,919,049</td>
<td>1,095,786</td>
<td>942,549</td>
<td>231,202</td>
<td>12,909</td>
<td>77.36</td>
<td>18.51</td>
<td>15.92</td>
<td>3.91</td>
<td>0.22</td>
</tr>
<tr>
<td>2002</td>
<td>5,255,358</td>
<td>865,627</td>
<td>712,744</td>
<td>65,145</td>
<td>8,356</td>
<td>82.13</td>
<td>16.47</td>
<td>13.56</td>
<td>1.24</td>
<td>0.16</td>
</tr>
<tr>
<td>2003</td>
<td>6,469,248</td>
<td>1,053,837</td>
<td>828,059</td>
<td>101,466</td>
<td>11,374</td>
<td>81.97</td>
<td>16.29</td>
<td>12.80</td>
<td>1.57</td>
<td>0.18</td>
</tr>
<tr>
<td>2004</td>
<td>7,107,180</td>
<td>1,415,387</td>
<td>1,177,675</td>
<td>127,996</td>
<td>13,785</td>
<td>78.09</td>
<td>19.91</td>
<td>16.57</td>
<td>1.80</td>
<td>0.19</td>
</tr>
<tr>
<td>2005</td>
<td>7,126,448</td>
<td>1,462,661</td>
<td>1,271,840</td>
<td>133,732</td>
<td>14,028</td>
<td>77.40</td>
<td>20.52</td>
<td>17.85</td>
<td>1.88</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>64,466,632</td>
<td>12,794,210</td>
<td>10,471,174</td>
<td>1,464,004</td>
<td>138,116</td>
<td>77.67</td>
<td>19.85</td>
<td>16.24</td>
<td>2.27</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Source: Research dataset, derived from BTS data
### Table 3-4 Percent differences between BTS summary and research data

<table>
<thead>
<tr>
<th>Year</th>
<th>Operations</th>
<th>Late Arrivals</th>
<th>Late Departures</th>
<th>Cancelled</th>
<th>Diverted</th>
<th>Percent On-Time Arrivals</th>
<th>Percent Late Arrivals</th>
<th>Percent Late Departures</th>
<th>Percent Cancelled</th>
<th>Percent Diverted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>-0.46</td>
<td>-0.50</td>
<td>-1.04</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td>1996</td>
<td>-0.35</td>
<td>-0.39</td>
<td>-1.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>1997</td>
<td>-0.27</td>
<td>-0.28</td>
<td>-0.84</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>1998</td>
<td>-0.29</td>
<td>-0.26</td>
<td>-0.89</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>1999</td>
<td>-0.25</td>
<td>-0.25</td>
<td>-0.85</td>
<td>-0.02</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>-0.10</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>2000</td>
<td>-0.18</td>
<td>-0.17</td>
<td>-0.73</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>0.00</td>
<td>-0.11</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>2001</td>
<td>-0.82</td>
<td>-0.78</td>
<td>-1.18</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.04</td>
<td>0.01</td>
<td>-0.06</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>2002</td>
<td>-0.30</td>
<td>-0.30</td>
<td>-0.64</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2003</td>
<td>-0.30</td>
<td>-0.38</td>
<td>-0.76</td>
<td>0.00</td>
<td>-0.06</td>
<td>0.01</td>
<td>-0.01</td>
<td>-0.06</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2004</td>
<td>-0.31</td>
<td>-0.42</td>
<td>-0.84</td>
<td>0.19</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.02</td>
<td>-0.09</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>2005</td>
<td>-0.20</td>
<td>-0.23</td>
<td>-0.59</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.01</td>
<td>-0.07</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>-0.34</td>
<td>-0.36</td>
<td>-0.85</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>-0.08</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Source: BTS (2008) and research dataset
Treatment of Data as Pooled Cross-Sectional Data

For the purpose of analysis, the data are treated as a single data set involving pooled cross-sectional data. The basic entity under observation is an individual aircraft. In much of the analysis in this research, individual aircraft are aggregated by airline/aircraft type (for example, American Airlines’ operation of B-757-200 aircraft). A basic assumption is that airline/aircraft types are observed over a large number of trips over a number of years, but the evolution of their behavior results from changes in operating strategies and volume-to-capacity ratios rather than in the form of ordered time series.

Time series analysis generally involves data that is naturally ordered. A main requirement that drives time series analysis is the estimation of future performance based on current and historical observations. Time series analysis focuses on removal of periodicity (seasonal and cyclic variation) and estimation of random variation and temporal trends, in support of development of trend-stationary estimates.

The period 1995-2005 can be characterized as having reasonably good data available, and also as a period preceding the widespread introduction into service of new air traffic management operational procedures and technology.

Mohler (2006) showed a chart with FAA projections for capacity growth through 2013, reproduced below as Figure 3-2. The baseline for this chart is 2001. From this chart, capacity growth between 2001 and 2004 is estimated to have been about 5 percent, with a projection for 2005 of an additional 4 percent. This chart shows that capacity did not grow significantly between 2001 and 2006, and that higher expected growth in system capacity would occur in 2007 and afterwards. This helps in understanding that reduced delays in 2002 and 2003, noted elsewhere in this research, occurred in an
environment in which traffic declined from 2001 levels, and capacity grew modestly. The chart reproduced as Figure 3-2 was based on effective capacity, defined at 14 minutes per flight, which was the average delay during 2001 (Mohler, 2006).

![Chart showing expected capacity change 2001-2013](image)

Source: Mohler (2006)

Figure 3-2. FAA 2005 chart showing expected capacity change 2001-2013

A recent FAA publication (2008e) reinforces the assumption that the 1995 through 2005 serves as a reasonable baseline period. Most of the 2008 accomplishments listed in FAA (2008e), relative to airport capacity, airspace capacity, and aircraft performance-based mechanisms, could be considered to be either research and development projects or design projects in the 1995-2005 period.
Data Analyses and Methods

The main analytical focus of this research was historical variation of airport-to-airport trip times between 1995 and 2005. Differences between airlines, routes, and equipment types were identified as a basis for establishing the “limits of the possible” in reducing trip time and turn time duration and variation. The research analysis classified airport-gate-to-airport-gate operations into six distinct phases:

1. Contracting (negotiation of flight plan, departure time, and planned trajectory)
2. Gate departure
3. Taxi-out
4. Airborne (takeoff, climb, en-route, descent, approach, landing)
5. Taxi-in
6. Gate arrival

The methodology was designed to support five metrics:

1. Departure delay
2. Excess aircraft airborne time relative to unimpeded airborne time (for calculation of excess flying time)
3. Excess aircraft ground time over unimpeded ground time (for calculation of time spent maneuvering in taxi-out for takeoff and taxi-in after landing)
4. Estimated traveler time delays and resultant costs (using value of time estimates)
5. Schedule buffers needed to meet schedule reliability and level of service goals.
The data were set up to be classified and modeled in the following ways:

1. Taxi-out time (minutes), by aircraft size and type, by airline, and airport. This allows analysis by airport classification (group), by hour of day, by weekday, by day of month, by month and by year.

2. Airborne time (minutes), by aircraft type, by airline, and origin-destination pair. This allow analysis by origin-destination pair, by hour of day, by weekday, by day of month, and by month and year.

3. Taxi-in time (minutes), by aircraft size type, by airline, and origin-destination pair. This allows analysis by destination, by hour of day, by weekday, by day of month, and by month and year.

The research dataset was designed to support flexibility, allowing the data to be extracted and classified in different ways. The methodology supports development relationships for the basic elements of trip time and delay, allowing comparison against unimpeded values for taxi times and airborne time:

- Departure delay
- Taxi-out time,
- Airborne time,
- Taxi-in time, and
- Arrival delay

The principal explanatory variables are:

- Airline,
- Aircraft type, size or capacity,
- Airport characteristics (for taxi and turn times), and
• Origin-destination routes (for airborne times).
• Time-varying factors (time of day, month, year)

Additional indicator variables were developed to classify and categorize data. Examples are hour of day, airport turn time, and stage length groupings.

Criteria for Identifying Unimpeded Times

In an environment characterized by high delays, scheduled departure and arrival times do not provide an adequate metric for measuring delays. Performance under delay should be measured against performance in the absence of delay. This research developed estimates of uncongested or unimpeded block times. This allows observed trip time (inclusive of departure and other delays) to be measured against unimpeded block time. "Impeded trip time" is defined as the difference between observed trip time and unimpeded block time.

Development of unimpeded time values required taxi-out, airborne, and taxi-in times to be considered separately. For taxi times, flights with no observed ground queues on the airport surface were selected. For airborne times, flights with no observed ground queues at the arrival airport and for which the flight arrival delay was less than or equal to the flight departure delay were selected.

The absence of ground queues was considered to be a situation in which there was no reported flight on the airport surface (in transit between the gate and the runway) during the same time that the unimpeded flight was in transit between the airport gate and the runway. Any other flight, either arriving or departing, reported to be in transit at the same time as the flight being evaluated automatically eliminated a flight from being considered as having an unimpeded taxi time.
This approach limits the sample from which unimpeded times are taken. Many short taxi times and airborne times in the same range as those accepted here were not included as unimpeded. The dataset, while it includes all scheduled U.S. domestic operations of major carriers, does not include international flights and other operations. These represent unobserved operations. By leaving out unobserved operations, the unimpeded taxi times may be biased. For major airports with extensive operations not included in the dataset, some taxi times that in reality concurrently had aircraft present on the airport surface were be treated as unimpeded. Thus the unimpeded taxi times developed in this analysis should be treated as an upper bound.

After eliminating flights with observed queues, approximately 10 percent of flights remained in the unimpeded pool for taxi-out and airborne times. For unimpeded taxi-in times, about 15 percent of flights were accepted. About one percent of all flights met all three criteria simultaneously, with taxi-out, airborne, and taxi-in times all unimpeded.

For modeling unimpeded airborne times, there exist about 36,000 carrier-aircraft-directional route combinations. The premise is that each of these has its own unique characteristics and patterns. The analysis defined a reference unimpeded airborne time for each reporting airline and aircraft type operated on a directional route.

Ground Taxi Time Estimation

A review was performed of reported aircraft taxi-out and taxi-in times. Taxi time in minutes was considered to vary by airport and the combination of airline and aircraft type. In reviewing the distribution of taxi times, the initial focus was on the departure and taxi-out process. On landing, the airport runway system is the principal constraint. Landing flights are metered onto the runway and generally face less queuing on their way
to the gate. Departing flights, on the other hand, must wait for availability of the runway. Departing flights are also held until airspace is available, and for predicted availability of arrival capacity at the destination airport.

Congestion on the airport surface was an unobserved variable in the research dataset. However, the dataset supports a methodology for estimating of unimpeded taxi times. As covered in the literature review, Andersson et al. (2001) estimated nominal, or unimpeded, taxi times by assigning an index to departing flights. The index was number of aircraft which took off while an observed flight was taxiing out on the aircraft surface. Idris et al. (2002) used a similar approach to estimating the number of departure aircraft present on the airport surface when the observed aircraft pushes back from the gate. These studies noted that there are interactions between surface arrival and departure flows, and that surface congestion and queuing can depend on the imbalance between the arrival and departure demand and capacity of the airport runway configuration.

The research in this study developed a surface queue value, which was the sum of the arrivals and departures that occurred while an observed aircraft was in transit between the gate and the runway. The surface queue value was calculated for aircraft taxiing in, as well as for aircraft taxiing out.

For departure, this approach compared the reported gate departure and wheels-off times for each flight with the same times of preceding and following flights. The observed flight was considered to have entered the system when it left the gate, and to leave the system when it took off. The same rule was applied for arriving flights, which entered the system upon landing, and left the system on gate arrival.
Other ASQP reporting flights entered the system when they left the gate and exited the system when they took off (departing flights) or entered the system when they landed and left the system when they arrived at the gate (arriving flights). As applied to departing flights, for any observed flight, the surface queue value was based on how many other flights in total were in the system at the time of the observed flight's entry, and entered or left the system prior to the observed flight's wheels-off time.

Since ASQP flights do not represent all traffic at major airports, this methodology does not completely capture the existence of queues on the airport surface. Observed flights may not taxi directly to the takeoff runway, even in the absence of queues, if they are required to wait for downstream constraints independent of the capacity of the airport takeoff runway. Similarly, other aircraft may be delayed en route between the gate and the runway while the observed aircraft is given a clearance to taxi without delay. For the purposes of this research, a surface queue value of zero was required. Observed flights in the dataset that had other flights recorded as being present on the surface were eliminated from consideration as "unimpeded." That is, the observed aircraft could occupy the airport surface with no other reporting aircraft.

For arriving aircraft, a zero queue value was the criterion for unimpeded taxi-in time. For departing aircraft, a zero queue value was required for taxi-out and for taxi-in on arrival of the flight at the destination airport. The arrival requirement was aimed at eliminating departing flights that might subject to downstream arrival congestion.

The a priori expectation was that these selection criteria would produce tightly clustered taxi times, with outliers representing delays in which unobserved factors interrupted the progress of an aircraft from between gate and runway.
Unimpeded taxi times were developed for all 300 airports and 166 airline-aircraft-type combinations operated by the 22 reporting air carriers. To be considered unimpeded, an observation had to meet a zero surface queue criterion. Values for unimpeded taxi time more than 3 standard deviations from the mean were considered to be outliers, and were eliminated from consideration. Unimpeded taxi time was the mean of all unimpeded (zero queue, non-outlying) observations in the dataset for a specific airport-airline-aircraft type.

Figures 3-3 and 3-4 show the probability distributions of taxi-out and taxi-in times for flights identified as having unimpeded taxi times. The values plotted are the differences between observed taxi times and unimpeded taxi times. The unimpeded taxi times are those developed through the methodology described in this section.

Source: Research dataset and MathWave (2008)
Figure 3-3. Distribution of unimpeded taxi-out time residuals
For taxi-out times in the unimpeded category, the mean difference was calculated to be -0.02 minutes (-1.2 seconds), the median was 0 minutes, and the standard deviation was calculated to be 2.4 minutes. The fitted distribution shown in Figure 3-3 is a Burr XII distribution (Burr, 1942; Kleiber and Kotz, 2003).

For taxi-in times in the unimpeded category, the mean residual difference was calculated to be -0.1 minutes (-6 seconds), the median was 0 minutes, and the standard deviation was calculated to be 1.7 minutes. The fitted distribution shown in Figure 3-4 is a Burr XII distribution (Burr, 1942; Kleiber and Kotz, 2003).

![Distribution of unimpeded taxi-in time residuals](image)

Source: Research dataset and MathWave (2008)

Figure 3-4. Distribution of unimpeded taxi-in time residuals

For airborne times in the unimpeded category, the mean residual difference was calculated to be -0.14 minutes (-8 seconds), the median was 0 minutes, and the standard
deviation was calculated to be 4.8 minutes. The fitted distribution shown in Figure 3-5 is a Burr XII distribution (Burr, 1942; Kleiber and Kotz, 2003).

![Distribution of unimpeded airborne time residuals](image)

Source: Research dataset and MathWave (2008)

Figure 3-5. Distribution of unimpeded airborne time residuals

**Observed Trip Time Estimation**

For comparison of observed trip times and unimpeded block times, the appropriate measurement unit is a specific airline operating a specific aircraft type over a specific route. A trip has four components: gate-hold/departure delay; taxi-out time; airborne time; and taxi-in time. Delay can be apportioned to any of these components, but it is only total delay that counts. This is in contrast to unimpeded block time, which has three components (taxi-out, airborne, taxi-in), and no delay element. Variability is associated
with overall trip time, and the relevant comparison is between observed trip time and unimpeded block time.

The air traffic control system attempts to avoid airborne delays through the use of ground delay and ground stop programs. Airborne times, however, are still subject to some uncertainty. Airborne times are dependent on wind, weather, and en-route vertical and horizontal routings through airspace. Some flights may be cleared for direct point-to-point operation, but most flights still operate over en-route airways linking navigational fixes. For airport departures and arrivals, flights are vectored on lengthened or shortened flight paths by air traffic control so as to maintain separation and follow prescribed departure and arrival routings.

Operating on an origin-destination airport pair, individual aircraft types have different performance characteristics. Different airlines also operate their aircraft differently. Thus, as described above, this research defined the measurement unit as a trip by a specific airline, operated with a specific aircraft type, on a directional route. Individual observed trips were compared with an estimate of the mean unimpeded airborne time for all flights by the same airline with the same aircraft type on the same route for 11-year period.

The time observed for an airline-aircraft-route observation can be expressed mathematically as:

\[
\text{obs}_{t,j,k,l} = f(Airline_j, AircraftType_k, ODPair_l)
\]

Where:

\[
\text{obs}_{t,j,k,l} = \text{observed trip time for airline } j, \text{ operating aircraft type } k, \text{ over origin-destination pair } l
\]

\[
j = \text{airline identity using 2-character BTS code}
\]
Unimpeded Block Times

To deal with the deficiency of arrival delay as a metric, estimates of unimpeded block times are required. In this research, separate estimates for mean unimpeded taxi-out times, airborne times, and taxi-in times were developed. Mean unimpeded taxi-out and taxi-in times were estimated by individual reporting airline for each aircraft type reported as operating at a specific airport. For airborne times, mean unimpeded time estimates were developed by airline by aircraft type reported as operating on a specific route. The separate taxi-out, airborne, and taxi-in time estimates were then additively combined in a single estimate of unimpeded block time.

Any procedure for selecting unimpeded taxi-out, airborne, and taxi-in unimpeded times should produce probability distributions that are symmetrical about their mean values. As expected, the methodology used in this research did produce symmetrical distributions for each of the three block time components.

Unimpeded block times were estimated by taking the mean of all of the observations: (a) considered to be unimpeded; (b) operated by a specific airline with a specific aircraft type between a specified origin and a specified destination; and (c) operated during the 11-year 1995-2005 period.
Unimpeded block time for a route-airline-aircraft observation can be expressed mathematically as:

\[
unimp_{blk\_t_{j,k,l}} = unimp_{txo\_t_{j,k,orig}} + unimp_{abn\_t_{j,k,l}} + unimp_{txi\_t_{j,k,dest}}
\]

\[
unimp_{blk\_t_{j,k,l}} = unimp_{txo\_t_{j,k,orig}} + unimp_{abn\_t_{j,k,l}} + unimp_{txi\_t_{j,k,dest}}
\]

Where:

- \(unimp_{blk\_t_{j,k,l}}\) = unimpeded block time for airline \(j\), operating aircraft type \(k\), over origin-destination pair \(l\)
- \(unimp_{abn\_t_{j,k,l}}\) = unimpeded airborne time for airline \(j\), operating aircraft type \(k\), over origin-destination pair \(l\)
- \(unimp_{txo\_t_{j,k,orig}}\) = unimpeded taxi-out time for airline \(j\), operating aircraft type \(k\), at airport \(orig\)
- \(unimp_{txi\_t_{j,k,dest}}\) = unimpeded taxi-in time for airline \(j\), operating aircraft type \(k\), at airport \(dest\)
- \(j\) = airline identity using 2-character BTS code
- \(k\) = aircraft type using 4-digit BTS code
- \(l\) = origin-destination pair, using 6-character string (3-character origin airport identifier followed by 3-character destination airport identifier)
- \(orig\) = origin airport identifier using 3-character code
- \(dest\) = destination airport identifier using 3-character code

For a flight to be considered to be unimpeded, no other aircraft could be reported as on the surface of the origin or destination airport at the times an unimpeded aircraft was reported to be taxiing out and taxiing in. An additional selection criterion for airborne times was the censoring of outliers (i.e., observations were deleted if their normalized standard deviation, or \(Z\)-value, was equal to or greater than 3). Mathematically, the mean unimpeded time can be expressed as:
\[
\text{mean}(\text{unimp}_{t, j, k, l}) = \frac{\sum_{n=1}^{N} \text{unimp}_{t, j, k, l}}{\sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} \text{Dep}_{j, k, l}}
\]

Where:

\( \text{unimp}_{t, j, k, l} \) = unimpeded block time for airline \( j \), operating aircraft type \( k \), over origin-destination pair \( l \). Unimpeded block times were derived by adding relevant values for unimpeded taxi-out time, unimpeded airborne time, and unimpeded taxi-in time.

\( \text{Dep}_{j, k, l} \) = Departure by airline \( j \), aircraft type \( k \), and origin-destination pair \( l \).

\( j \) = airline identifier using 2-character BTS code

\( k \) = aircraft type using 4-digit BTS code

\( l \) = origin-destination pair, using 6-character string (3-character origin airport identifier followed by 3-character destination airport identifier)

For block times in the unimpeded category (about 1 percent of all flights in the dataset), the mean residual difference between observed unimpeded block times and mean unimpeded block times was calculated to be -0.63 minutes (-38 seconds), the median was 0 minutes, and the standard deviation was calculated to be 3.9 minutes. The fitted distribution shown in Figure 3-6 is Burr XII distribution (Burr, 1942; Kleiber and Kotz, 2003).
Impeded Trip Time

Using similar notation, the "impeded" trip time was derived for each observation:

\[ imp_{t,j,k,l} = obs_{t,j,k,l} - \text{mean}(unimp_{t,j,k,l}) \]

Where:

- \( imp_{t,j,k,l} \) = impeded trip time for airline \( j \), operating aircraft type \( k \), over origin-destination pair \( l \)
- \( obs_{t,j,k,l} \) = observed block time for airline \( j \), operating aircraft type \( k \), over origin-destination pair \( l \)
- \( unimp_{t,j,k,l} \) = unimpeded block time for airline \( j \), operating aircraft type \( k \), over origin-destination pair \( l \)

Source: Research dataset and MathWave (2008)

Figure 3-6. Distribution of unimpeded block time residuals
Having defined impeded trip time as the difference between any observed trip time and the unimpeded time corresponding to the associated airline, aircraft type and route, the mean impeded time can be derived for all observations departing a specified origin airport \( o \) can be expressed as:

\[
\text{mean}(\text{imp}_t_{\text{origin}}) = \frac{\sum_{j=1}^J \sum_{k=1}^K \text{imp}_t_{j,k,\text{origin}}}{\sum_{j=1}^J \sum_{k=1}^K \text{Dep}_{j,k,\text{origin}}}
\]

Where:

\[
\text{mean}(\text{imp}_t_{\text{origin}}) = \text{mean impeded trip time for the specified airport origin}
\]

\[
\text{Dep}_{j,k,\text{origin}} = \text{Departure by airline } j \text{ and aircraft type } k \text{ at airport origin}
\]

\[
j = \text{airline identity using 2-character BTS code}
\]

\[
k = \text{aircraft type using 4-digit BTS code}
\]

Similarly, the mean impeded trip time can derived for all observations arriving at a specified destination airport, for all airlines and all aircraft types, is given by:

\[
\text{mean}(\text{imp}_t_{\text{dest}}) = \frac{\sum_{j=1}^J \sum_{k=1}^K \text{imp}_t_{j,k,\text{dest}}}{\sum_{j=1}^J \sum_{k=1}^K \text{Arr}_{j,k,\text{dest}}}
\]

Where:

\[
\text{mean}(\text{imp}_t_{\text{dest}}) = \text{mean impeded trip time for the specified airport destination}
\]

\[
\text{Arr}_{j,k,\text{dest}} = \text{Arrival by airline } j \text{ and aircraft type } k \text{ at airport destination}
\]

\[
j = \text{airline identity using 2-character BTS code}
\]

\[
k = \text{aircraft type using 4-digit BTS code}
\]
The same process can be applied in developing mean impeded times by route, by aircraft type, by time of day, or by any measure tracked in the dataset.

Trip Time Probability Distributions

A problem in working with trip time variability is that delay distributions are positively skewed and heavy-tailed. Assumptions based on normal distributions are inappropriate. The approach to statistical analysis in this research focused on distributions which reasonably approximate observed delay distributions in the research dataset.

The probability distributions of trip time and delay element vary with operating conditions, principally weather and congestion. The approach taken in this research was to develop unimpeded times by identifying individual flights in the dataset which operated in delay-free or nearly delay-free conditions. These unimpeded flights represent a baseline for evaluating the impact and cost of delays. For taxi times, this was a fairly straightforward process to understand. For airborne times, the process of developing unimpeded times needed to take into account the effects of wind, weather and indirect routings on airborne times.
Arrival Delay Variability

Figure 3-7 shows the probability density function for arrival delays relative to scheduled arrival times during the 11-year period 1995-2005.

Figure 3-7 is drawn with a fitted Burr XII distribution (Burr, 1942; Kleiber and Kotz, 2003). Figure 3-7 indicates that arrival delays reported under the ASQP program are, in many cases, rounded to the nearest 5 minutes. Although a clear conclusion cannot be drawn from the figure, an indication is that flights with arrival delays in the range -20 minutes to +30 minutes were managing their trip times (through choice of routings, flight levels, flight speeds, or otherwise) in order to arrive closer to schedule.

Source: Research dataset and MathWave (2008)
Figure 3-7. Arrival delay distribution 1995-2005
Air Time Variability

The observed air time and the mean unimpeded air time for a specific airline, with a specific aircraft type over a specific origin-destination route, together with the standard deviation of unimpeded air times, can be compared using a standard $Z$-transformation:

$$Z = \frac{x-\mu}{\sigma}$$

where:

- $Z$ = standardized measure of dispersion
- $x$ = observed air time for any individual flight operated with parameters conforming to $\mu$ and $\sigma$ (identical airline, identical aircraft type, identical origin-destination pair).
- $\mu$ = population mean for all unimpeded air times over the 11-year period (identical airline, identical aircraft type, identical origin-destination pair)
- $\sigma$ = population standard deviation for all unimpeded air times over the 11-year period (identical airline, identical aircraft type, identical origin-destination pair)

thus:

$$Z_{impeded\ air\ time} = \frac{\text{observed\ air\ time} - \text{mean}_{unimpeded\ air\ time}}{\text{standard\ deviation}_{unimpeded\ air\ time}}$$

Figure 3-8 graphically portrays the distribution of 6.5 million observation sample from the dataset. The residual $Z$-values are based on the 11-year pooled means and standard deviations.

For consistency with other graphs in this proposal, the box-plot in Figure 3-8 includes a line showing the mean (dashed line) and a line showing the 85th percentile (solid line). The graphs show a slow, generally upward trend in the $Z$-value over this time period. The
Z-values have therefore increased over the period. The magnitude of the increase is estimated to be between 10 and 12 seconds per trip over the 11 year period. An extra 12 seconds per flight represents added variable flight costs of $19. For the year 2005, an added 12 seconds per departure represents $135 million (at 2005 levels of 7 million departures at $2,790 per block hour and 2.1 block hours per departure).

The $Z$-values presented in Figure 3-8 represent an 11-year baseline for overall system performance. Each airline-aircraft-directional route combinations was evaluated to find the 11-year mean and standard deviation. The $Z$-values were calculated for individual
observations based on (a) the observed air time for the individual observation, and (b) the overall 1995-2005 mean and standard deviation for all air time observations on the same airline-aircraft-directional route. For example, the Z-value for a specific American Airlines flight, operated with a Boeing 757 from Dallas-Fort Worth (DFW) to Chicago-O'Hare (ORD), was based on the airborne time for that specific flight evaluated against the mean and standard deviation for all American Airlines flights operated with B-757 aircraft from DFW to ORD in the 11-year dataset. The intent was to remove bias and allow for aircraft types and airlines entering and leaving the BTS on-time reporting system.

Trip Time Variability

In the following discussion, trip time will be used as the relevant measure when considering impeded times. The discussion will focus on impeded trip times, the measure of the difference in time between any observed trip time and the corresponding unimpeded block time.

Figure 3-9 shows results of the analysis of trip time over 11 years, with a histogram and a fitted probability distribution function, of the Z-transformed residuals for the impeded trip time. The Z-values were calculated from trip time observations taken from a 10 percent random sample of the full dataset. The sample size was 6.3 million.

Z-values in Figure 3-9 are plotted for a range from 0 to 2. Impeded trip time Z-Values were observed between $Z = - 4$ and $Z = + 14$. However, only 0.34 percent of all observed trip times had Z-values less than zero, and only 0.09 percent of all observed trip times had Z-values above 1.4. Since the range of interest for trip on-time performance is in the
upper tail, the range plotted in Figure 3-9 (impeded trip time Z-values between 0 and 2) captures nearly all of the upper tail of the distribution.

Source: Research dataset
Figure 3-9. Distribution of impeded trip time Z residuals

The corresponding cumulative distribution function is shown in Figure 3-10:

Source: Research dataset
Figure 3-10. Cumulative probability distribution of trip time Z residuals
Also shown, in Figure 3-11, is a P-P plot of the distribution against the sample data:

![P-P plot](image)

Source: Research dataset

Figure 3-11. Probability P-P plot for fitted and empirical trip time distributions

The equations for the fitted cumulative and density functions of the Burr III distribution (Burr, 1942) or three-parameter Dagum distribution (Dagum, 1977) are as follows:

Parameters

\[
\begin{align*}
    k & = 0.28472 \quad \text{continuous shape parameter 1} \quad (k > 0) \\
    \alpha & = 11.68100 \quad \text{continuous shape parameter 2} \quad (\alpha > 0) \\
    \beta & = 0.86677 \quad \text{continuous scale parameter} \quad (\beta > 0) \\
    \gamma & = 0.00000 \quad \text{continuous location parameter}
\end{align*}
\]

Cumulative Distribution Function

\[
F(x) = \left(1 + \left(\frac{x}{\beta}\right)^{-\alpha}\right)^{-k}
\]
A frequency distribution was developed for Z-values from a 10 percent sample of the dataset. The probabilities of each of the 99 percentiles in the observed (empirical) distribution were paired with the probabilities calculated from the cumulative distribution function CDF formula. The correlation coefficient was determined to be 1.0. A paired t-test was performed. The hypotheses were:

\[ H_0: \mu_d = 0 \]
\[ H_1: \mu_d \neq 0 \]

Where \( \mu_d \) is the mean difference between paired values.

The test statistic was \( t \), and level of significance was set at \( \alpha = 0.01 \). The critical \( t \) value is therefore 2.63 at 98 degrees of freedom. The null hypothesis should be rejected if the calculated \( t \) value is above the critical \( t \) value. The calculated \( t \) value was 1.95, which is below 2.63, and so the null hypothesis was not rejected. Table 3-5 shows these results.
Table 3-5  Paired t-test results for fitted Z-distribution for impeded trip time

<table>
<thead>
<tr>
<th>Observed Frequency minus Calculated Frequency</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error of the Mean</th>
<th>99% Confidence Interval of the Difference</th>
<th>Degrees of Freedom</th>
<th>Significance (2-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00223</td>
<td>.01136</td>
<td>.00011</td>
<td>-.0008</td>
<td>.0052</td>
<td>1.95</td>
<td>98</td>
</tr>
</tbody>
</table>

Source: Dataset SPSS analysis

Since the null hypothesis is not rejected, the Dagum-Burr III distribution with the above parameters can be accepted as possibly fitting the empirical distribution of impeded trip times.

Estimating Delay Costs

For the purpose of this research, estimates of the variable costs associated with changes in flight time and taxi time were required. Estimates were derived by airline for each aircraft type operated by that airline. The appropriate variable costs are those affected by the short time differences associated with variable trip times. The additional costs associated with long delays, interrupted trips or disruption were not considered in the estimation of the costs of variable trip times.

Small changes in the three components of trip time (taxi-out, airborne, and taxi-in) affect costs. The affected costs include fuel, variable maintenance, flight operations and flight attendant costs.
Three basic guidelines were followed in estimating and assigning values to flight and taxi time differences. The first was that observed trip times were compared to unimpeded block times, where unimpeded times were defined as the sum of unimpeded taxi-out, airborne, and taxi-in times. The second guideline was that actual quarterly costs reported by air carriers for their domestic operations were allocated to individual flights operated in a particular quarter, using a standard methodology. Under government regulations, airlines are required to file their quarterly expenses, using a prescribed uniform system of accounts and reports. The third guideline was that all costs were converted to 2005 dollars using the Gross Domestic Product Implicit Price Deflator Series GDPEF (U.S. Department of Commerce, 2008).

There are two components of cost required for measuring the costs of delayed flights (or for measuring cost reduction from delay avoidance). The first component consists of flying operations, flight attendant, variable maintenance, and any additional airline-incurred costs for flights with departure delays. The second component is jet fuel usage, which was used, together with an individual airline's reported cost per gallon for each calendar quarter, to develop fuel expense. Unit costs were developed, by airline, by aircraft type, by calendar quarter and were allocated to individual flights. Once allocated to flights, the costs could be aggregated in a flexible manner.

Excluded from short-term variable costs analysis are aircraft servicing expense, traffic servicing expense and other costs that can be considered as indirect. For example, airport landing fees are properly excluded from short term variable costs, since landing fees do not vary with short trip time differences.
The approach used to develop unit costs in this research was designed to track variations in overall airline-reported quarterly fuel and operating expense. The allocation of costs to individual flights appears to be conform to costs used in FAA (2005; 2008c; 2008d), as discussed in Chapter 2 above. Although the research methodology was designed to derive representative absolute values for unit costs, the main use of costs in this research was to evaluate relative cost differences (as opposed to absolute cost values). For fuel costs for example, the difference in fuel consumption between an observed trip and an unimpeded trip were compared. Observed and unimpeded taxi times were compared to obtain the difference in taxi fuel consumption. Observed and unimpeded airborne times were compared to obtain differences in airborne fuel consumption. The same amount of fuel for a landing-takeoff cycle was assumed for the observed flight and the unimpeded flight. The difference in trip fuel consumption was then multiplied by the airline's reported unit fuel cost for the applicable calendar quarter to obtain a fuel cost difference between an observed flight and the unimpeded flight.

A similar procedure was followed in estimating flight crew, flight attendant, and variable maintenance costs. The relevant research question was: how much more did the trip cost than an unimpeded trip would have cost, if operated by the same airline over the same route with the same aircraft type during the same calendar quarter?

The issue that must be considered is whether the costs that are allocated using this methodology can be considered as representative of actual short-term variable costs. Flying operations (pilot) and flight attendant costs were assumed to vary directly with duty hours and block time. Fuel usage was assumed to vary with taxi and airborne time.
(Fuel used per landing-takeoff cycle was assumed to be the same for observed and unimpeded flights). A proportion of maintenance costs were variable.

A number of studies have attempted to classify aircraft maintenance costs by flight cycle and by flight time (ATA, 1967; Boeing, 1973). The approach taken in this research was to assume that 60 percent of maintenance expense varied with block hours. This estimate was based on a subjective judgment that 50 percent was too low, and 70 percent was too high. The evidence in Airbus Industrie (1998) is that an estimate of 50 percent, a common rule of thumb in airline costing, may underestimate the variability of maintenance costs. An earlier review of the distribution of per-hour and per-cycle maintenance costs (Boeing, 1973) covered individual aircraft subsystems, with variable costs generally estimated as 60 to 70 percent of total costs for typical flight stage lengths.

The flowchart in Figure 3-12 shows steps for allocating quarterly airline-reported costs and jet fuel costs and usage to individual flights observed during the same quarter.
Figure 3-12. Cost assignment methodology flow chart
The cost assignment process started with BTS data on airline reported quarterly
expenses for nonfuel flying operations (flight crew), flight attendants, fuel and certain
components of maintenance costs. Costs for the U.S. domestic reporting entity were used
for carriers reporting on-time data. The associated BTS monthly airline traffic reports and
quarterly jet fuel consumption reports for individual aircraft types were aggregated by
calendar quarter.

Quarterly operating costs were adjusted for charter and nonrevenue flying, based on
airline traffic reports filed with BTS. Airline traffic reports were also used to develop
block hours in scheduled service for each reporting airline by aircraft type.

For airlines operating multiple types of aircraft, overall quarterly domestic costs were
allocated to aircraft types based on weighted block hours. A reference aircraft (Boeing
737-300) was used to establish a unit weight, with other aircraft weighted based on
maximum landing weight for a generic aircraft of that type. The Boeing 737-300
represented the aircraft with the most-reported block hours in the research dataset, and
was in the mid-range of all aircraft in the dataset in terms of seating capacity.

Relative weights were developed for the 57 individual aircraft types in the dataset.
Each aircraft type was assigned a weight relative to the reference aircraft with respect to
its maximum landing weight, operating weight empty, takeoff gross weight, and seating
capacity. Table 3-6 shows relative weighting factors for the leading 35 aircraft (ranked by
number of departures) in the research dataset.
<table>
<thead>
<tr>
<th>Aircraft type</th>
<th>Relative maximum takeoff weight</th>
<th>Relative maximum landing weight</th>
<th>Relative operating weight empty</th>
<th>Relative average seats</th>
<th>Percent of departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-737-300</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>18.0</td>
</tr>
<tr>
<td>MD-80 series</td>
<td>1.011</td>
<td>1.115</td>
<td>1.119</td>
<td>1.030</td>
<td>15.2</td>
</tr>
<tr>
<td>B-757-200</td>
<td>1.841</td>
<td>1.801</td>
<td>1.803</td>
<td>1.386</td>
<td>8.8</td>
</tr>
<tr>
<td>B-737-200</td>
<td>0.834</td>
<td>0.901</td>
<td>0.838</td>
<td>0.856</td>
<td>6.0</td>
</tr>
<tr>
<td>B-727-200</td>
<td>1.372</td>
<td>1.325</td>
<td>1.351</td>
<td>1.121</td>
<td>5.8</td>
</tr>
<tr>
<td>DC-9-30</td>
<td>0.874</td>
<td>0.875</td>
<td>0.815</td>
<td>0.758</td>
<td>5.1</td>
</tr>
<tr>
<td>Airbus A320</td>
<td>1.226</td>
<td>1.220</td>
<td>1.282</td>
<td>1.129</td>
<td>4.4</td>
</tr>
<tr>
<td>B-737-500</td>
<td>0.895</td>
<td>1.033</td>
<td>1.138</td>
<td>0.833</td>
<td>4.3</td>
</tr>
<tr>
<td>RJ-200</td>
<td>0.383</td>
<td>0.403</td>
<td>0.427</td>
<td>0.371</td>
<td>3.6</td>
</tr>
<tr>
<td>B-737-700</td>
<td>1.116</td>
<td>1.108</td>
<td>1.170</td>
<td>1.015</td>
<td>3.5</td>
</tr>
<tr>
<td>Airbus A319</td>
<td>1.202</td>
<td>1.153</td>
<td>1.230</td>
<td>0.932</td>
<td>2.6</td>
</tr>
<tr>
<td>B-737-400</td>
<td>1.036</td>
<td>1.063</td>
<td>1.061</td>
<td>1.076</td>
<td>2.6</td>
</tr>
<tr>
<td>Embraer-145</td>
<td>0.334</td>
<td>0.365</td>
<td>0.369</td>
<td>0.379</td>
<td>2.6</td>
</tr>
<tr>
<td>Fokker 100</td>
<td>0.661</td>
<td>0.755</td>
<td>0.754</td>
<td>0.697</td>
<td>2.6</td>
</tr>
<tr>
<td>B-737-800</td>
<td>1.258</td>
<td>1.255</td>
<td>1.271</td>
<td>1.152</td>
<td>2.1</td>
</tr>
<tr>
<td>Embraer-135</td>
<td>0.302</td>
<td>0.350</td>
<td>0.347</td>
<td>0.280</td>
<td>1.5</td>
</tr>
<tr>
<td>B-767-300</td>
<td>2.975</td>
<td>2.573</td>
<td>2.720</td>
<td>1.758</td>
<td>1.4</td>
</tr>
<tr>
<td>DC-9-50</td>
<td>0.874</td>
<td>0.943</td>
<td>0.855</td>
<td>0.939</td>
<td>1.2</td>
</tr>
<tr>
<td>B-717-200</td>
<td>0.874</td>
<td>0.943</td>
<td>0.949</td>
<td>0.886</td>
<td>1.0</td>
</tr>
<tr>
<td>Embraer-120</td>
<td>0.186</td>
<td>0.221</td>
<td>0.231</td>
<td>0.227</td>
<td>1.0</td>
</tr>
<tr>
<td>B-767-200</td>
<td>1.364</td>
<td>2.384</td>
<td>2.533</td>
<td>1.326</td>
<td>0.8</td>
</tr>
<tr>
<td>RJ-100</td>
<td>0.368</td>
<td>0.403</td>
<td>0.416</td>
<td>0.394</td>
<td>0.7</td>
</tr>
<tr>
<td>SF-340</td>
<td>0.209</td>
<td>0.244</td>
<td>0.263</td>
<td>0.250</td>
<td>0.7</td>
</tr>
<tr>
<td>DC-9-10</td>
<td>0.655</td>
<td>0.701</td>
<td>0.690</td>
<td>0.576</td>
<td>0.4</td>
</tr>
<tr>
<td>DC-9-40</td>
<td>0.823</td>
<td>0.875</td>
<td>0.811</td>
<td>0.833</td>
<td>0.4</td>
</tr>
<tr>
<td>L-1011</td>
<td>3.682</td>
<td>3.070</td>
<td>3.434</td>
<td>2.242</td>
<td>0.4</td>
</tr>
<tr>
<td>MD-90</td>
<td>1.126</td>
<td>1.218</td>
<td>1.218</td>
<td>1.129</td>
<td>0.4</td>
</tr>
<tr>
<td>Airbus A300-600</td>
<td>2.626</td>
<td>2.647</td>
<td>2.750</td>
<td>1.977</td>
<td>0.3</td>
</tr>
<tr>
<td>Airbus A321</td>
<td>1.321</td>
<td>1.381</td>
<td>1.469</td>
<td>1.288</td>
<td>0.2</td>
</tr>
<tr>
<td>ATR-72</td>
<td>0.350</td>
<td>0.413</td>
<td>0.395</td>
<td>0.492</td>
<td>0.2</td>
</tr>
<tr>
<td>B-757-300</td>
<td>1.971</td>
<td>1.921</td>
<td>1.958</td>
<td>1.720</td>
<td>0.2</td>
</tr>
<tr>
<td>B-767-400</td>
<td>3.249</td>
<td>3.002</td>
<td>3.163</td>
<td>2.068</td>
<td>0.2</td>
</tr>
<tr>
<td>B-777</td>
<td>3.935</td>
<td>3.816</td>
<td>4.180</td>
<td>2.227</td>
<td>0.2</td>
</tr>
<tr>
<td>DC-10-10</td>
<td>3.105</td>
<td>3.117</td>
<td>3.392</td>
<td>2.144</td>
<td>0.2</td>
</tr>
<tr>
<td>Dornier 328</td>
<td>0.223</td>
<td>0.250</td>
<td>0.276</td>
<td>0.242</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Source: FAA and manufacturer data
Four different weighting methods were evaluated. These were: (1) maximum takeoff gross weight; (2) maximum landing weight; (3) operating weight empty; and (4) nominal seating capacity. The weighting factors were used to develop weighted block hours and weighted duty hours. Weighted block hours and weighted duty hours were used to allocate the relevant quarterly airline reported costs to the individual aircraft types operated by the airline in the same calendar quarter.

Use of these alternative weighting methods did not produce major differences in the cost allocations. For airlines operating a limited number of aircraft types, this was to be expected, since quarterly reported costs were allocated to a homogeneous fleet.

Since not all airlines are in this category, each of the four weighting methods was evaluated against the other methods in a series of pairwise tests of confidence intervals. This was done separately for flying operations (flight crew) costs, flight attendant costs and variable maintenance costs. The statistical test was set up to compare reported airline quarterly total expense for flight crew, flight attendants, and variable maintenance with the calculated expense in the same categories. The calculated expense was developed by allocating costs downwards to the individual flight level, then aggregating all flights in a calendar quarter upward to reproduce the reported quarterly airline expense as closely as possible.

The results of the test procedure are shown in Table 3-7. The desired outcome was to find the smallest confidence range for the mean that includes zero at a level of significance $\alpha = 0.01$. 
Table 3-7. Confidence intervals for allocating variable cost elements

<table>
<thead>
<tr>
<th>Pair</th>
<th>Description</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>Std. Error of the Mean</th>
<th>99% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair 1</td>
<td>reported_pilot - MLW_pilot</td>
<td>-0.009</td>
<td>2.044</td>
<td>.087</td>
<td>-.234 to .216</td>
</tr>
<tr>
<td>Pair 2</td>
<td>reported_pilot - OWE_pilot</td>
<td>-0.594</td>
<td>2.448</td>
<td>.104</td>
<td>-.863 to -.325</td>
</tr>
<tr>
<td>Pair 3</td>
<td>reported_pilot - Seat_pilot</td>
<td>0.446</td>
<td>2.028</td>
<td>.086</td>
<td>.223 to .669</td>
</tr>
<tr>
<td>Pair 4</td>
<td>reported_pilot - TOGW_pilot</td>
<td>0.103</td>
<td>2.430</td>
<td>.103</td>
<td>-.164 to .371</td>
</tr>
<tr>
<td>Pair 1</td>
<td>reported_flt_att - MLW_flt_att</td>
<td>-0.082</td>
<td>2.168</td>
<td>.092</td>
<td>-.320 to .157</td>
</tr>
<tr>
<td>Pair 2</td>
<td>reported_flt_att - OWE_flt_att</td>
<td>-0.194</td>
<td>2.007</td>
<td>.085</td>
<td>-.415 to .027</td>
</tr>
<tr>
<td>Pair 3</td>
<td>reported_flt_att - Seat_flt_att</td>
<td>0.018</td>
<td>2.054</td>
<td>.087</td>
<td>-.208 to .244</td>
</tr>
<tr>
<td>Pair 4</td>
<td>reported_flt_att - TOGW_flt_att</td>
<td>-0.047</td>
<td>2.920</td>
<td>.124</td>
<td>-.368 to .274</td>
</tr>
<tr>
<td>Pair 1</td>
<td>reported_maint - MLW_maint</td>
<td>0.025</td>
<td>2.458</td>
<td>.105</td>
<td>-.245 to .296</td>
</tr>
<tr>
<td>Pair 2</td>
<td>reported_maint - OWE_maint</td>
<td>-0.254</td>
<td>2.244</td>
<td>.096</td>
<td>-.500 to -.007</td>
</tr>
<tr>
<td>Pair 3</td>
<td>reported_maint - Seat_maint</td>
<td>0.150</td>
<td>2.278</td>
<td>.097</td>
<td>-.100 to .401</td>
</tr>
<tr>
<td>Pair 4</td>
<td>reported_maint - TOGW_maint</td>
<td>0.018</td>
<td>2.090</td>
<td>.089</td>
<td>-.212 to .248</td>
</tr>
</tbody>
</table>

Source: SPSS analysis of research data

For flying operations, a weighting based on aircraft maximum landing weight met the selection criteria. For flight attendant expense, nominal aircraft seating capacity met the criteria. For variable maintenance costs, aircraft maximum takeoff gross weight met the criteria.

The next step in developing variable costs was to test for a relationship between departure delay and airline passenger service costs. A statistically significant relationship was found (p less than 0.001) between costs reported as passenger service expense and weighted departure delay hours (weighted by aircraft maximum landing gross weight).
The model employed was:

\[
passenger\ service\ cost = a \times \text{weighted\ hours\ of\ departure\ delay} + b_{1,1} \\
\times \text{annual\ passengers}_{1,1} + \ldots + b_{j,y} \times \text{annual\ passengers}_{j,y} \\
+ \ldots + b_{j,y} \times \text{annual\ passengers}_{j,y}
\]

where:

- passenger service cost = passenger service cost
- weighted hours of departure delay = weighted departure delay hours
- annual passengers\textsubscript{\textit{j},\textit{y}} = annual passengers for airline \textit{j} in year \textit{y}
- \textit{a} = coefficient for weighted departure delay hours
- \textit{b}_{\textit{j},\textit{y}} = coefficient for annual passengers\textsubscript{\textit{j},\textit{y}}

The model estimated coefficient \textit{a} to be $284 per weighted departure-delay hour, or $4.73 per weighted departure-delay minute. The model likelihood ratio chi-square value was 2.84 times 10\textsuperscript{12}, with 141 degrees of freedom, compared to an intercept-only model. This represents a \textit{p} value of less than 0.001.

Thus for a reference aircraft (B-737-300) the additional passenger service cost per minute of departure delay was estimated as $4.73. This value applied to departure delays for all airlines except for Southwest Airlines. Southwest Airlines has a different operating model from other airlines, and has lower passenger service costs. Applying $4.73 per weighted minute of departure delay to Southwest's costs resulted in negative quarterly passenger service costs for the years 1998 and 2000. This presented a problem, in that there was insufficient data to estimate a cost per minute of departure delay for a single airline. To avoid implied negative annual passenger service costs, the cost per weighted
minute of departure delay for Southwest was adjusted proportionally downwards to $3.00 for a B-737-300 reference aircraft.

Expenses associated with departure delays include additional gate agents, ground crew, maintenance troubleshooting, gate occupancy and aircraft parking fees, as well as potential costs of missed connections, missed baggage transfers, and rebooking passengers on other flights. In this research, only those costs associated with passenger service expense were considered. Departure delay-associated flying operations and flight attendant expense are assumed to be covered separately under duty hours.

Airline reported quarterly costs for flying operations, flight attendant cost, and estimated variable maintenance cost (at 60 percent of total maintenance cost) were divided by the weighted activity factors for the quarter. This gave weighted unit costs for an airline for that quarter. The computed unit costs and weights were stored in a table and were applied at the individual flight level according to the airline, the cost category, and the weight for the specific aircraft type assigned to the flight. The basic variable cost equation for non-fuel expense at the individual flight level was the following:

\[
\text{op\_exp\_less\_fuel\_var} = \text{flight\_crew\_cost} + \text{flt\_att\_cost} + \text{maint\_cost\_var}
\]

where:

- \(\text{op\_exp\_less\_fuel\_var}\): non-fuel variable operating expense
- \(\text{flight\_crew\_cost}\): flying operations expense (excluding fuel) using the calculated airline unit cost for this category, weighted by aircraft maximum landing weight for the crew duty time calculated for the flight
- \(\text{flt\_att\_cost}\): flight attendant expense using the calculated airline unit cost for this category, weighted by aircraft seating capacity for the crew duty time calculated for this flight
The maintenance variable expense using the calculated airline unit cost for this category, weighted by aircraft maximum takeoff gross weight for the number of observed block hours for this flight.

Crew duty time was assumed to begin at the scheduled time of flight departure, and end at the reported actual time of flight arrival. The cost allocation program was written in C/C++, and the above variable names were assigned to keep track of the costs allocated at the flight level.

A term to account for delay expense was added to the variable operating expense:

\[
\text{op\_exp\_less\_fuel\_del} = \text{op\_exp\_less\_fuel\_var} + \text{car\_psgr\_svc\_delay\_cost}
\]

Where:

\[
\text{car\_psgr\_svc\_delay\_cost} \quad \text{is a measure of the variable cost incurred by an airline for a delayed departure.}
\]

Unimpeded costs were developed at the same time as each individual flight was evaluated.

\[
\text{u\_op\_exp\_less\_fuel\_var} = \text{u\_flight\_crew\_cost} + \text{u\_flt\_att\_cost} + \text{u\_maint\_cost\_var}
\]

Where:

\[
\text{u\_op\_exp\_less\_fuel\_var} \quad \text{unimpeded non-fuel variable operating expense}
\]

\[
\text{u\_flight\_crew\_cost} \quad \text{unimpeded flying operations variable expense (excluding fuel) using the calculated airline unit cost for this category,}
\]
weighted by aircraft maximum landing weight for the number of unimpeded block hours for this flight

\[ u_{flt\_att\_cost} \]
unimpeded flight attendant expense using the calculated airline unit cost for this category, weighted by aircraft seating capacity for the number of unimpeded block hours for this flight

\[ u_{maint\_cost\_var} \]
unimpeded maintenance variable expense using the calculated airline unit cost for this category, weighted by aircraft maximum takeoff gross weight, for the number of unimpeded block hours for this flight

For unimpeded flying operations and flight attendant expense, block hours were used instead of duty hours. Unimpeded flights are assumed to operate with no departure delays, so block hours are a measure comparable to duty hours for observed flights.

There is an advantage to the approach taken here. The advantage is one of allocating costs consistently across carriers. Although the U.S. DOT prescribes in great detail how costs are to be allocated under its uniform system of airline accounts and reports (BTS, 2008d), there are differences between airlines in their internal expense allocation processes. The use of top level expenses for the major categories of flying operations, fuel, flight attendants and maintenance, for the domestic reporting entity, minimizes differences between airlines in internal allocation.

Fuel usage by aircraft type was developed separately, as follows: total fuel usage across all airlines by individual aircraft type was analyzed, together with total block time and airborne time. Total fuel usage by aircraft type was obtained from airline quarterly data reported to BTS. Taxi-out time, airborne time, and taxi-in time were tracked separately by airline, aircraft type, and flight.
Fuel flow rates for individual engine types was obtained from the ICAO engine emissions databank (ICAO, 2008). Fuel usage was assumed to be related to taxi time (basically at ground idle thrust), landing-takeoff (LTO) cycle, and airborne time. Data for engine idle fuel flow and fuel usage per LTO cycle (ICAO, 2008a) were used to estimate rates of taxi fuel and airborne fuel usage by engine type for the 41 engines types representative of those installed in aircraft reported in the dataset. These values were next applied to the individual aircraft types powered by those engines (77 different aircraft types were included in a lookup table). Taxi fuel consumption (based on reported taxi times) and LTO cycle fuel were each subtracted from reported gallons issued, leaving the residual as airborne fuel. The airborne fuel calculated in this manner was divided by the associated airborne hours to obtain an estimated fuel flow rate per unit of airborne time.

Torenbeek (1982) provides an introduction to jet transport aircraft propulsion and performance. In actual operation, fuel consumption varies mainly with aircraft weight, speed, altitude, temperature, and change in altitude (climb, level flight, or descent). The methodology used here is approximate.

Additional references in Cook et al. (2004), CASA (2007), EUROCONTROL (2007a), were used as a basis for comparison with fuel burn estimates prescribed for regulatory analyses for individual aircraft types.

When the model was tested by aggregating costs and fuel usage for all flights in the research dataset by airline and calendar quarter, the results for reported top-down operating expense and fuel cost were generally in agreement with aggregated bottom-up operating expense and fuel cost within two to three percent. The aggregated operating
costs and fuel costs were typically in a range two or three percent below an airline's quarterly expense report for each category.

In the course of this analysis, some discrepancies arose for airlines that started reporting their on-time performance in mid-quarter. Their top down costs needed to be adjusted proportionally to represent costs allocated to the flights reported to BTS in on-time reports.

The costing approach used in this research excludes aircraft rental expense (associated with leased aircraft) and does not allocate depreciation expense to short term costs. This raises a concern that the costing approach might underestimate short term variable costs for airlines that lease aircraft and engines, and whose lease contracts include payments based on hourly usage. However, for the purpose of this research, the variable cost model captures the major elements of short-term variable costs, does not depart materially from current costs used in FAA regulatory analyses, and thus can be considered adequate for its purpose.

A second concern was with the assignment of costs to activity factors. Fuel usage was estimated separately for taxi time and for airborne time. Fuel cost was determined using each airline's reported fuel cost per gallon by calendar quarter. This allocation seemed justified by a bottom-up aggregation that closely matched each airline's quarterly overall fuel usage.

Maintenance costs were assumed to vary by block hour, consistent with accepted airline costing analysis. A possible refinement would have been to develop variable maintenance costs by cycle and by hour separately. This approach was rejected in favor
of the simpler approach. The simpler block-hour approach was considered to be adequate for cost allocation in this research.

Flight crew and flight attendant costs were at first allocated by block hour. The problem in this case was the treatment of flights with departure delays, since a crew needs to be assigned to cover a flight at the scheduled time of departure, and thus departure delays need to be charged against flight crew monthly time limits. Even in cases where flight crews assigned to delayed flights can be reassigned at short notice to cover other flights, another crew has to be found for the original flight. This issue was resolved in the allocation process by constructing a "duty hour" variable, defined as the sum of a flight's departure delay and block hours. Flight crew expense was thus allocated according to duty hours, as noted previously. This was done by dividing an airline's quarterly reported crew expense by the sum of all reported weighted departure delays and calculated weighted duty hours (by airline and aircraft type) for that quarter.

For the value of passenger time, a separate methodology was required. The U.S. DOT standard value of $28.60 per person-hour (DOT, 2003a) was applied to departure delays and to impeded trip times (the excess of observed trip times over unimpeded trip times). The reported actual number of passengers carried and departures performed by airline using a specific aircraft type on specific airport-pair nonstop segment was used to develop a monthly average number of passengers per departure. This monthly average was applied to each flight in the dataset, according to airline, route, segment, and aircraft type. A number of passengers based on this average could then be associated with any departure delay and excess flight time above unimpeded flight time for an individual flight.
Research Methodology in Summary

The methodology presented in this chapter was used to address the research questions. The research dataset was developed from airline data filed with BTS, from FAA aircraft registry data, and other publicly available sources. The research dataset was used for analysis. Unimpeded times were developed for taxi-out, airborne, and taxi-in flight phases. Costs were allocated from quarterly reported airline costs for flying operations, flight attendants and maintenance down to individual flights. Individual airline quarterly reported fuel cost per gallon was used, with fuel consumption estimated for taxi, for landing-takeoff cycle, and for airborne hour for individual aircraft types. All costs were converted to 2005 (constant) dollars.

Results of the analysis are presented in chapter 4.
CHAPTER 4

RESULTS AND ANALYSIS

Summary of Results

This chapter begins with an analysis of the pattern of delays as currently reported, and continues with a discussion of unimpeded trip times and costs. An analysis of the overall size of the problem in terms of impeded trip times and costs is followed by an analysis of time and cost incidence of trip times viewed from different perspectives. The chapter ends with an evaluation of how various levels of improved system operation could reduce impeded costs and trip time variability.

The results of this research are presented in the following sequence:

1. Flight arrival delays as currently reported
2. Distribution of flight arrival delays
3. Shortcomings of reported arrival delays
4. Impeded trip times and costs as a better measure
5. Sizing the impact of impeded trip times
6. The incidence of impeded trip times and costs
7. The value of reducing impeded trip times and impeded trip time variability

There were three parts to this research: unimpeded times; short-term variable costs; and the distribution of delays.
Flight Arrival Delays as Measured Today

Table 4-1 shows characteristics of flight (airborne) times, stage lengths and arrival delays for U.S. domestic scheduled air service. Mean flight arrival delay was 7.0 minutes in 1995. Between 1995 and 2005 mean flight arrival delay reached a peak of 10.5 minutes in 2000, dropped to a low of 3.2 minutes in 2002, and ended the period in 2005 at 7.2 minutes. Arrival delay standard deviation showed a similar rise and fall pattern: increasing from 26.1 minutes in 1995 to 32.9 minutes in 1999; reaching a peak of 34.9 minutes in 2000; falling to 29.3 minutes in 2002; and rising in 2003 an 2004 to end the period in 2005 at 34.0.

Table 4-1. Airline flight time, distance, and arrival delay 1995-2005

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight time in minutes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>97</td>
<td>100</td>
<td>101</td>
<td>103</td>
<td>105</td>
<td>106</td>
<td>103</td>
<td>106</td>
<td>101</td>
<td>101</td>
<td>103</td>
</tr>
<tr>
<td>Median</td>
<td>79</td>
<td>82</td>
<td>83</td>
<td>85</td>
<td>86</td>
<td>88</td>
<td>84</td>
<td>87</td>
<td>82</td>
<td>82</td>
<td>84</td>
</tr>
<tr>
<td>Flight stage length in statute miles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>695</td>
<td>713</td>
<td>725</td>
<td>740</td>
<td>754</td>
<td>765</td>
<td>736</td>
<td>760</td>
<td>713</td>
<td>716</td>
<td>727</td>
</tr>
<tr>
<td>Median</td>
<td>545</td>
<td>558</td>
<td>575</td>
<td>588</td>
<td>595</td>
<td>602</td>
<td>574</td>
<td>599</td>
<td>550</td>
<td>547</td>
<td>569</td>
</tr>
<tr>
<td>Arrival delay per flight in minutes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>7.0</td>
<td>9.7</td>
<td>7.5</td>
<td>7.6</td>
<td>8.2</td>
<td>10.5</td>
<td>5.5</td>
<td>3.2</td>
<td>3.5</td>
<td>6.5</td>
<td>7.2</td>
</tr>
<tr>
<td>Median</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-2</td>
<td>-3</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td>75th percentile</td>
<td>10</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>11</td>
<td>14</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>85th percentile</td>
<td>20</td>
<td>24</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>28</td>
<td>20</td>
<td>17</td>
<td>17</td>
<td>22</td>
<td>23</td>
</tr>
<tr>
<td>95th percentile</td>
<td>43</td>
<td>53</td>
<td>46</td>
<td>52</td>
<td>55</td>
<td>65</td>
<td>50</td>
<td>41</td>
<td>43</td>
<td>55</td>
<td>57</td>
</tr>
<tr>
<td>Std. deviation</td>
<td>26.1</td>
<td>30.2</td>
<td>28.2</td>
<td>31.3</td>
<td>32.9</td>
<td>35.9</td>
<td>31.2</td>
<td>29.3</td>
<td>29.6</td>
<td>33.2</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Source: Research dataset

Table 4-1 also includes changes in mean and median values for trip time and trip distance. The mean trip times and flight stage lengths fall within a narrow range.
Airborne speed can be calculated from mean flight stage lengths and mean flight times. A conclusion can be drawn that flight times for comparable stage lengths increased by one to two minutes in the second half of the study period compared to the first half.

Standard deviation is a basic statistical measure of variability, and helps explain relative trip time variability. However, airline trip times and arrival delays are not normally distributed. The mean and standard distribution are inflated, influenced by delay values in the heavy right tail of the distribution. An indication that the distribution of arrival delays is not governed by normal theory is the relationship of the standard deviation of arrival delays to their mean values is that, between 1995 and 2005, the standard deviation of arrival delays ranged from 26 minutes to 36 minutes, while mean values ranged from 3 minutes to 10 minutes. Median arrival delays ranged from -3 minutes to +2 minutes. For distributions with extreme values, the median and upper extreme values, along with selected percentiles, are better indicators of trends in delay and its variability than are the mean and standard deviation (Gumbel, 1958).

Table 4-1 includes the median (50th percentile), 75th percentile, 85th percentile, and 95th percentile. The box-plot in Figure 3-2 portrays the trends in median annual arrival delay, with upper and lower quartiles boxing the median, with whiskers extending to fences at the 5th and 95th percentiles. Two lines have been overlaid on the box-plot. The lower line (dashed line) graphs the mean annual arrival delay. The upper line (solid line) graphs the 85th percentile arrival delay.
A close look at Figure 4-1 shows that median flight arrival delays are close to zero, that the upper quartile of flight delays (upper limit of the box) are below 15-minutes. The length of the box and the length of the upper whiskers indicate the degree of trip time variability. The position of the median relative to zero can be interpreted as an indicator of extra buffer time has been added to the schedule in order to reduce reported delays. Positive values of the median in the 1990s may be an indicator of buffer times that were too low, and negative values of the median after 2000 may indicate schedule buffer times added to improve consumer reporting and to offset poor system performance.

The patterns in Table 4-1 and Figure 4-1 reflect high air traffic growth from 1995 to 2000. Unusual summer 2000 convective weather across the United States, together with
an action by Congress to remove airport slot limitations at New York LaGuardia Airport, introduced the term “gridlock” to air traffic management discussions. One explanation is that poor 2000 delay performance led to improvement in FAA air traffic flow control between 2001 and 2005. U.S. domestic airline passenger traffic declined after September 11, 2001. By 2005, air traffic had exceeded 2000 levels, but FAA and airline cooperation on flow control had improved.

Arrival Delay Distribution

Reporting of airline delays serves a dual purpose. One purpose is to inform consumers. The other is to report on system performance (Odoni, 2000). The concern in this research is system performance.

The discussion in this section begins with arrival delays as currently reported. In current airline delay reporting, the standard against which delay is measured is the airline schedule in an airline's computer reservation system (CRS). The scheduled flight departure and flight arrival times are defined by the individual airline.

Arrival delay is a measure of system performance. Delays can be taken at any stage of a trip, but the delay that counts is the delay as measured on arrival. It is useful to consider the 85th percentile value of arrival delay expressed in minutes. This corresponds to a probability of 0.85 that a flight's arrival will occur inside a time limit. If the 85th percentile delay is below 15 minutes, and 15 minutes is the standard for being on-time, then more than 85 percent of flights will be on-time.

As shown above in Table 4-1 and Figure 4-1, the lowest annual 85th percentile arrival delays reported between 1995 and 2005 were 17 minutes each in 2002 and 2003. The highest reported annual 85th percentile arrival delay was 28 minutes in 2000.
Figure 4-2 shows graphically how 85 percent arrival punctuality varied over the period 1995-2005, as a function of flight distance in statute miles.

Source: Research dataset

Figure 4-2. 85-percent arrival punctuality by year and stage length

Figure 4-2 illustrates that there was variation in arrival punctuality with distance between 1995 and 1999, but the difference lessened in 2000 and following years. Figure 4-3 extracts two years from those shown in Figure 4-2 above: 1996 and 2003. In 1996 flights operated in the 2,250 and 2,500 mile blocks were consistently less punctual, and thus had 85 percent delays that were higher than reported for flights with shorter stage lengths in that year. There could be two explanations for this—either the delays were actually higher, or the scheduled flight times did not have enough buffer time.
By 2003, the variation of punctuality with stage length had flattened. A possible explanation is that airlines increased their long distance scheduled trip times in order to improve reported on-time performance. Arrival punctuality can be improved either by adding buffer time to the published schedule, or through operational improvements. For consumer reporting, truth in advertising requires buffer time so that schedules are not misrepresented. For operational reporting, adding buffer time hides poor performance.

An approach that maintains a balance between consumer reporting and performance reporting aims of delay reporting is to control for buffer time through a median-adjusted upper 85th percentile delay value. Delay value would be expressed as the difference between the 85th percentile delay and the median (50th percentile) delay.
Arrival delay is today determined by measuring average minutes of delay relative to a scheduled arrival time set by an airline. The airline can absorb expected poor ATM system performance, or poor company dispatch reliability, by including more slack in its schedule, at the expense of extra time imposed on customers and lower operational productivity. Negative values for median flight delays (as shown in Table 4-1 and Figure 4-1 for the years 2001 through 2006) are an indicator of excess slack in a schedule, necessitated to report on-time operation. A positive value for median flight delay (for example, in 1996) indicates inadequate slack. The median arrival delay is thus controlled by airline selection of a published flight schedule time.

Given the current system for measuring and reporting delays, and given the distribution of arrival delays, median-adjusted delay would be a useful system performance measure:

\[
d_{median-adjusted \ delay} = t_{on-time, 85} - t_{on-time, 50}
\]

Median-adjusted delay offers a better 85th percentile metric for system management and performance reporting. This would correct bias created by buffering for consumer reporting and would serve to focus attention on improving schedule punctuality and reducing trip time variability.

Figure 4-4 applies such a median adjustment to get a better view of 85 percent arrival punctuality by distance. Figures 4-2 (with no median adjustment) and 4-4 (with median adjustment) both portray the across-the-board increase in the delay measure in 2000, with a reduction in 2001 through 2003, followed by an increase in 2004 and 2005.
After median adjustment, the 1996 long flights have less of a peaking effect. There is still some peaking, which shows that these flights are experiencing more minutes of delay. It is also evident that the 1996 scheduled times for these flights were too short.

Between 2000 and 2005, reported on-time performance does not appear to vary significantly with distance at the longer stage lengths, and there do not appear to be obvious differences between the unadjusted and adjusted charts.

Source: Research dataset

Figure 4-4. Median-adjusted arrival punctuality
Another view of the variation in on-time performance over the 1995-2005 period is shown in Figure 4-5, which groups airports into 10 categories. The airports and airport groupings are used were:

- SMAH: Small and non hub airports
- MEDH: Medium Hub airports
- OEP1: FAA OEP tier 1 airports
- OEP2: FAA OEP tier 2 airports
- JFK: New York JFK International
- LGA: New York LaGuardia
- EWR: Newark Liberty International
- DFW: Dallas-Fort Worth International
- ORD: Chicago O'Hare International
- ATL: Atlanta Hartsfield-Jackson

The groupings reflect an assignment of airports into 10 categories. The choice not to categorize six leading airports (Atlanta, Chicago, Dallas-Fort Worth, New York LaGuardia, New York JFK, and Newark) was made because these airports have a significant impact on the National Airspace System (NAS).

The FAA defines 35 airports as Operational Evolution Partnerships (OEP) airports, according to estimates of capacity increases needed to serve future demand (Mohler, 2006; FAA 2007a). The original OEP report was issued in 2001, focusing on 35 of the busiest U.S. airports. The 35 airports include 31 airports designated as large hubs, together with Cleveland (CLE), Memphis (MEM), Portland (PDX), and Washington National (DCA) (FAA, 2004).
This research divided OEP airports into two categories, according to 2005 arrival delay performance, with OEP1 airports reporting lower delays. An airport was classified as an OPE2 airport if its combined inbound and outbound delay exceeded 5,000 hours in 2005.

Source: Research dataset

Figure 4-5. 85th percentile less median arrival delay by year and airport

Figure 4-5 plots minutes difference between the 85th percentile arrival delay and the median arrival delay. Figure 4-5 graphically portrays the severe delay problems of Chicago, Newark, and LaGuardia, (ORD, EWR, and LGA) leading up to 2000, and again
in 2004 and 2005. To a lesser extent Atlanta and Kennedy (ATL and JFK) have delay
issues.

Shortcomings of Reported Arrival Delays

The definition of impeded time as the difference between the reported actual arrival
time of a trip and the unimpeded (delay-free) time provides a time metric. However,
impeded time does not measure trip time variability.

Since trip time and delay distributions are not normally distributed, care needs to be
taken in using the mean and standard deviation as measures for reporting central
tendency and variability. The problem is how to track and report actual trip time
performance against required trip time performance, and at the same time measure both
central tendency and variability. Performance reporting should focus on the difference
between actual and required performance in both areas. Good metrics should aim for
simplicity and ease of understanding.

In contrast to the usual statistics, where the mean and standard deviation play a
dominant role, trip times and delay distributions are dominated by extreme values
(Gumbel, 1958). Use of the mean and standard deviation as measures becomes less
appropriate as distributions depart from normality and take on the attributes of extreme
value distributions. The mode becomes a more important average (Gumbel, 1958).
Closed form cumulative distribution functions are theoretically much better adapted to
dealing with the probability of delays over given class intervals or other ranges (Burr,
1942). With knowledge of the delay distribution, and with a closed form for the
cumulative distribution function, then the buffer time can be calculated directly.
Figure 4-6 builds on Figure 1-2, derived from Institut du Transport Aérien (2000) and EUROCONTROL (2002). The basic diagram was later used in presentations by Aguado (2005), Fron (2007) and EUROCONTROL (2008b). This diagram illustrates how selection of a schedule buffer can cover up poor schedule quality while maintaining “on-time” performance. The arrival delay distribution is positively skewed, with its mode, median mean and standard deviation as shown in Figure 4-6. The poor schedule quality is denoted by the high value of the assumed standard deviation (25.4 minutes).

Given trip time standard deviation, the required buffer time to include in the scheduled time is determined by the desired level of on-time reliability. Since standard
deviation is defined with reference to the mean, it is appropriate to use the mean rather than the median as the measure of central tendency for this calculation.

In this example, if \((\text{buffer} + 15)\) is set at \(0.9\sigma\) (23 minutes), then 85 percent of trips can be expected to arrive within 15 minutes of schedule. Similarly, if \((\text{buffer} + 15)\) is set to \(1.18\sigma\) (30 minutes), then 90 percent of trips can be expected to arrive within 15 minutes of schedule.

The scheduled trip time is determined by the following relationship between buffer time and scheduled time:

\[
\text{Scheduled Trip Time (minutes)} = \text{Mean Trip Time} + (\text{Buffer} + 15)
\]

Figure 4-6 illustrates how schedule buffer times are used to compensate for operational uncertainty. A desirable objective would be to have zero buffer, using only the 15-minute grace period. This would require reduction in trip time variability. From Figure 4-6 it can be seen that 0.9 times the standard deviation \((\sigma)\) is the required buffer to attain 85 percent reliability within 15 minutes. If this is the predictability target, then the maximum allowable arrival standard deviation, relative to unimpeded trip time, would be 16.7 minutes (15 minutes divided by 0.9).

The standard deviation of 16.7 minutes in the above example compares to the lowest annual arrival delay standard deviation achieved between 1995 and 2005 (26.1 minutes in 1995). The highest arrival delay standard deviation recorded during the study period was 35.9 minutes in 2000. The difference between the reported trip time variability levels and the level needed to contain schedule buffer time within a 15-minute limit suggests that an
operational objective of 15 to 20 minutes trip time variability should be considered in conjunction with an 85 percent on-time arrival standard.

Schedule buffers are necessary for maintaining a desired level of arrival performance. From the above example, three conclusions can be drawn. First, greater trip time variability requires more buffer time. Second, the buffer time required depends on the arrival delay probability distribution. Third, given a cumulative probability function, in a form that can be calculated, and that is based on a good estimate of trip time variability, the required buffer time can be calculated directly for a selected level of on-time performance.

This research developed unimpeded times as the reference against which to compare actual times. Use of unimpeded times can be justified in a research and analysis environment when a baseline can be established and when the goal is to obtain a better understanding of uncertainty and variability. Unimpeded times are problematic, however, in an operating environment when conditions are constantly changing and when there has been no sustained and systematic attempt to monitor, measure, and adjust unimpeded performance standards.

Delay can be considered to have two components corresponding to a location parameter and a scale parameter—punctuality and variability. A practical approach, which combines both central tendency and variability, would be to measure and report 85th percentile performance relative to either mean or median performance.

For operations characterized by short delays relative to trip times, the distribution of delays is symmetrical. In a symmetrical distribution, the mean and median are equal. In a situation characterized by long delays, the mean exceeds the median. In such a case, the
mean begins to lose its value as an estimator for the central tendency of delays, and other estimators are required.

A single estimator for delay is desirable. One such measure would be the definition of flight punctuality as the range between median delay and the 85th percentile delay. Variability would then be bounded by an upper containment limit.

Figure 4-7, using on-time data for all flight arrivals for all ASQP reporting airlines between 1995 and 2005, shows actual performance against such an 85th percentile requirement, with and without median adjustment. It is clear that actual performance fell short of 85 percent on-time within 15 minutes for the whole study period.
The interpretation of Figure 4-7 is that 15 percent of flights experienced arrival delays of between 19 and 27 minutes during the 1995-2005 period. The trend showed an increase between 1995 and 2000, peaking in 2000, dropped in 2001 and 2002, was level in 2003, then climbed to a plateau in 2004 and 2005.

Impeded Trip Times and Costs as a Better Measure

The obvious choice for evaluation is the combined impeded passenger time value and airline impeded cost. The research dataset supports flexible aggregation and presentation of both time and cost analyses.

As an illustrative example, Figure 4-8 plots mean impeded time variations for arrivals at 12 major airports, by calendar quarter between 1995 and 2005. The plots are shown to a common scale, with a notation for identified changes. One change is noted that affected all operations in U.S. airspace. This was the introduction of reduced vertical separation minimums (RVSM), which became effective in U.S. airspace on January 20, 2005. RVSM effectively doubled airspace capacity between 29,000 feet and 41,000 feet (Flight levels 290 to 410), as prior vertical separation minimums were reduced from 2,000 feet to 1,000 feet.
Figure 4-8. Impeded trip time variation for 12 airports by quarter 1995-2005

Source: Research dataset

Atlanta (ATL)
Cleveland (CLE)
Dallas/Fort Worth (DFW)
Houston (IAH)
Las Vegas (LAS)
Los Angeles (LAX)
Orlando (MCO)
Minneapolis/St. Paul (MSP)
New York Area Airports (NYC)
Oakland (OAK)
Chicago (ORD)
Phoenix (PHX)

RVSM in U.S. en route airspace January 2005
New IAH runway March 2004
New MCO runway February 2004
New PHX runway October 2000
CLE extension runway August 2004
The lowest level for ASQP data reporting is the individual airline flight. The research approach was to assign costs to individual flights, using the methodology described in Chapter 3. For passenger time, this was done multiplying together impeded trip time, a standard value for traveler time, and the number of passengers estimated to be on the flight. For airline costs, this was done by multiplying together impeded trip time and unit flight operating costs.

Chapters 2 and 3 included discussion of the basis in the literature for the cost assignment used in this research and the methodology used in the research. The discussion of results presented in this chapter depends on the appropriateness of the values developed in the research.

Use of a $28.60 per person-hour value for small time differences is established for regulatory and government analyses. Studies of value of time and value of disruption in the literature conclude that long delays and flight cancellations involve higher costs to travelers. There has been an ongoing debate over valuation of short time savings. However, valuation of air traveler time in the United States at $28.60 per person-hour for short variations in air traveler time has not been challenged in the literature nor in judicial or regulatory proceedings.

Traveler time value per hour was applied to the number of passengers per flight. The number was the average monthly number of on-board passengers per flight, as reported by operating airline for the specific flight route and aircraft type. This may underestimate passengers on some flights and overestimate passengers on other flights, but, on balance, represents a reasonable approach to estimating passengers by trip time variability. Using the average passenger counts will underestimate passenger loads on peak flights and
overestimate passenger counts on off-peak flights, however. This may understate the costs of delays in peak periods.

Costs of operation applied to individual ASQP flights are described in Chapter 3. The methodology developed in this research uses a standard approach to allocating individual airline quarterly reported costs and reported fuel usage across different aircraft in their fleets. For airlines operating a homogeneous fleet of aircraft, the assignment of unit costs is insensitive to the allocation methodology. For airlines operating heterogeneous fleets, the allocation methodology employed in this research may understate the costs of some aircraft and overstate others. Over 50 percent of estimated airline delay costs during the 11-year period were incurred by aircraft with between 121 and 150 seats. This category accounted for 57 percent of departures, and 56 percent of impeded trip time (Table 4-11). This does not seem an unreasonable result. Comparison of other relationships in Table 4-11 between time and cost across aircraft seat capacity categories does not indicate cause for concern over the cost allocation approach taken in this study. Airlines in the lowest seat category, up to 60 seats, are regional carriers with relatively homogeneous fleets, and the cost assignment for this group is insensitive to the allocation methodology.

Fuel usage and cost estimates were built up for individual aircraft types, based on airline quarterly reports to U.S. DOT on gallons of fuel issued, quarterly and monthly jet fuel expense reports in their domestic operations, and taxi and airborne hours reported to U.S. DOT in airline ASQP and T100 reports. This approach is relatively straightforward, and ensures that airline fuel usage and fuel expense is accounted for each aircraft type. The allocation of fuel between ground taxi and airborne times may vary from actual results, but the combined total reasonably reflects airline reports to DOT.
Table 2-2, shown earlier, presented results from two regulatory evaluations performed in 2008 (FAA, 2008c; FAA, 2008d). Table 2-2 showed average variable costs per block hour for standard jet operations by "legacy" air carriers.

An earlier regulatory evaluation performed by the FAA (2005a) used $1,364 as the variable cost per block hour. Adjusting this value for the larger reference aircraft size in the current research (132 seats) yields an estimate of between $1,600 and $1,700 per block hour for non-fuel variable operating costs. The average cost per weighted block hour developed in this research is $1,575 (in 2005 dollars).

If the assumptions of the current research are applied to fuel consumption for aircraft of the same size, using a calendar year 2007 U.S. domestic average fuel cost of $2.07 per gallon, the imputed non-fuel cost per block hour is estimated to be $1,800 for operations at JFK International Airport, and $1,600 for operations at LaGuardia and Newark Liberty Airports. These estimates are in 2005 dollars, after adjustment to reflect the 132-seat reference aircraft used in the current research.

The results of this research are developed in three steps. The first step sizes the problem of airline delays in terms of time and short-term variable cost relative to unimpeded time and cost. The second step is identification of incidence of delays in various areas. The third step is a discussion of what might be achievable from reduction of trip time variability.

Impeded Trip Times and Costs: The Size of the Problem

Table 4-2 shows, for the 11-year period from the beginning of 1995 to the end of 2005, that airline delays reported under the ASQP program imposed a cost of $86 billion on travelers and air carriers. The reporting carriers account for an estimated 76 percent of
scheduled domestic and international airline traffic at U.S. airports. Thus an approximate national delay cost for all U.S. airports over the 11 years would be $112 billion ($86 billion divided by 0.76), or $10 billion per year.

The remainder of this chapter is organized as follows. Table 4-2 provides an overview of air carrier and traveler costs by year. Table 4-3 shows how aircraft size differs for various airlines and airline groups presented in this section. The next series of tables shows aggregate time and cost figures for the 11-year period for selected factors and rankings (Tables 4-4 through 4-14). Tables 4-15 through 4-17 costs for the main components of impeded trip time. Tables 4-18 and 4-19 show the added fuel consumption and fuel costs associated with impeded trip times.

Following this, Tables 4-20 and 4-21 show how aggregate daily delays were distributed over the 4,018 days in the 11-year study period.

Table 4-2 presents an overview of the results of this research. For the estimate of aggregate 11-year delay cost of $86 billion, costs are apportioned 56 percent to the value of traveler time, and 44 percent to airline short term variable costs. The airline cost buildup is based on excess, or impeded, trip time (block time plus departure delay) over unimpeded block time. For travelers, the value of time associated with delayed departures is shown here separately from the excess trip time above unimpeded block time.

As noted earlier, unimpeded times assume no departure delay, so that unimpeded trip time is equivalent to unimpeded block time. The same is not true for impeded trip time, which includes: (1) reported departure delay; and (2) excess block time above unimpeded block time.
Table 4-2. Annual cost of impeded and delayed flights 1995-2005

<table>
<thead>
<tr>
<th>Year</th>
<th>Carrier impeded trip expense</th>
<th>Traveler time value</th>
<th>Total impeded trip cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of 2005 Dollars</td>
<td>impeded flight time</td>
<td>delayed flight time</td>
</tr>
<tr>
<td>1995</td>
<td>$2,800</td>
<td>$1,900</td>
<td>$1,800</td>
</tr>
<tr>
<td>1996</td>
<td>3,300</td>
<td>2,400</td>
<td>2,100</td>
</tr>
<tr>
<td>1997</td>
<td>3,200</td>
<td>2,100</td>
<td>2,100</td>
</tr>
<tr>
<td>1998</td>
<td>3,300</td>
<td>2,200</td>
<td>2,200</td>
</tr>
<tr>
<td>1999</td>
<td>3,500</td>
<td>2,400</td>
<td>2,400</td>
</tr>
<tr>
<td>2000</td>
<td>4,300</td>
<td>3,000</td>
<td>2,600</td>
</tr>
<tr>
<td>2001</td>
<td>3,700</td>
<td>2,000</td>
<td>2,300</td>
</tr>
<tr>
<td>2002</td>
<td>2,800</td>
<td>1,300</td>
<td>1,800</td>
</tr>
<tr>
<td>2003</td>
<td>3,000</td>
<td>1,300</td>
<td>2,200</td>
</tr>
<tr>
<td>2004</td>
<td>3,800</td>
<td>2,100</td>
<td>2,800</td>
</tr>
<tr>
<td>2005</td>
<td>3,800</td>
<td>2,600</td>
<td>2,900</td>
</tr>
<tr>
<td>Total</td>
<td>$37,500</td>
<td>$23,300</td>
<td>$25,200</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset

In Table 4-2, the drop in U.S. domestic airline traffic after September 2001 is reflected in the lower total impeded trip cost in 2002 and 2003. By 2004 and 2005, airline passenger travel had recovered, and this is reflected in the costs.

The Incidence of Impeded Trip Times and Costs

Table 4-3 shows average seats per departure by carrier group, together with the index of each carrier group's average seats per departure (relative to the overall 131 average seats per departure for all ASQP departures during the study period). In interpreting
Table 4-4, note that different carrier groups operate different fleet mixes, and thus both passengers per departure and seats per departure vary between carrier groups.

Table 4-3  Average seats per departure by carrier group

<table>
<thead>
<tr>
<th>Carrier Group</th>
<th>Seats per departure</th>
<th>Seats per departure index</th>
<th>Percent of departures</th>
</tr>
</thead>
<tbody>
<tr>
<td>JetBlue/ATA</td>
<td>171</td>
<td>1.31</td>
<td>1</td>
</tr>
<tr>
<td>Delta</td>
<td>163</td>
<td>1.24</td>
<td>14</td>
</tr>
<tr>
<td>United</td>
<td>149</td>
<td>1.14</td>
<td>11</td>
</tr>
<tr>
<td>Continental</td>
<td>141</td>
<td>1.08</td>
<td>6</td>
</tr>
<tr>
<td>American/TWA</td>
<td>140</td>
<td>1.07</td>
<td>15</td>
</tr>
<tr>
<td>Southwest</td>
<td>134</td>
<td>1.02</td>
<td>15</td>
</tr>
<tr>
<td>Northwest</td>
<td>132</td>
<td>1.01</td>
<td>9</td>
</tr>
<tr>
<td>Other major carriers</td>
<td>132</td>
<td>1.01</td>
<td>4</td>
</tr>
<tr>
<td>USAir/Amer. West</td>
<td>130</td>
<td>0.99</td>
<td>14</td>
</tr>
<tr>
<td>Regional carriers</td>
<td>44</td>
<td>0.34</td>
<td>11</td>
</tr>
<tr>
<td>Overall</td>
<td>131</td>
<td>1.00</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Research dataset

From Table 4-3 an observation can be made that Delta Air Lines and United Airlines operate with both a higher than average number of seats per departure and have a high market share. The combination of higher capacity (and consequent higher passenger loads) and high market share means that Delta and United will have a higher share of passenger delay value and air carrier delay cost than is reflected by their share of departures. To a lesser extent, this should be true of the combination of American Airlines and Trans World Airlines (TWA).
Tables 4-4 through 4-14 show the variation of aggregate 11-year results according to different grouping categories. The tables have a common format with percentage columns to help identify principal attributes of delay, including time and costs. For each table the columns add to the same total aircraft departures, aircraft block hours attributed to delayed and impeded trips, passenger delay hours, and costs of delayed and impeded time to passengers and air carriers.

Tables 4-4 through 4-14 each have ten categories, with the exception of Table 4-4, which has five categories. Examination of Tables 4-4 through 4-14 reveals a number of categories in which the aggregate cost for several categories together exceeds 50 percent. These categories deserve further attention. High cost values are, of course, associated with high numbers of departures, but in some cases the delay impacts are disproportionate to the number of departures.

Tables 4-4 through 4-14 also include a column showing mean delay hours per passenger. This figure represents total passenger delay plus impeded time divided by total passengers in the relevant category. The total number of passengers was obtained by aggregating the passengers assigned to each flight, derived from airline reporting of monthly passengers transported by route and aircraft type in BTS T100 reports.

In interpreting Tables 4-4 through 4-14, it is helpful to focus on categories that represent a large proportion of delays and impeded flights. Particularly interesting are the results shown for scheduled (CRS) departure and arrival times (Tables 4-9 and 4-10) and delay distributions by scheduled and actual gate turns immediately preceding a flight. The evidence indicates that a leading factor in delays is short turns in the afternoon and evening hours.
In analyzing the information in Tables 4-4 through 4-14, it is helpful to begin by reviewing the relationship between the first two percent columns—aircraft departures and impeded trip time. The ratio of impeded trip hour share of total and aircraft departure share of total is a measure of delay per departure, and is not directly affected by aircraft size. On the other hand, the ratio of passenger delay hours share to impeded trip hours share is directly related to passengers per trip and therefore to aircraft size.

Table 4-4 shows that 57 percent of aircraft departures in the 11-year period were performed by aircraft in the 121-150 seat category. Together with the 17 percent of departures performed by 61-120 seat aircraft, the two leading categories together account for 74 percent of aircraft departures. Table 4-4 also shows the relationship between aircraft seats and cost. The percentage cost share for aircraft in the 121-150 seat category is about equal to the percent departure share for this category. Smaller aircraft have a lower cost share than their departure share. Larger aircraft have a higher cost share than their departure share, and this can be seen for the aircraft in the 211 and up seat category.

Table 4-5 uses the same format as Table 4-4 to show departure share and cost share by origin-destination airport category. Note that over 50 percent of the value of passenger delays and air carrier delay cost are associated with operations between large hubs and between high density airports (HDAs) and large hubs. The disproportionate impeded cost and trip time (55 percent of passenger and airline cost and 49 percent of impeded trip time associated with 40 percent of departures) reflects both higher delay per departure (through the ratio 49:40) and a higher passenger count per departure on flights between large airports (through the ratio 55:49).
Tables 4-6 and 4-7 show that 50 percent of costs of delays are associated with flights with origins or destinations at large hub 1 (OEP1) and large hub 2 (OEP2) airports.

Table 4-8 shows that 65 percent of departures and 49 percent of delay hours and costs are accounted for on stage lengths under 750 miles. Flights over 1,500 miles account for 10 percent of departures and 20 percent of passenger delay hours and costs.

Table 4-9 reflects differences in aircraft size. As shown in Table 4-3, Delta Air Lines and United Airlines operated with a seat per departure index of 1.24 and 1.14 respectively. An index value of 1.00 represents 131 seats per departure. Impeded trip time for Delta at 14 percent of total matches Delta's departure share of 14 percent, which indicates that Delta was not disproportionately affected by delays. Delta's passenger delay hours and passenger and airline delay costs can thus be explained as primarily driven by larger aircraft size.
Table 4-4. Delay distribution by aircraft seat capacity (1995-2005)

<table>
<thead>
<tr>
<th>Origin-Destination</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>Up to 60</td>
<td>6,710</td>
<td>11</td>
<td>1,727,700</td>
<td>10</td>
<td>52,400</td>
<td>3</td>
</tr>
<tr>
<td>61-120</td>
<td>10,540</td>
<td>17</td>
<td>2,706,900</td>
<td>15</td>
<td>189,700</td>
<td>11</td>
</tr>
<tr>
<td>121-150</td>
<td>35,850</td>
<td>57</td>
<td>10,016,100</td>
<td>56</td>
<td>942,700</td>
<td>56</td>
</tr>
<tr>
<td>151-210</td>
<td>7,800</td>
<td>12</td>
<td>2,637,400</td>
<td>15</td>
<td>346,600</td>
<td>20</td>
</tr>
<tr>
<td>211 and up</td>
<td>1,960</td>
<td>3</td>
<td>809,700</td>
<td>5</td>
<td>163,300</td>
<td>10</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
<table>
<thead>
<tr>
<th>Origin-Destination</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>Between small/med/non hubs</td>
<td>3,850</td>
<td>6</td>
<td>664,100</td>
<td>4</td>
<td>54,800</td>
<td>3</td>
</tr>
<tr>
<td>Large hub 2 to small/med/non hubs</td>
<td>5,560</td>
<td>9</td>
<td>1,285,600</td>
<td>7</td>
<td>100,800</td>
<td>6</td>
</tr>
<tr>
<td>Small/med/non hubs to large hub 2</td>
<td>5,550</td>
<td>9</td>
<td>993,900</td>
<td>6</td>
<td>78,600</td>
<td>5</td>
</tr>
<tr>
<td>Large hub 2 to large hub 2</td>
<td>3,810</td>
<td>6</td>
<td>974,100</td>
<td>5</td>
<td>95,500</td>
<td>6</td>
</tr>
<tr>
<td>Large hub 1 to small/med/non hubs</td>
<td>9,520</td>
<td>15</td>
<td>2,921,400</td>
<td>16</td>
<td>243,400</td>
<td>14</td>
</tr>
<tr>
<td>Small/med/non hubs to large hub 1/HDA</td>
<td>9,490</td>
<td>15</td>
<td>2,354,400</td>
<td>13</td>
<td>193,900</td>
<td>11</td>
</tr>
<tr>
<td>Major airport group</td>
<td>25,080</td>
<td>40</td>
<td>8,704,300</td>
<td>49</td>
<td>927,600</td>
<td>55</td>
</tr>
<tr>
<td>Large hub 1/HDA to large hub 2</td>
<td>7,320</td>
<td>12</td>
<td>2,449,900</td>
<td>14</td>
<td>262,200</td>
<td>15</td>
</tr>
<tr>
<td>Large hub 2 to large hub 1/HDA</td>
<td>7,320</td>
<td>12</td>
<td>2,327,200</td>
<td>13</td>
<td>244,400</td>
<td>14</td>
</tr>
<tr>
<td>Large hub 1/HDA to and from large hub 1</td>
<td>8,760</td>
<td>14</td>
<td>3,183,800</td>
<td>18</td>
<td>345,900</td>
<td>20</td>
</tr>
<tr>
<td>HDA to HDA</td>
<td>1,680</td>
<td>3</td>
<td>743,400</td>
<td>4</td>
<td>75,100</td>
<td>4</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-6. Delay distribution by origin airport group (1995-2005)

<table>
<thead>
<tr>
<th>Origin airport</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Hours</td>
<td>Thousands</td>
<td>Hours</td>
<td>Millions</td>
<td>Millions</td>
</tr>
<tr>
<td>Small or non hub</td>
<td>7,440</td>
<td>12</td>
<td>1,489,800</td>
<td>8</td>
<td>0.2</td>
<td>2,800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>97,200</td>
<td>6</td>
<td>2,600</td>
<td></td>
</tr>
<tr>
<td>Medium hub</td>
<td>11,450</td>
<td>18</td>
<td>2,522,600</td>
<td>14</td>
<td>0.2</td>
<td>6,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>230,200</td>
<td>14</td>
<td>4,700</td>
<td></td>
</tr>
<tr>
<td>Large hub tier 2</td>
<td>16,690</td>
<td>27</td>
<td>4,586,900</td>
<td>26</td>
<td>0.3</td>
<td>12,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>440,700</td>
<td>26</td>
<td>10,100</td>
<td></td>
</tr>
<tr>
<td>Large hub tier 1</td>
<td>14,700</td>
<td>23</td>
<td>4,611,400</td>
<td>26</td>
<td>0.3</td>
<td>13,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>471,500</td>
<td>28</td>
<td>10,200</td>
<td></td>
</tr>
<tr>
<td>John F Kennedy JFK</td>
<td>620</td>
<td>1</td>
<td>275,000</td>
<td>2</td>
<td>0.5</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>31,300</td>
<td>2</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>LaGuardia LGA</td>
<td>1,100</td>
<td>2</td>
<td>436,800</td>
<td>2</td>
<td>0.4</td>
<td>1,200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40,300</td>
<td>2</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Newark EWR</td>
<td>1,350</td>
<td>2</td>
<td>618,600</td>
<td>3</td>
<td>0.5</td>
<td>1,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>56,900</td>
<td>3</td>
<td>1,300</td>
<td></td>
</tr>
<tr>
<td>Dallas-Ft Worth DFW</td>
<td>3,000</td>
<td>5</td>
<td>982,300</td>
<td>5</td>
<td>0.4</td>
<td>2,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>89,200</td>
<td>5</td>
<td>2,000</td>
<td></td>
</tr>
<tr>
<td>O'Hare ORD</td>
<td>3,380</td>
<td>5</td>
<td>1,266,200</td>
<td>7</td>
<td>0.4</td>
<td>3,300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>115,800</td>
<td>7</td>
<td>2,600</td>
<td></td>
</tr>
<tr>
<td>Atlanta ATL</td>
<td>3,120</td>
<td>5</td>
<td>1,108,200</td>
<td>6</td>
<td>0.4</td>
<td>3,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>121,700</td>
<td>7</td>
<td>2,400</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>100</td>
<td>48,500</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>37,500</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
### Table 4-7. Delay distribution by destination airport group (1995-2005)

<table>
<thead>
<tr>
<th>Destination airport</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Hours</td>
<td>Millions</td>
</tr>
<tr>
<td>Small or non hub</td>
<td>7,460</td>
<td>1,905,800</td>
<td>11</td>
<td>125,500</td>
<td>0.3</td>
<td>3,600</td>
</tr>
<tr>
<td>Medium hub</td>
<td>11,470</td>
<td>2,965,300</td>
<td>17</td>
<td>273,600</td>
<td>0.3</td>
<td>7,800</td>
</tr>
<tr>
<td>Large hub tier 2</td>
<td>16,680</td>
<td>4,417,900</td>
<td>25</td>
<td>436,400</td>
<td>0.3</td>
<td>12,500</td>
</tr>
<tr>
<td>Large hub tier 1</td>
<td>14,700</td>
<td>4,375,100</td>
<td>24</td>
<td>451,600</td>
<td>0.3</td>
<td>12,900</td>
</tr>
<tr>
<td>John F Kennedy JFK</td>
<td>620</td>
<td>221,900</td>
<td>1</td>
<td>25,800</td>
<td>0.4</td>
<td>700</td>
</tr>
<tr>
<td>LaGuardia LGA</td>
<td>1,100</td>
<td>378,900</td>
<td>2</td>
<td>35,200</td>
<td>0.4</td>
<td>1,000</td>
</tr>
<tr>
<td>Newark EWR</td>
<td>1,350</td>
<td>550,600</td>
<td>3</td>
<td>50,800</td>
<td>0.4</td>
<td>1,500</td>
</tr>
<tr>
<td>Dallas-Ft Worth DFW</td>
<td>2,990</td>
<td>903,000</td>
<td>5</td>
<td>81,400</td>
<td>0.3</td>
<td>2,300</td>
</tr>
<tr>
<td>O'Hare ORD</td>
<td>3,380</td>
<td>1,204,800</td>
<td>7</td>
<td>108,100</td>
<td>0.4</td>
<td>3,100</td>
</tr>
<tr>
<td>Atlanta ATL</td>
<td>3,110</td>
<td>974,500</td>
<td>5</td>
<td>106,400</td>
<td>0.3</td>
<td>3,000</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>0.2</td>
<td>48,500</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-8. Delay distribution by flight stage length (1995-2005)

<table>
<thead>
<tr>
<th>Stage length</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Thousands</td>
</tr>
<tr>
<td>Under 250</td>
<td>10,050</td>
<td>16</td>
<td>2,132,500</td>
<td>12</td>
<td>145,600</td>
<td>9</td>
</tr>
<tr>
<td>250-499</td>
<td>17,920</td>
<td>29</td>
<td>4,423,000</td>
<td>25</td>
<td>355,700</td>
<td>21</td>
</tr>
<tr>
<td>500-749</td>
<td>11,930</td>
<td>19</td>
<td>3,567,400</td>
<td>20</td>
<td>318,100</td>
<td>19</td>
</tr>
<tr>
<td>750-999</td>
<td>8,390</td>
<td>13</td>
<td>2,578,400</td>
<td>14</td>
<td>255,400</td>
<td>15</td>
</tr>
<tr>
<td>1000-1249</td>
<td>5,440</td>
<td>9</td>
<td>1,793,100</td>
<td>10</td>
<td>192,500</td>
<td>11</td>
</tr>
<tr>
<td>1250-1499</td>
<td>2,410</td>
<td>4</td>
<td>874,800</td>
<td>5</td>
<td>97,800</td>
<td>6</td>
</tr>
<tr>
<td>1500-1749</td>
<td>2,680</td>
<td>4</td>
<td>979,400</td>
<td>5</td>
<td>120,800</td>
<td>7</td>
</tr>
<tr>
<td>1750-1999</td>
<td>1,290</td>
<td>2</td>
<td>474,500</td>
<td>3</td>
<td>62,200</td>
<td>4</td>
</tr>
<tr>
<td>2000-2249</td>
<td>890</td>
<td>1</td>
<td>350,200</td>
<td>2</td>
<td>45,000</td>
<td>3</td>
</tr>
<tr>
<td>Over 2250</td>
<td>1,870</td>
<td>3</td>
<td>724,600</td>
<td>4</td>
<td>101,500</td>
<td>6</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
<table>
<thead>
<tr>
<th>Carrier group</th>
<th>Aircraft departures Thousands</th>
<th>Aircraft departures Percent</th>
<th>Impeded trip time Hours</th>
<th>Impeded trip time Percent</th>
<th>Passenger delay hours Thousands</th>
<th>Passenger delay hours Percent</th>
<th>Mean delay per psngr. Hours</th>
<th>Passenger cost Millions</th>
<th>Passenger cost Percent</th>
<th>Air carrier cost Millions</th>
<th>Air carrier cost Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest</td>
<td>9,590</td>
<td>15</td>
<td>2,065,100</td>
<td>12</td>
<td>184,600</td>
<td>11</td>
<td>0.2</td>
<td>5,300</td>
<td>11</td>
<td>2,300</td>
<td>6</td>
</tr>
<tr>
<td>American/TWA</td>
<td>9,410</td>
<td>15</td>
<td>3,138,000</td>
<td>18</td>
<td>315,600</td>
<td>19</td>
<td>0.3</td>
<td>9,000</td>
<td>19</td>
<td>7,400</td>
<td>20</td>
</tr>
<tr>
<td>Continental</td>
<td>3,940</td>
<td>6</td>
<td>1,244,200</td>
<td>7</td>
<td>127,100</td>
<td>8</td>
<td>0.3</td>
<td>3,600</td>
<td>7</td>
<td>3,000</td>
<td>8</td>
</tr>
<tr>
<td>Delta</td>
<td>8,740</td>
<td>14</td>
<td>2,520,300</td>
<td>14</td>
<td>303,100</td>
<td>18</td>
<td>0.3</td>
<td>8,700</td>
<td>18</td>
<td>6,400</td>
<td>17</td>
</tr>
<tr>
<td>Northwest</td>
<td>5,570</td>
<td>9</td>
<td>1,565,000</td>
<td>9</td>
<td>154,200</td>
<td>9</td>
<td>0.3</td>
<td>4,400</td>
<td>9</td>
<td>3,600</td>
<td>10</td>
</tr>
<tr>
<td>United</td>
<td>7,140</td>
<td>11</td>
<td>2,361,900</td>
<td>13</td>
<td>254,700</td>
<td>15</td>
<td>0.3</td>
<td>7,300</td>
<td>15</td>
<td>5,800</td>
<td>15</td>
</tr>
<tr>
<td>USAir/Amer. West</td>
<td>8,780</td>
<td>14</td>
<td>2,444,500</td>
<td>14</td>
<td>223,000</td>
<td>13</td>
<td>0.3</td>
<td>6,400</td>
<td>13</td>
<td>5,700</td>
<td>15</td>
</tr>
<tr>
<td>JetBlue/ATA</td>
<td>450</td>
<td>1</td>
<td>131,000</td>
<td>1</td>
<td>17,400</td>
<td>1</td>
<td>0.3</td>
<td>500</td>
<td>1</td>
<td>300</td>
<td>1</td>
</tr>
<tr>
<td>Other major carriers</td>
<td>2,350</td>
<td>4</td>
<td>638,400</td>
<td>4</td>
<td>59,300</td>
<td>3</td>
<td>0.3</td>
<td>1,700</td>
<td>4</td>
<td>1,400</td>
<td>4</td>
</tr>
<tr>
<td>Regional carriers</td>
<td>6,890</td>
<td>11</td>
<td>1,789,300</td>
<td>10</td>
<td>55,500</td>
<td>3</td>
<td>0.3</td>
<td>1,600</td>
<td>3</td>
<td>1,600</td>
<td>4</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
<td>0.2</td>
<td>48,500</td>
<td>100</td>
<td>37,500</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
<table>
<thead>
<tr>
<th>CRS departure time</th>
<th>Aircraft departures Thousands</th>
<th>Impeded trip time Hours</th>
<th>Passenger delay hours Thousands</th>
<th>Mean delay per psngr. Hours</th>
<th>Passenger cost Millions Percent</th>
<th>Air carrier cost Millions Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0001-0559</td>
<td>570</td>
<td>74,800</td>
<td>6,700</td>
<td>0.1</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>0600-0759</td>
<td>8,130</td>
<td>1,401,100</td>
<td>126,800</td>
<td>7</td>
<td>3,600</td>
<td>7</td>
</tr>
<tr>
<td>0800-0959</td>
<td>8,590</td>
<td>2,013,500</td>
<td>199,000</td>
<td>12</td>
<td>5,700</td>
<td>12</td>
</tr>
<tr>
<td>1000-1159</td>
<td>7,760</td>
<td>1,835,400</td>
<td>180,000</td>
<td>11</td>
<td>5,100</td>
<td>11</td>
</tr>
<tr>
<td>1200-1359</td>
<td>8,200</td>
<td>2,238,800</td>
<td>220,200</td>
<td>13</td>
<td>6,300</td>
<td>13</td>
</tr>
<tr>
<td>1400-1559</td>
<td>7,730</td>
<td>2,452,800</td>
<td>231,600</td>
<td>14</td>
<td>6,600</td>
<td>14</td>
</tr>
<tr>
<td>1600-1759</td>
<td>8,150</td>
<td>3,034,500</td>
<td>285,500</td>
<td>17</td>
<td>8,200</td>
<td>17</td>
</tr>
<tr>
<td>1800-1959</td>
<td>7,310</td>
<td>2,826,900</td>
<td>259,800</td>
<td>15</td>
<td>7,400</td>
<td>15</td>
</tr>
<tr>
<td>2000-2159</td>
<td>4,970</td>
<td>1,654,500</td>
<td>148,500</td>
<td>9</td>
<td>4,200</td>
<td>9</td>
</tr>
<tr>
<td>2200-2359</td>
<td>1,450</td>
<td>365,600</td>
<td>36,700</td>
<td>2</td>
<td>1,000</td>
<td>2</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>17,897,700</td>
<td>1,694,700</td>
<td>100</td>
<td>48,500</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-11. Delay distribution by CRS arrival time (1995-2005)

<table>
<thead>
<tr>
<th>CRS arrival time</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>0001-0559</td>
<td>1,060</td>
<td>2</td>
<td>267,000</td>
<td>1</td>
<td>28,500</td>
<td>2</td>
</tr>
<tr>
<td>0600-0759</td>
<td>2,580</td>
<td>4</td>
<td>315,500</td>
<td>2</td>
<td>27,900</td>
<td>2</td>
</tr>
<tr>
<td>0800-0959</td>
<td>6,450</td>
<td>10</td>
<td>1,141,700</td>
<td>6</td>
<td>95,700</td>
<td>6</td>
</tr>
<tr>
<td>1000-1159</td>
<td>8,120</td>
<td>13</td>
<td>1,821,300</td>
<td>10</td>
<td>172,000</td>
<td>10</td>
</tr>
<tr>
<td>1200-1359</td>
<td>7,620</td>
<td>12</td>
<td>1,742,100</td>
<td>10</td>
<td>166,400</td>
<td>10</td>
</tr>
<tr>
<td>1400-1559</td>
<td>7,710</td>
<td>12</td>
<td>1,991,800</td>
<td>11</td>
<td>190,900</td>
<td>11</td>
</tr>
<tr>
<td>1600-1759</td>
<td>8,470</td>
<td>13</td>
<td>2,746,600</td>
<td>15</td>
<td>262,600</td>
<td>15</td>
</tr>
<tr>
<td>1800-1959</td>
<td>8,180</td>
<td>13</td>
<td>3,090,700</td>
<td>17</td>
<td>293,500</td>
<td>17</td>
</tr>
<tr>
<td>2000-2159</td>
<td>7,820</td>
<td>12</td>
<td>3,074,700</td>
<td>17</td>
<td>293,500</td>
<td>17</td>
</tr>
<tr>
<td>2200-2359</td>
<td>4,850</td>
<td>8</td>
<td>1,706,200</td>
<td>10</td>
<td>163,800</td>
<td>10</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-12. Delay distribution by prior scheduled turn (1995-2005)

<table>
<thead>
<tr>
<th>Prior scheduled turn in minutes</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>1-20</td>
<td>3,360</td>
<td>5</td>
<td>871,300</td>
<td>5</td>
<td>72,100</td>
<td>4</td>
</tr>
<tr>
<td>21-40</td>
<td>13,460</td>
<td>21</td>
<td>3,578,300</td>
<td>20</td>
<td>273,700</td>
<td>16</td>
</tr>
<tr>
<td>41-60</td>
<td>18,020</td>
<td>29</td>
<td>5,395,600</td>
<td>30</td>
<td>501,000</td>
<td>30</td>
</tr>
<tr>
<td>61-80</td>
<td>8,080</td>
<td>13</td>
<td>2,351,900</td>
<td>13</td>
<td>262,400</td>
<td>15</td>
</tr>
<tr>
<td>81-100</td>
<td>2,530</td>
<td>4</td>
<td>708,200</td>
<td>4</td>
<td>80,200</td>
<td>5</td>
</tr>
<tr>
<td>101-120</td>
<td>1,080</td>
<td>2</td>
<td>289,400</td>
<td>2</td>
<td>31,700</td>
<td>2</td>
</tr>
<tr>
<td>121-140</td>
<td>620</td>
<td>1</td>
<td>166,500</td>
<td>1</td>
<td>17,600</td>
<td>1</td>
</tr>
<tr>
<td>141-160</td>
<td>420</td>
<td>1</td>
<td>120,400</td>
<td>1</td>
<td>12,600</td>
<td>1</td>
</tr>
<tr>
<td>161-180</td>
<td>280</td>
<td>0</td>
<td>83,700</td>
<td>0</td>
<td>8,800</td>
<td>1</td>
</tr>
<tr>
<td>Overnight &amp; other</td>
<td>15,020</td>
<td>24</td>
<td>4,332,500</td>
<td>24</td>
<td>434,500</td>
<td>26</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-13. Delay distribution by prior actual turn (1995-2005)

<table>
<thead>
<tr>
<th>Prior actual turn in minutes</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>1-20</td>
<td>2,220</td>
<td>4</td>
<td>680,000</td>
<td>4</td>
<td>49,000</td>
<td>3</td>
</tr>
<tr>
<td>21-40</td>
<td>14,770</td>
<td>23</td>
<td>4,016,700</td>
<td>22</td>
<td>322,000</td>
<td>19</td>
</tr>
<tr>
<td>41-60</td>
<td>15,510</td>
<td>25</td>
<td>3,976,500</td>
<td>22</td>
<td>384,600</td>
<td>23</td>
</tr>
<tr>
<td>61-80</td>
<td>8,970</td>
<td>14</td>
<td>2,308,700</td>
<td>13</td>
<td>239,300</td>
<td>14</td>
</tr>
<tr>
<td>81-100</td>
<td>3,580</td>
<td>6</td>
<td>1,198,500</td>
<td>7</td>
<td>124,100</td>
<td>7</td>
</tr>
<tr>
<td>101-120</td>
<td>1,550</td>
<td>2</td>
<td>683,300</td>
<td>4</td>
<td>69,600</td>
<td>4</td>
</tr>
<tr>
<td>121-140</td>
<td>820</td>
<td>1</td>
<td>441,400</td>
<td>2</td>
<td>44,200</td>
<td>3</td>
</tr>
<tr>
<td>141-160</td>
<td>510</td>
<td>1</td>
<td>308,000</td>
<td>2</td>
<td>30,600</td>
<td>2</td>
</tr>
<tr>
<td>161-180</td>
<td>340</td>
<td>1</td>
<td>222,000</td>
<td>1</td>
<td>22,200</td>
<td>1</td>
</tr>
<tr>
<td>Overnight &amp; other</td>
<td>14,600</td>
<td>23</td>
<td>4,062,600</td>
<td>23</td>
<td>409,200</td>
<td>24</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-14.   Delay distribution by impeded day deciles (1995-2005)

<table>
<thead>
<tr>
<th>Impeded day decile</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>First</td>
<td>6,070</td>
<td>10</td>
<td>775,300</td>
<td>4</td>
<td>72,900</td>
<td>4</td>
</tr>
<tr>
<td>Second</td>
<td>5,980</td>
<td>10</td>
<td>1,032,200</td>
<td>6</td>
<td>98,800</td>
<td>6</td>
</tr>
<tr>
<td>Third</td>
<td>6,340</td>
<td>10</td>
<td>1,274,300</td>
<td>7</td>
<td>122,500</td>
<td>7</td>
</tr>
<tr>
<td>Fourth</td>
<td>6,460</td>
<td>10</td>
<td>1,456,000</td>
<td>8</td>
<td>138,600</td>
<td>8</td>
</tr>
<tr>
<td>Fifth</td>
<td>6,010</td>
<td>10</td>
<td>1,490,700</td>
<td>8</td>
<td>141,400</td>
<td>8</td>
</tr>
<tr>
<td>Sixth</td>
<td>6,570</td>
<td>10</td>
<td>1,798,900</td>
<td>10</td>
<td>172,100</td>
<td>10</td>
</tr>
<tr>
<td>Deciles 7 - 10</td>
<td>25,430</td>
<td>40</td>
<td>10,070,300</td>
<td>56</td>
<td>948,400</td>
<td>56</td>
</tr>
<tr>
<td>Seventh</td>
<td>6,110</td>
<td>10</td>
<td>1,863,700</td>
<td>10</td>
<td>177,100</td>
<td>10</td>
</tr>
<tr>
<td>Eighth</td>
<td>6,590</td>
<td>10</td>
<td>2,259,400</td>
<td>13</td>
<td>212,400</td>
<td>13</td>
</tr>
<tr>
<td>Ninth</td>
<td>6,460</td>
<td>10</td>
<td>2,596,600</td>
<td>15</td>
<td>243,900</td>
<td>14</td>
</tr>
<tr>
<td>Tenth</td>
<td>6,270</td>
<td>10</td>
<td>3,350,600</td>
<td>19</td>
<td>315,000</td>
<td>19</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>17,897,700</td>
<td>100</td>
<td>1,694,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-9 is best interpreted by first comparing share of impeded trip time to share of departures. As mentioned above, this comparison is not directly influenced by aircraft size. The comparison, however, is directly influenced by average delay per departure. Thus an airline with an impeded trip time share higher than its departure share was delay-prone in its operations during the study period. Southwest Airlines is the only listed airline to have a lower impeded share than its departure share. As an approximation, it can be seen from Table 4-9 that Southwest was 20 percent less delay per departure than the average for all ASQP carriers (12 percent impeded trip time share divided by 15 percent departure share, giving a ratio of 0.8, which is 20 percent below the overall 1:1 ratio).

American Airlines, on the other hand, with impeded trip time 18 percent, compared to a departure share of 14 percent, appears to be affected more by delays. This is borne out by passenger delays and costs of 19 percent, and airline costs of 20 percent of the total, indicating a small effect from aircraft size. This is consistent with Table 4-3 which shows American's aircraft size index of 1.07, which roughly equates to the ratio of American's costs of 20 percent of the total to American's impeded trip time of 18 percent of the total.

Tables 4-10 and 4-11 show a consistent pattern. Fifty percent of delays are associated with CRS departure times between 12 noon and 8 PM, and 50 percent of delays are also associated with CRS arrival times between 2 PM and 10 PM.

Tables 4-12 for prior flight scheduled turnarounds does not reveal any surprises. However, taken together with Table 4-13, the two tables show an interesting phenomenon. Although scheduled turns between 100 and 160 minutes have impeded trip times shares that are at the same level as aircraft departure shares, the same cannot be
said about actual turn times. Actual turns between 100 and 160 minutes have impeded trip time shares that are double the value of their associated departure shares. However, these flights account for only 4 percent of departures. This suggests that these flights represent those delayed by weather, congestion, or mechanical problems, and that the resulting delays are one to two hours longer than a normal airport turnaround.

Table 4-14 ranks days according average aircraft impeded time per departure. The ranked days were grouped in deciles. The results shown Table 4-14 are of interest in that about 56 percent of delays and impeded times are accounted for by the high delay deciles—the seventh, eighth, ninth and tenth deciles.

From an analysis of Tables 4-4 through 4-14, certain conclusions can be drawn from reviewing the percentage shares of total departures, impeded trip time, passenger delay hours, passenger time value, and air carrier cost:

1. Aircraft in the 121-150 seat group represent 57 percent of all departures, 56 percent of all impeded trip time, 56 percent of passenger delay cost, and 51 percent of air carrier delay cost.
2. Origin-destination flights between large hubs/HDA airports represent 40 percent of all departures, 49 percent of impeded trip time, and 55 percent of delay costs.
3. Flights with origins or destinations at OEP1 or OEP2 airports represent 50 percent of all departures, about 50 percent of impeded trip time, and 54 percent of delay costs.
4. Flights scheduled to leave between noon and 8 PM, and to arrive between 2 PM and 10 PM, represent 50 percent of all departures, 60 percent of impeded trip time and nearly 60 percent of delay costs.
5. The four highest decile days, with days ranked by average delay per departure, represent 40 percent of all departures, but account for 56 percent of delays, impeded times and passenger costs, and 53 percent of air carrier costs.
The next series of tables reviews some components of impeded time, delays and costs from an air carrier perspective. Table 4-15 shows that, out of 129.5 million block hours operated by reporting carriers between 1995 and 2005, 17.9 million hours represented either impeded trip time or departure delays. Table 4-15 also shows that impeded trip time of 9.3 million hours exceeded the 8.6 million block hours associated with departure delays in the 1995-2005 period. These times, however, are the same order of magnitude.

Table 4-15 also shows the calculation of impeded block hours. Mathematically, this relationship is expressed as:

\[
\text{impeded trip time} = \text{departure delay hours} + (\text{operated block hours} - \text{unimpeded block hours})
\]

Table 4-15. Annual airline impeded trip times

<table>
<thead>
<tr>
<th>Year</th>
<th>Operated block hours</th>
<th>Unimpeded block hours</th>
<th>Impeded block hours</th>
<th>Departure delay hours</th>
<th>Impeded trip time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C=A-B</td>
<td>D</td>
<td>E=C+D</td>
</tr>
<tr>
<td>1995</td>
<td>10,090</td>
<td>9,420</td>
<td>670</td>
<td>710</td>
<td>1,380</td>
</tr>
<tr>
<td>1996</td>
<td>10,340</td>
<td>9,610</td>
<td>730</td>
<td>850</td>
<td>1,580</td>
</tr>
<tr>
<td>1997</td>
<td>10,690</td>
<td>9,930</td>
<td>750</td>
<td>710</td>
<td>1,460</td>
</tr>
<tr>
<td>1998</td>
<td>10,730</td>
<td>9,980</td>
<td>760</td>
<td>760</td>
<td>1,520</td>
</tr>
<tr>
<td>1999</td>
<td>11,270</td>
<td>10,430</td>
<td>830</td>
<td>820</td>
<td>1,650</td>
</tr>
<tr>
<td>2000</td>
<td>11,750</td>
<td>10,830</td>
<td>920</td>
<td>1,020</td>
<td>1,940</td>
</tr>
<tr>
<td>2001</td>
<td>11,810</td>
<td>10,940</td>
<td>870</td>
<td>770</td>
<td>1,640</td>
</tr>
<tr>
<td>2002</td>
<td>10,990</td>
<td>10,320</td>
<td>670</td>
<td>470</td>
<td>1,140</td>
</tr>
<tr>
<td>2003</td>
<td>12,970</td>
<td>12,090</td>
<td>880</td>
<td>540</td>
<td>1,420</td>
</tr>
<tr>
<td>2004</td>
<td>14,340</td>
<td>13,200</td>
<td>1,130</td>
<td>900</td>
<td>2,030</td>
</tr>
<tr>
<td>2005</td>
<td>14,510</td>
<td>13,390</td>
<td>1,120</td>
<td>1,010</td>
<td>2,130</td>
</tr>
<tr>
<td>Total</td>
<td>129,490</td>
<td>120,140</td>
<td>9,340</td>
<td>8,570</td>
<td>17,900</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS (2008A)
Table 4-16 breaks out the 9,340 hours total excess impeded time by flight phase, showing that excess taxi-out time is the major contributor to excess impeded time, contributing 54 percent of the total (4,980 hours out of the total 9,340 hours). The proportion of taxi-out, airborne and taxi-in remains in the range of 50:33:17 percent for most of the 11-year period. Low values for airborne impeded times are evident in 2002 and 2003. Across-the-board increases in impeded times in 2004 and 2005 are evident in Table 4-16, as shown graphically in Figures 4-2 and 4-3 above.

Table 4-16. Annual impeded hours by trip phase

<table>
<thead>
<tr>
<th>Year</th>
<th>Impeded taxi-out time</th>
<th>Impeded taxi-in time</th>
<th>Impeded airborne time</th>
<th>Impeded block time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands of Hours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>360</td>
<td>210</td>
<td>100</td>
<td>670</td>
</tr>
<tr>
<td>1996</td>
<td>380</td>
<td>240</td>
<td>110</td>
<td>730</td>
</tr>
<tr>
<td>1997</td>
<td>390</td>
<td>260</td>
<td>110</td>
<td>750</td>
</tr>
<tr>
<td>1998</td>
<td>390</td>
<td>250</td>
<td>120</td>
<td>760</td>
</tr>
<tr>
<td>1999</td>
<td>450</td>
<td>250</td>
<td>130</td>
<td>830</td>
</tr>
<tr>
<td>2000</td>
<td>490</td>
<td>290</td>
<td>140</td>
<td>920</td>
</tr>
<tr>
<td>2001</td>
<td>450</td>
<td>270</td>
<td>150</td>
<td>870</td>
</tr>
<tr>
<td>2002</td>
<td>390</td>
<td>230</td>
<td>40</td>
<td>670</td>
</tr>
<tr>
<td>2003</td>
<td>510</td>
<td>300</td>
<td>70</td>
<td>880</td>
</tr>
<tr>
<td>2004</td>
<td>600</td>
<td>350</td>
<td>180</td>
<td>1,130</td>
</tr>
<tr>
<td>2005</td>
<td>570</td>
<td>380</td>
<td>180</td>
<td>1,120</td>
</tr>
<tr>
<td>Total</td>
<td>4,980</td>
<td>3,030</td>
<td>1,340</td>
<td>9,340</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS (2008A)

Table 4-17 shows how the costs of delays and impeded flight hours add to the variable cost of operation. Table 4-17 shows that the $37.5 billion expense associated
with trip times in excess of the unimpeded trip time accounted for 10.3 percent of variable operating costs over the 1995-2005 period.

Annual airline impeded expense remained at a level of about $3 billion between 1995 and 1998, rose to over $4 billion in 2000, dropped to about $3 billion in 2002 and 2003, than increased sharply in 2004 and 2005 to $3.8 billion annually.

Table 4-17. Added carrier expense above unimpeded operating expense

<table>
<thead>
<tr>
<th>Year</th>
<th>Variable unimpeded operating expense including fuel</th>
<th>Added carrier impeded expense</th>
<th>Variable operating expense including fuel</th>
<th>Added impeded expense as percent of variable operating expense</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>C</td>
<td>B/C</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>$24,700</td>
<td>$2,800</td>
<td>$27,500</td>
<td>10.3</td>
</tr>
<tr>
<td>1996</td>
<td>26,400</td>
<td>3,300</td>
<td>29,700</td>
<td>11.1</td>
</tr>
<tr>
<td>1997</td>
<td>27,500</td>
<td>3,200</td>
<td>30,700</td>
<td>10.4</td>
</tr>
<tr>
<td>1998</td>
<td>26,600</td>
<td>3,200</td>
<td>29,800</td>
<td>10.9</td>
</tr>
<tr>
<td>1999</td>
<td>27,700</td>
<td>3,600</td>
<td>31,300</td>
<td>11.4</td>
</tr>
<tr>
<td>2000</td>
<td>31,900</td>
<td>4,300</td>
<td>36,200</td>
<td>11.8</td>
</tr>
<tr>
<td>2001</td>
<td>31,900</td>
<td>3,700</td>
<td>35,600</td>
<td>10.4</td>
</tr>
<tr>
<td>2002</td>
<td>29,200</td>
<td>2,800</td>
<td>32,000</td>
<td>8.7</td>
</tr>
<tr>
<td>2003</td>
<td>31,100</td>
<td>3,000</td>
<td>34,100</td>
<td>8.9</td>
</tr>
<tr>
<td>2004</td>
<td>33,800</td>
<td>3,800</td>
<td>37,600</td>
<td>10.0</td>
</tr>
<tr>
<td>2005</td>
<td>36,700</td>
<td>3,800</td>
<td>40,500</td>
<td>9.4</td>
</tr>
<tr>
<td>Total</td>
<td>$327,500</td>
<td>$37,500</td>
<td>$365,000</td>
<td>10.3</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS (2008A)

Table 4-17 calculates annual airline unimpeded expense using short term variable costs. This figure omits medium-term variable and fixed- cost components of airline
operating costs. The relevant cost is the added air carrier impeded expense. Other columns in this table are provided in order to provide additional context.

Table 4-18 shows the excess jet fuel consumed by flight phase. Excess airborne fuel is the main contributor to excess fuel consumption, accounting for 56 percent of overall excess fuel for the 1995-2005 period. Estimated fuel use in the taxi-out phase is the next leading contributor, at 35 percent of the total.

Table 4-18. Excess fuel by flight phase for impeded flights

<table>
<thead>
<tr>
<th>Year</th>
<th>Total fuel consumed</th>
<th>Impeded total fuel</th>
<th>Impeded taxi-out fuel</th>
<th>Impeded airborne fuel</th>
<th>Impeded taxi-in fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of gallons</td>
<td>Percent of impeded total fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>10,320</td>
<td>390</td>
<td>36</td>
<td>54</td>
<td>10</td>
</tr>
<tr>
<td>1996</td>
<td>10,450</td>
<td>430</td>
<td>35</td>
<td>56</td>
<td>9</td>
</tr>
<tr>
<td>1997</td>
<td>10,720</td>
<td>440</td>
<td>34</td>
<td>57</td>
<td>9</td>
</tr>
<tr>
<td>1998</td>
<td>10,660</td>
<td>430</td>
<td>35</td>
<td>56</td>
<td>9</td>
</tr>
<tr>
<td>1999</td>
<td>11,000</td>
<td>460</td>
<td>37</td>
<td>52</td>
<td>11</td>
</tr>
<tr>
<td>2000</td>
<td>11,220</td>
<td>500</td>
<td>36</td>
<td>54</td>
<td>10</td>
</tr>
<tr>
<td>2001</td>
<td>10,680</td>
<td>440</td>
<td>34</td>
<td>55</td>
<td>11</td>
</tr>
<tr>
<td>2002</td>
<td>9,870</td>
<td>350</td>
<td>37</td>
<td>57</td>
<td>6</td>
</tr>
<tr>
<td>2003</td>
<td>10,420</td>
<td>400</td>
<td>35</td>
<td>58</td>
<td>7</td>
</tr>
<tr>
<td>2004</td>
<td>11,170</td>
<td>480</td>
<td>33</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>2005</td>
<td>11,150</td>
<td>490</td>
<td>31</td>
<td>59</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>117,660</td>
<td>4,810</td>
<td>35</td>
<td>56</td>
<td>9</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS (2008A)

Table 4-18 also shows that jet fuel consumption in all phases (taxi-out, airborne, and taxi-in) by the ASQP reporting carriers remained in a fairly narrow range (between 10 and 11 billion annual gallons) over the 11-year period. This is evidence that airlines
became more efficient in their use of fuel. The expansion of the number of reporting
carriers after 2000 also needs to be considered in interpreting Table 4-18 and other tables.

Table 4-19. Fuel expense by flight phase

<table>
<thead>
<tr>
<th>Year</th>
<th>Total fuel expense</th>
<th>Impeded total fuel expense</th>
<th>Impeded taxi-out fuel expense</th>
<th>Impeded air fuel expense</th>
<th>Impeded taxi-in fuel expense</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of dollars</td>
<td>Percent of impeded total fuel expense</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>$7,363</td>
<td>$280</td>
<td>35</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>1996</td>
<td>8,851</td>
<td>362</td>
<td>34</td>
<td>56</td>
<td>10</td>
</tr>
<tr>
<td>1997</td>
<td>8,706</td>
<td>363</td>
<td>33</td>
<td>58</td>
<td>9</td>
</tr>
<tr>
<td>1998</td>
<td>6,988</td>
<td>286</td>
<td>34</td>
<td>56</td>
<td>10</td>
</tr>
<tr>
<td>1999</td>
<td>7,290</td>
<td>301</td>
<td>37</td>
<td>52</td>
<td>11</td>
</tr>
<tr>
<td>2000</td>
<td>10,574</td>
<td>470</td>
<td>35</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>2001</td>
<td>9,816</td>
<td>410</td>
<td>34</td>
<td>55</td>
<td>11</td>
</tr>
<tr>
<td>2002</td>
<td>8,232</td>
<td>291</td>
<td>37</td>
<td>59</td>
<td>4</td>
</tr>
<tr>
<td>2003</td>
<td>10,231</td>
<td>394</td>
<td>35</td>
<td>59</td>
<td>6</td>
</tr>
<tr>
<td>2004</td>
<td>13,895</td>
<td>598</td>
<td>33</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>2005</td>
<td>19,091</td>
<td>840</td>
<td>31</td>
<td>59</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>$111,037</td>
<td>$4,595</td>
<td>34</td>
<td>57</td>
<td>9</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS (2008A)

The cost of jet fuel rose sharply in the 2003-2005 period. Table 4-19 clearly shows a
$2 billion increase in 2003, a nearly $4 billion increase in 2004, and a $5 billion increase
in 2005. Total impeded fuel expense remained constant as a proportion of total fuel
expense at the 4 percent level. By 2005, however, this 4 percent represented $840 million
annually.
Figure 4-9 shows the trend in jet fuel consumed per weighted block hour between 1995 and 2005. Air carriers replaced older, less fuel efficient aircraft between 1995 and 2002. Fuel burned per weighted block hour decreased from 784 gallons in 1995 to 694 gallons in 2002, and remained constant since that time at a level of 700 gallons per weighted block hour.

Following the above review of results with respect to the time and cost impact of impeded trips, the next section will turn to the distribution of impeded times. The discussion is framed in terms of the variability of delay characteristics for a full day, rather than in terms of the variability of individual flights. The metric used is average delay per flight, taking total impeded hours for each day and dividing by the number of flights for that day.
Figures 4-10 and 4-11 show the distribution of mean daily impeded times for the period 1995-2005, with the fitted curve representing a generalized extreme value (GEV) distribution. This distribution is discussed in greater detail in Appendix A.

The relationship between mean daily impeded minutes and total daily impeded hours needs to be understood. With about 16,000 ASQP trips per day reported by air carriers, a mean value of 16 minutes per trip represents about 4,300 hours of daily delay. This figure derives from the median value: about half of all days experience mean impeded trip times below 16 minutes, and half have mean impeded times above 16 minutes. This follows from the impeded trip times and departures shown in Table 4-14. The impeded time per departure in the fifth decile in Table 4-14 is calculated to be 14.9 minutes, and the corresponding average delay per departure for the sixth decile is 16.4 minutes.

Any future transformation of the ATM system will change the distribution of daily impeded times. Table 4-14 shows the impeded hours and costs for daily delays ranked by decile. The lowest decile represents about 4 percent of total impeded hours and passenger costs, and about six percent of airline costs. The highest decile represents 19 percent of impeded hours and passenger costs, and 17 percent of airline impeded costs.

Table 4-14 should be reviewed together with Figures 4-20 and 4-21, which present the distribution of daily average impeded times for all reporting carriers for all days in the dataset. The distribution of times and cost impacts shown in the table and figures provides a basis for a scenario for assigning a range of values to delay reductions. The scenario is based on reducing the gap between visual meteorological conditions (VMC) and instrument meteorological conditions (IMC), assuming that the lowest decile in Table 4-14 represents VMC and the higher deciles represent IMC and severe weather.
Source: Research dataset

Figure 4-10. Probability density function of mean daily impeded times

Source: Research dataset

Figure 4-11. Cumulative distribution function of mean daily impeded times
The Value of Reducing Trip Times and Trip Time Variability

Reduction in trip times and trip time variability requires a system that operates with demand and capacity in balance. With demand growth, reduction in the system demand to capacity ratio requires system capacity to be increased.

NextGen planning for increased capacity includes use of probabilistic weather and demand projections together with synthetic vision to support "equivalent to visual" operations during periods of reduced visibility (Mundra, 2008; FAA, 2008e). The FAA Operational Evolution Partnership (OEP) implementation activity supporting NextGen includes a number of capacity initiatives (FAA, 2008h). The current FAA focus is on four areas identified in which capacity problems exist–terminal area congestion, ATM flow efficiency, and airport congestion (FAA, 2008h).

Current FAA strategic capacity initiatives include (FAA, 2008h):

- Metropolitan Airspace Redesign and Terminal Airspace Redesign.
- Area Navigation Routes (RNAV), Standard Instrument Departures (SIDs) and Standard Terminal Arrivals (STARs).
- Bad Weather Traffic Flow.
- Traffic Management Advisor (TMA) and Expansion of Time-Based Metering.
- Arrival and Departure Rate Improvement (including wake turbulence mitigation and standards revision).
- Deployment of Automatic Surveillance-Broadcast (ADS-B).
Current FAA planning also envisions coordination between NextGen and SESAR ATM transformation programs (FAA, 2008h). SESAR (2008) identifies a target for airports of reducing the gap between IMC (instrument meteorological conditions) and VMC (visual meteorological conditions) capacity from 50 percent in 2008 to 20 percent by 2020. The VMC airport capacity goal is an increase by 20 percent above current best-in-class performance. The implied net result is that goals for future IMC airport operations will be close to today's capacity for handling VMC operations.

The above FAA initiatives represent actions now planned for implementation. To evaluate the potential that such initiatives offer for delay and variability reduction, the 1995-2005 baseline classification of delay deciles in Table 4-14 represents a starting point. The following analysis examines the potential reductions in terms of a range of possible delay and delay variability reduction, as delays in the higher deciles are reduced in stages toward the delay levels represented by the lower deciles.

Tables 4-20 through 4-22 show three scenarios, representing three stages of improved system performance. Tables 4-20 through 4-22 are set up in the same format as Table 4-14. The scenarios build on Table 4-14 and the distribution shown in Figures 4-9 and 4-10. The hypothetical scenarios are designed to show what the impact of reducing trip time variability would be over the 11-year study period.

The premise behind the scenarios is that the improved performance that air traffic management system transformation offers will reduce the proportion of flights in the high delay categories represented by the upper deciles in Table 4-14. If Table 4-14 deciles are treated as delay bands, then an approach to assessing improved system performance is to make some assumptions about how flights might shift from higher to lower delay bands.
The scenarios show the sensitivity of delay costs to assumptions about delay and trip time variability reduction.

The three scenarios assume that a proportion of flights will transition down from those in a higher band to those in a lower band. For the purpose of this exposition, a common assumption is made that there is a 50 percent shift of flights out of the initial conditions in higher band to those of a lower band. Scenario 1 assumes that shifted flights shift down by three bands, Scenario 2 assumes that the shifted flights move down by four bands, and scenario 3 assumes the shifted flights move down by five bands. Clearly, flights can move down only as far as band 1. The parameters (mean and variability) within each decile are maintained as they are represented in Table 4-14. Thus the mean impeded hours per departure within any delay band is fixed at the value of the mean impeded hours for departure for the corresponding decile in Table 4-14.
Table 4-20. Scenario 1 delay distribution by day bands

<table>
<thead>
<tr>
<th>Impeded day band</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per pnsgr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>First</td>
<td>15,460</td>
<td>25</td>
<td>1,974,900</td>
<td>13</td>
<td>185,700</td>
<td>13</td>
</tr>
<tr>
<td>Second</td>
<td>5,990</td>
<td>10</td>
<td>1,034,000</td>
<td>7</td>
<td>99,000</td>
<td>7</td>
</tr>
<tr>
<td>Third</td>
<td>6,460</td>
<td>10</td>
<td>1,297,400</td>
<td>9</td>
<td>124,700</td>
<td>9</td>
</tr>
<tr>
<td>Fourth</td>
<td>6,290</td>
<td>10</td>
<td>1,417,100</td>
<td>9</td>
<td>134,900</td>
<td>9</td>
</tr>
<tr>
<td>Fifth</td>
<td>6,300</td>
<td>10</td>
<td>1,563,200</td>
<td>10</td>
<td>148,300</td>
<td>10</td>
</tr>
<tr>
<td>Sixth</td>
<td>6,520</td>
<td>10</td>
<td>1,783,000</td>
<td>12</td>
<td>170,600</td>
<td>12</td>
</tr>
<tr>
<td>Seventh</td>
<td>6,190</td>
<td>10</td>
<td>1,887,200</td>
<td>13</td>
<td>179,300</td>
<td>13</td>
</tr>
<tr>
<td>Eighth</td>
<td>3,290</td>
<td>5</td>
<td>1,129,700</td>
<td>8</td>
<td>106,200</td>
<td>7</td>
</tr>
<tr>
<td>Ninth</td>
<td>3,230</td>
<td>5</td>
<td>1,298,300</td>
<td>9</td>
<td>122,000</td>
<td>9</td>
</tr>
<tr>
<td>Tenth</td>
<td>3,130</td>
<td>5</td>
<td>1,675,300</td>
<td>11</td>
<td>157,500</td>
<td>11</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>15,060,100</td>
<td>100</td>
<td>1,428,200</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-21. Scenario 2 delay distribution by day bands

<table>
<thead>
<tr>
<th>Impeded day band</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>First</td>
<td>18,470</td>
<td>29</td>
<td>2,358,300</td>
<td>16</td>
<td>221,800</td>
<td>16</td>
</tr>
<tr>
<td>Second</td>
<td>6,280</td>
<td>10</td>
<td>1,083,100</td>
<td>7</td>
<td>103,700</td>
<td>8</td>
</tr>
<tr>
<td>Third</td>
<td>6,230</td>
<td>10</td>
<td>1,251,000</td>
<td>9</td>
<td>120,300</td>
<td>9</td>
</tr>
<tr>
<td>Fourth</td>
<td>6,520</td>
<td>10</td>
<td>1,470,800</td>
<td>10</td>
<td>140,000</td>
<td>10</td>
</tr>
<tr>
<td>Fifth</td>
<td>6,230</td>
<td>10</td>
<td>1,547,000</td>
<td>11</td>
<td>146,700</td>
<td>11</td>
</tr>
<tr>
<td>Sixth</td>
<td>6,420</td>
<td>10</td>
<td>1,756,800</td>
<td>12</td>
<td>168,000</td>
<td>12</td>
</tr>
<tr>
<td>Seventh</td>
<td>3,060</td>
<td>5</td>
<td>931,900</td>
<td>6</td>
<td>88,500</td>
<td>6</td>
</tr>
<tr>
<td>Eighth</td>
<td>3,290</td>
<td>5</td>
<td>1,129,700</td>
<td>8</td>
<td>106,200</td>
<td>8</td>
</tr>
<tr>
<td>Ninth</td>
<td>3,230</td>
<td>5</td>
<td>1,298,300</td>
<td>9</td>
<td>122,000</td>
<td>9</td>
</tr>
<tr>
<td>Tenth</td>
<td>3,130</td>
<td>5</td>
<td>1,675,300</td>
<td>12</td>
<td>157,500</td>
<td>11</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>14,502,200</td>
<td>100</td>
<td>1,374,700</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
### Table 4-22. Scenario 3 delay distribution by day bands

<table>
<thead>
<tr>
<th>Impeded day band</th>
<th>Aircraft departures</th>
<th>Impeded trip time</th>
<th>Passenger delay hours</th>
<th>Mean delay per psngr.</th>
<th>Passenger cost</th>
<th>Air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousands</td>
<td>Percent</td>
<td>Hours</td>
<td>Percent</td>
<td>Thousands</td>
<td>Percent</td>
</tr>
<tr>
<td>First</td>
<td>21,750</td>
<td>35</td>
<td>2,778,100</td>
<td>20</td>
<td>261,300</td>
<td>20</td>
</tr>
<tr>
<td>Second</td>
<td>6,050</td>
<td>10</td>
<td>1,043,300</td>
<td>7</td>
<td>99,900</td>
<td>8</td>
</tr>
<tr>
<td>Third</td>
<td>6,470</td>
<td>10</td>
<td>1,298,900</td>
<td>9</td>
<td>124,900</td>
<td>9</td>
</tr>
<tr>
<td>Fourth</td>
<td>6,460</td>
<td>10</td>
<td>1,456,000</td>
<td>10</td>
<td>138,600</td>
<td>10</td>
</tr>
<tr>
<td>Fifth</td>
<td>6,140</td>
<td>10</td>
<td>1,523,200</td>
<td>11</td>
<td>144,500</td>
<td>11</td>
</tr>
<tr>
<td>Sixth</td>
<td>3,290</td>
<td>5</td>
<td>899,500</td>
<td>6</td>
<td>86,000</td>
<td>6</td>
</tr>
<tr>
<td>Seventh</td>
<td>3,060</td>
<td>5</td>
<td>931,900</td>
<td>7</td>
<td>88,500</td>
<td>7</td>
</tr>
<tr>
<td>Eighth</td>
<td>3,290</td>
<td>5</td>
<td>1,129,700</td>
<td>8</td>
<td>106,200</td>
<td>8</td>
</tr>
<tr>
<td>Ninth</td>
<td>3,230</td>
<td>5</td>
<td>1,298,300</td>
<td>9</td>
<td>122,000</td>
<td>9</td>
</tr>
<tr>
<td>Tenth</td>
<td>3,130</td>
<td>5</td>
<td>1,675,300</td>
<td>12</td>
<td>157,500</td>
<td>12</td>
</tr>
<tr>
<td>Overall</td>
<td>62,860</td>
<td>100</td>
<td>14,034,200</td>
<td>100</td>
<td>1,329,400</td>
<td>100</td>
</tr>
</tbody>
</table>

Source: Analysis of research dataset and BTS, 2008
Table 4-23 summarizes the baseline values from Table 4-14 and the three scenarios from Tables 4-20 through 4-22. The figures represent the application of the scenario assumptions to activity in the 1995-2005 period.

Table 4-23   Overview of scenarios 1 through 3

<table>
<thead>
<tr>
<th></th>
<th>Passenger delay hours in thousands</th>
<th>Passenger value</th>
<th>Air carrier cost</th>
<th>Combined passenger and air carrier cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of 2005 Dollars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>1,694,700</td>
<td>$48,500</td>
<td>$37,500</td>
<td>$86,000</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>1,428,400</td>
<td>40,800</td>
<td>33,000</td>
<td>73,800</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>1,374,700</td>
<td>39,200</td>
<td>32,100</td>
<td>71,300</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1,329,400</td>
<td>38,100</td>
<td>31,300</td>
<td>69,400</td>
</tr>
</tbody>
</table>

Source: Tables 4-14, 4-20 through 22

Although these are simplified scenarios, they illustrate the order of magnitude of savings that can be expected through delay reduction. The largest benefit ($12.2 billion over the 11-year period) derives from the assumed reduction in the highest delay bands. Under the scenario assumptions, the order of magnitude of the savings is $1 billion out of the approximately $8 billion total annual cost of impeded trips.

The discussion of the results of this research ends with the scenarios. These scenarios illustrate the integration of the three main parts of this research—unimpeded times, short-term variable costs, and the distribution of delays.
CHAPTER 5

SUMMARY, DISCUSSION AND RECOMMENDATIONS

Summary

The study accomplishments were these: (1) the study developed a comprehensive database for individual major U.S. airline domestic trips between 1995 and 2005; (2) the study explored the central tendency and variability of airline gate-to-gate trip times and delays; (3) the study developed values for unimpeded trip times, and (4) the study developed delay and variability costs relative to unimpeded trip times for travelers and airlines.

In the performance of the study, trip times were used as a primary indicator, unimpeded trip times were used as a delay reference, and costs were assigned at the individual flight level to the excess of reported trip time over unimpeded trip time. This allowed delays and costs to be aggregated in a many different ways to support analysis of the time savings and operating cost impacts of initiatives for increasing capacity and reducing impedance in the system.

The study results and conclusions were derived from a review of the differences between total departures, impeded trip time, passenger time value, and air carrier cost. The most important of these results are those concerning: (1) origin and destination airports and corridors; (2) times of day; and (3) delay days in the high deciles.
1. Aircraft in the 121-150 seat group represent 57 percent of all departures, 56 percent of all impeded trip time, 56 percent of passenger delay cost, and 51 percent of air carrier delay cost.

2. Origin-destination flights between large hubs/HDA airports represent 40 percent of all departures, 49 percent of impeded trip time, and 55 percent of delay costs.

3. Flights with origins or destinations at OEP1 or OEP2 airports represent 50 percent of all departures, about 50 percent of impeded trip time, and 54 percent of delay costs.

4. Flights scheduled to leave between noon and 8 PM, and to arrive between 2 PM and 10 PM (33 percent of the time in a day), represent 50 percent of all departures, 60 percent of impeded trip time and nearly 60 percent of delay costs.

5. The four highest decile days, with days ranked by average delay per departure, represent 40 percent of all departures, but account for 56 percent of delays, impeded times and passenger costs, and 53 percent of air carrier costs. The lowest decile represents about 4 percent of total impeded hours and passenger costs, and about 6 percent of airline costs. The highest decile represents 19 percent of impeded hours and passenger costs, and 17 percent of airline impeded costs.

The study found that, while annual average delays ranged from a low of 3.2 minutes in 2002 to a high of 10.5 minutes in 2000, 85th percentile delays remained at levels higher than 15 minutes throughout the entire study period. The lowest annual 85th percentile delay values were reported in 2002 and 2003 (17 minutes) and the highest in 2000 (28 minutes). For 95th percentile delays, the range was 41 minutes to 65 minutes.
Arrival delay performance during 2000 was the poorest of any year in the study period. In 2000, air travel was perceived to be in crisis, with traffic volumes at a level approaching system capacity, in a year in which summer convective weather activity placed an unusual strain on the National Airspace System. Many of the references cited in the literature review in this study represent reports on research projects that started in the 1990s as it continued to be apparent that action was needed if future system capacity was to keep up with demand growth. The response was apparent in 2001, as delay mitigation programs took effect. Delays in 2001 were reduced, partly as a result of better summer weather, airline schedule depeaking at major hub airports, reduced schedules at Chicago, Newark and LaGuardia Airport (and possibly other system choke-points), and improved FAA traffic flow management and severe weather avoidance processes.

A significant, but little-recognized, contributing factor to the reported delay improvement after 2000 was the addition of an average of 3 minutes in additional buffer time for scheduled flights. This is apparent from Table 4-1, which shows median minutes delay per flight dropping from 1995-2000 levels of between 0 and 2 minutes, to -2 minutes in 2001, and -3 minutes in 2002 and 2003. Figure 4-7 shows the effect of an additional 4 minutes in schedule buffer time (as one minute of median delay in 2000 changed to -3 minutes in 2003) needs to be recognized in context of the dramatic drop in average delay of 7 minutes between 2000 and 2003 (as average delay fell from 10.5 minutes in 2000 to 3.5 minutes in 2003). The added schedule buffer times after the air travel delay crisis of 2000 were apparently difficult to maintain, as it is likely that competitive schedule pressures are reflected in the median schedule delay of -2 minutes and -1 minutes shown in Table 4-1 for 2004 and 2005.
The distortion in reporting of arrival delays measured against schedule times is apparent in the preceding summary. A conclusion can be drawn that a median-adjusted arrival delay would have been a better measure to apply in reporting true delay performance improvement between 2000 and 2003. As reported, average delays dropped from 10.5 minutes in 2000 to 3.5 minutes in 2003, a dramatic improvement of 62 percent. With median adjustment, 2000 delays would have been reported as 9.5 minutes and 2003 delays as 6.5 minutes, a less dramatic delay reduction of 32 percent (from Table 4-2, after subtracting annual median delay from annual mean delay, to adjust for changed schedule buffer times).

As shown in Table 4-1, delays in 2002 and 2003 were reduced to the lowest levels in the study years, as system volume dropped after September 2001 (when aviation terrorism attacks occurred in the U.S.), and as air traffic flow management continued to improve. However, system performance worsened, as traffic volume resumed its growth. The 85th percentile delay measurement rose from its low of 17 minutes in 2002 and 2003 to 22 and 23 minutes in 2004 and 2005, levels that equaled those of 1998 and 1999.

Other results of the study are summarized as follows:

1. As indicated in Figure 4-2 and 4-3, between 1995 and 1999, arrival delay increased with increasing flight stage length. The amount of this increase lessened after 2000. This was likely the result of inadequate buffer times in the early study years, and the urgent need after 2000 to add buffer time in order to mitigate high reported delays. The evidence for this is shown in Figure 4-4 uses a median adjustment to average delay to correct for changes in buffer time. This flattens the slope of delay versus distance.
2. As indicated in Figure 4-5, three airports had unusually high arrival delays in 2000 and 2005. Chicago, Newark, and LaGuardia delays grew steadily between 1997 and 2000, dropped sharply in 2001 and 2002, then resumed their growth in 2003, with Newark reaching a new peak in 2005. This appears to indicate that delays were amplified at congested airports, and that actions taken to reduce schedule peaking were effective until traffic growth resumed.

3. Comparison of the results of the cost allocation methodology against the costs used in several FAA regulatory evaluations shows a close correlation, with a $1,575 average 2005 dollar cost per weighted block hour developed in this study, compared to an estimated at between $1,600 and $1,800 average 2005 cost per block hour in three FAA regulatory evaluations (after aircraft size adjustment to be comparable to the baseline B-737-300 used in this research).

4. The study found that airline delays imposed an $86 billion cost on travelers and air carriers over the study period, compared to the costs of unimpeded operation. As shown in Table 4-2, annual costs ranged from $6.5 billion in 1995, were highest at $9.9 billion in 2000, and ended the period at $9.3 billion in 2005. About 56 of total costs relate to traveler time value, and 44 percent relate to airline variable costs.

5. About 57 percent of aircraft departures were performed with 121 to 150 seat aircraft, with about 17 percent of departures performed by 61 to 102 seat aircraft, representing a combined 74 percent for 61 to 150 seat aircraft. They also accounted for a commensurate proportion of the delay costs to passengers and air carriers. However the largest aircraft group based on seat capacity (211 and up)
accounted for only 3 percent of the departures but 10 percent of the delay costs to passengers and to air carriers.

6. Over 50 percent of the value of passenger delays and air carrier delay cost are associated with operations between large hubs and between high density airports (HDAs) and large hubs. The disproportionate impeded cost and trip time (55 percent of passenger and airline cost and 49 percent of impeded trip time associated with 40 percent of departures) reflects both higher delay per departure (through the ratio 49:40) and a higher passenger count per departure on flights between large airports (through the ratio 55:49).

7. About 65 percent of departures and 49 percent of delay hours and costs are accounted for on stage lengths under 750 miles. Flights over 1,500 miles account for 10 percent of departures and 20 percent of passenger delay hours and costs.

8. As shown in Table 4-3, Delta Air Lines operated with a seat per departure index of 1.24. An index value of 1.00 represents 131 seats per departure. Impeded trip time for Delta at 14 percent of total matches Delta's departure share of 14 percent, which indicates that Delta was not disproportionately affected by delays. Delta's passenger delay hours and passenger and airline delay costs can thus be explained as primarily driven by larger aircraft size. American Airlines, on the other hand, with impeded trip time 18 percent, compared to a departure share of 14 percent, appears to be affected more by delays. Passenger delays and costs were 19 percent, and airline costs were 20 percent of the total, indicating a small effect from aircraft size. This is consistent with Table 4-3 which shows American's aircraft size index of 1.07, which roughly equates to the ratio of American's costs
of 20 percent of the total to American's impeded trip time of 18 percent of the total.

9. Southwest Airlines is the only listed airline to have a lower impeded share than its departure share. As an approximation, it can be seen from Table 4-9 that Southwest reported 20 percent less delay per departure than the average for all ASQP carriers (12 percent impeded trip time share divided by 15 percent departure share, giving a ratio of 0.8, which is 20 percent below the overall 1:1 ratio).

10. Fifty percent of delays are associated with CRS departure times between 12 noon and 8 PM, and 50 percent of delays are also associated with CRS arrival times between 2 PM and 10 PM.

11. Analysis of the effect of airport turn times on delays does not reveal any direct relationship between the two. However, taken together with information related to actual prior turn times (Table 4-13), the two tables indicate an interesting phenomenon. Although scheduled turns between 100 and 160 minutes have impeded trip time shares that are at the same level as aircraft departure shares, the same cannot be said about actual turn times. Actual turns between 100 and 160 minutes have impeded trip time shares that are double the value of their associated departure shares. These flights, however, account for only 4 percent of departures. This suggests that these flights represent those delayed by weather, congestion, or mechanical problems, and that the resulting delays are one to two hours longer than a normal airport turnaround.
12. When average daily delays per flight are ranked for the 4,018 days in the study period, about 56 percent of delays and impeded times are accounted for by the days in the four highest deciles—the seventh, eighth, ninth and tenth deciles (40 percent of the days). The lowest decile represents about 4 percent of total impeded hours and passenger costs, and about six percent of airline costs. The highest decile represents 19 percent of impeded hours and passenger costs, and 17 percent of airline impeded costs.

13. Out of 129.5 million block hours operated by reporting carriers between 1995 and 2005, 17.9 million hours represented either impeded trip time or departure delays. Table 4-15 shows that the 9.3 million hours of impeded block time in the study period exceeded the 8.6 million block hours associated with departure delay. These times, however, are the same order of magnitude.

14. Of the 9,340 hours total excess impeded trip time by flight phase, excess taxi-out time contributed 54 percent of the total (4,980 hours). The proportion of taxi-out, airborne and taxi-in was in the range of 50:33:17 percent for most of the 11-year period. Low values for airborne impeded times were evident in 2002 and 2003. Across-the-board increases in impeded times in 2004 and 2005 were evident (Table 4-16, and shown graphically in Figures 4-2 and 4-3).

15. The $37.5 billion in air carrier costs associated with trip times in excess of the unimpeded trip time accounted for 10.3 percent of variable operating costs over the study period (Table 4-17).
16. Annual airline impeded expense remained at a level of about $3 billion between 1995 and 1998, rose to over $4 billion in 2000, dropped to about $3 billion in 2002 and 2003, than increased sharply in 2004 and 2005 to $3.8 billion annually.

17. Table 4-18 shows the excess jet fuel consumed by flight phase. Excess airborne fuel is the main contributor to excess fuel consumption, accounting for 56 percent of overall excess fuel for the 1995-2005 period. Estimated fuel use in the taxi-out phase is the next leading contributor, at 35 percent of the total.

18. Jet fuel consumption in all phases (taxi-out, airborne, and taxi-in) by the ASQP reporting carriers remained in a fairly narrow range (between 10 and 11 billion annual gallons) over the 11-year period (Table 4-19). Airlines became more efficient in their use of fuel. The expansion of reporting carriers to regional airlines after 2000 needs to be considered in interpreting this result.

19. The cost of jet fuel rose sharply in the 2003-2005 period, with a $2 billion increase in 2003, a nearly $4 billion increase in 2004, and a $5 billion increase in 2005. Total impeded fuel expense remained relatively constant as a proportion of total fuel expense. For 2005, total impeded fuel expense represented $840 million annually.

20. Air carriers replaced older, less fuel efficient aircraft between 1995 and 2002. As shown in Figure 4-9, fuel burned per weighted block hour decreased from 784 gallons in 1995 to 694 gallons in 2002, and remained constant through at a level of 700 gallons per weighted block hour.
Discussion

Increased flight efficiency is a primary goal for the current transformation of the air traffic management and air navigation systems globally. Improving flight efficiency involves more direct aircraft routings (horizontally), operation of aircraft at optimum altitudes (vertically), at efficient speeds (longitudinally), and with predictable trajectory times. Reduction in trip time variability can be considered as one measure of progress as flights become more efficient and flight trajectories become predictable. But trip time variability is also a measure of operational performance that relates directly to the service provided to travelers and shippers.

In the preceding summary and explanation of changes in reported arrival delays during the study period, as in most examinations of air travel delays, there is no mention of the variability of delays. While median adjustment of reported delays may provide a good depiction of delay levels when buffer times are changing, measuring delay against unimpeded time would provide a better measure, as it is unaffected by schedule buffer time. However, the argument is stronger for use of unimpeded times as a reference. A shift in describing delay is needed, away from a measure that focuses attention on average delay as a single metric, to a measure that leads to the examination of the distribution of delays. Delay variability during the study period, ranging from a low of 26 minutes in 1995 to a high of nearly 36 minutes in 2000, deserves more attention. High trip time variability creates a need for high schedule buffer times.

The 2025 vision of the Next Generation Air Transportation System initiative started out with goals to improve passenger transit time and trip time variability (domestic airport curb to airport curb time cut by 30 percent), and to reduce the impact of weather
and other disruptions on system performance, with 95 percent of scheduled aircraft operations within 15 minutes of timetable (NextGen, 2004). A European Commission goal for 2020 was set for 99 percent of all flights to operate within 15 minutes of timetable (Knoerzer, 2006). Both objectives implicitly recognize a need for variability to be incorporated in trip time performance measures. Both objectives use a single metric to designate a standard that includes both the amount of delay and the variability of delay.

A general conclusion of this research is that schedule buffers are necessary for maintaining a desired level of arrival performance. Greater trip time variability requires more buffer time. The buffer time required depends on the arrival delay probability distribution. Given a cumulative probability function, in a form that can be calculated, and that is based on a good estimate of trip time variability, the required buffer time can be calculated directly for a selected level of on-time performance.

If trip time variability is to be reduced, both trip time variability and flight time predictability will need to be managed. The standards proposed for Europe in SESAR (2008) can serve to model the way. However, based on the methodology developed in chapter 3 and the analysis performed in chapter 4 of this dissertation, achieving these stated goals for 2020 and 2025 appears to represent an extreme challenge. There is a wide gap between the historical standard deviations of 26 to 36 minutes reported for the years 1995 to 2005, and the 15 to 20 minutes standard deviation that would be required to maintain buffer times under 15 minutes.

Before considering the problem of delay reduction in a future in which volume and capacity, together with the management of volume, capacity and levels of service, are not yet defined, the more basic problem of the measurement and reporting of delays will need
to be addressed. Today, flight delays under 15 minutes are not reportable as delays. The issue is the dual purpose of delay reporting—measuring quality of schedules for consumers versus measuring performance for service providers. It is undesirable to confuse the two purposes.

The current delay standard (arrival delay against computer reservation system schedule) is also problematic for operational reporting. Delay is measured against an airline-set reference time that itself includes an element of delay, since the buffer that an airline builds into its schedule is on its own an allowance for delay. There exist several other measures for assessing progress toward reducing delays, including current FAA tracking of performance against an 88 percent NAS on-time arrival standard for 35 OEP airports (FAA, 2007d; FAA, 2008g). In that system, delay is measured against airline-filed flight plan time of arrival, with all delays that are not considered attributable to the FAA's management of the NAS excluded from the measure. By excluding extreme weather, airline-caused delay, security delay, and part of propagated delays, the FAA on-time performance arrival rate was reported as 88 percent in 2005. This compares to a 79 percent on-time arrival rate in 2005, before exclusion of non-NAS-related delays.

Thus, in practice, the measurement and reporting of delays can be considered to serve three purposes—consumer reporting, system performance reporting, and system management reporting. This research has addressed the issues of trip time variability and costs in U.S. scheduled air transportation, and has derived values for unimpeded trip times as a basis for valuing delay and trip time variability.

Ideally there would be a single measurement system that would serve consumers, system planners and airline operators, and system managers. This would require an
accepted or mandated common reference for measuring unconstrained or unimpeded trip time and trip time elements. This research has shown that it is possible to develop unimpeded trip times and to apply unimpeded times to the valuation of delays.

As an exercise demonstrating the limits of what may be possible, consider the distribution of unimpeded block times developed in Chapter 3. For block times in the unimpeded category (about 1 percent of all flights in the dataset), the mean residual difference between observed unimpeded block times and mean unimpeded block times was calculated to be -0.63 minutes (-38 seconds), the median was 0 minutes, and the standard deviation was calculated to be 3.9 minutes. Figure 3-5 is reproduced here as Figure 5-1.

Source: Research dataset and MathWave (2008)

Figure 5-1. Distribution of unimpeded block time residuals
Recommendations for Further Study

Beyond this dissertation, the relevant questions that remain to be answered are what ranges of improvements are attainable, how these improvements will be sequenced, what benefits will result, and when can changes be introduced into operation to achieve these results.

It is clear that better and less variable trip time performance will produce time savings to travelers and cost savings to airlines. Delays and impeded flight times have been shown in this study to add up to nearly 1.7 billion hours over the 11-year study period for travelers on the reporting airlines. Time savings together with operating cost savings are valued at eight billion dollars per year (in constant 2005 dollars) for the ASQP research dataset.

To support system performance improvement, better estimating procedures are required for developing reference values and for valuing performance improvements. A conclusion of this research is that unimpeded reference times are necessary as reference values. These do not exist today. Standards would need to be developed for reference times to represent unconstrained operation. The standards would need to deal with issues such as whether unimpeded times should be seasonally adjusted, based on more extensive analysis of the data. Impeded times could be adjusted to reflect validated actual experience as capacity-expanding measures are introduced into operation.

This research explored some of the issues involved in developing a set of unimpeded times and attaching costs to trip time variability around unimpeded times. The analysis in this research did not consider the cost of disruption and flight cancellations. The analysis in this research also did not include the cost of provision of air navigation services. This
research did not include consideration of deadweight loss to the economy and the potential value of the economic surplus generated for society. Future research should include these considerations.

**Closing Commentary**

In reviewing differences between the United States and Europe during the course of this research, it became clear that there are significant differences in performance measurement and reporting. It was fortunate that airlines in the United States are required to report their on-time performance and other operating and financial results to the U.S. DOT, and that BTS makes these data publicly available. The United States has no counterpart to EUROCONTROL’s independent Performance Review Commission. It would be valuable to have such an organization. There are independent analyses performed by the Government Accountability Office and the U.S. DOT Inspector General, but there is no institutionalized process for independent setting and review of performance standards.
APPENDIX A

PATTERNS OF DELAY
Airport Runway Capacity

Runway and taxiway capacity to accommodate aircraft at an acceptable quality of service level represents the limiting constraint for most airports. The two other aspects, terminal and airport ground access capacity are more easily scalable than runway capacity.

Airport performance improvement strategies are most beneficial if they target runway system inefficiencies. Idris et al. (1998) established that the runway system is the key constraint at major airports. Although the research involved identifying the flow constraints that impede departure operations, the conclusions apply to both departure and arrival operations.

An airport's runway system and its surrounding airspace can be understood in terms of a queuing system, with streams of arriving and departing aircraft and one or more runway servers. The arrival process is defined by spacing between aircraft (between aircraft in flight as well as spacing between aircraft at the time an aircraft crosses the runway threshold on arrival or becomes airborne on departure).

The rules that have evolved are: (1) terminal air traffic control is responsible for maintaining separation between aircraft within the airspace surrounding an airport; (2)
spacing between aircraft must be maintained at or above the prescribed minimums; and
(3) no more than one aircraft may be active on a runway at any point in time. These rules are applied by air traffic control in directing and sequencing aircraft. Under certain circumstances, in good visibility conditions, air traffic control can delegate the responsibility for spacing to pilots, who then become responsible for maintaining separation.

The relevant literature reports on analyses and research on the relationship between airport runway capacity and queuing delay. Early studies in the 1940s of airport saturation landing rates considered capacity as the reciprocal of the service rate. Thus if the runway server time was one minute per operation, then the limiting capacity was 60 operations per hour (Bowen & Pearcey, 1948; Pearcey, 1948). Galliher and Wheeler (1958) developed probability distributions for airport landing times in the New York area, through analysis of nonstationary waiting line transient behavior, assuming Poisson-distributed arrivals, constant service times and service in order of arrival. Blumstein (1959) introduced two additional runway landing capacity factors. These were minimum separation on approach under instrument weather conditions, and velocity differences between successive aircraft.

Pestalozzi (1964) treated the airport runway as a service facility in a queuing mechanism, used by both landing and departing aircraft, but extended the analysis to consider different priority rules and their impact on average waiting time and average delay cost. His conclusion was that the impact of these rules on average waiting time was small, but that delay cost could be significantly reduced. The reduction in delay cost came at the expense of uneven treatment of different groups. Pestalozzi suggested this
disparity might be handled through differential airport charges, increasing fees for high
priority groups, and decreasing them for disadvantaged users.

Oliver (1964) also considered priority classes in his analysis of delay problems for
departure and landing operations on a runway or within the approach path of a terminal
air traffic system. He considered conditions under which two priority classes were served
by a single runway, and discussed conditions under which assigning the highest priority
reduces expected costs or average delays. Oliver concluded that the simplifying
assumptions of Poisson arrivals and constant service times were inadequate as a basis for
understanding air traffic procedures for handling high volume mixed traffic. Oliver
cautioned against reliance on average delay, since extreme delays must be also
considered as average flow rates approach the theoretical capacity of the service facility.
He observed that the nature of the terminal control process was one of taking a random
flow of arriving and departing aircraft and making it into "a highly controlled and
regularly scheduled operation and of resolving potential conflicts in a common service
facility" (Oliver, 1964)."

Simpson (1965), in a paper based on his doctoral research, applied computer
simulation to investigate operational procedures for different terminal area traffic control
schemes. Simpson proposed a general definition of the traffic control problem in the
terminal area: "The derandomization of ... random arrivals into an efficient arrangement
of takeoffs and landings, such as to maximize the total operation rate and minimize the
delays in both landing and takeoff processes, consistent with safety, passenger comfort,
vehicle limitations, and other operational considerations arising from the environment."
Simpson found that the instrument landing "funnel" was the capacity restrictive element
in the simulation, and that the terminal area system was a "multi-channel, correlated service, stochastic system" and that it was difficult to apply any useful models from existing queuing theory to form a general policy about its operation. A main conclusion of Simpson's research was that a smaller, higher-performance terminal area system could result from higher landing interval accuracy, but that this would require advanced means of giving accurate navigational data to the pilot or autopilot.

From the 1970s on, the literature focuses on capacity improvement. Astholz et al. (1970) review changes in separation between aircraft, use of additional parallel runways, and more precise control of terminal traffic to obtain higher capacity. The magnitude of improvement was estimated to be 40 percent without change to existing separation standards, and 100 percent with the introduction of improved guidance, flight control, air traffic control automation, and surveillance. A factor in obtaining these improvements was closer spacing of independent instrument runways.

Hockaday and Kanafani (1974) took a probabilistic approach to aircraft separation, postulating that aircraft deviate from their intended trajectory when approaching to land. These deviations are normally distributed with mean zero. Controllers introduce buffers in order to reduce the probability of inadequate separation. Their approach separates capacity analysis from delay analysis, and applies the concept of airport practical capacity, as opposed to airport ultimate capacity. Ultimate capacity is the maximum number of aircraft able to be handled in a period under conditions of continuous demand, and is the reciprocal of the mean service time of aircraft using a facility. Practical capacity was defined as the number of operations that could be handled during a time period such that the mean delay did not exceed a set value. The concept of practical
capacity linked delay with capacity, and this troubled the authors, since the implication was that the capacity of a runway is influenced by user demand characteristics without changing the physical or operating characteristics of the runway.

Hockaday and Kanafani (1974) used runway occupancy time (ROT) in their model as the time separation required between consecutive aircraft in order to ensure that the leading aircraft clears the runway before the following aircraft can use the runway.

In their analysis, Hockaday and Kanafani used observed data from New York LaGuardia Airport to compare observed flow rates with capacities calculated by their model. The calculated capacity for a landing runway was 35 landings per hour, with the comparable observed value of 33 arrivals per hour. This compares with the Current FAA arrival rate of 37 per hour under reduced (instrument) conditions (FAA, 2008a).

Credeur (1977) analyzed benefits from reduced separation minima, assuming a normal distribution of arrivals, with buffer times between arrivals and allowance for final approach speed differentials. Meyn (2002) proposed the use of a probabilistic approach for predicting airport arrival rates (AARs) and sector loadings. Meyn used Monte Carlo simulation to develop uncertainty in airport arrival time predictions by 25 to 35 percent. Meyn worked with both normal distributions and empirical distributions. However, his empirical distributions were based on a very small sample of data for a 3-hour time period during a single day at Dallas/Fort Worth International Airport (Meyn, 2002). Meyn concluded that the relatively simple probabilistic methods for arrival and sector demand forecasting had the potential to provide significantly improved short-term demand projections, even if the error distributions of arrival time predictions were not known (Meyn, 2002).
Gilbo (1993) developed a concept of an airport capacity envelope for the entire range of deterministic arrival/departure ratios. Starting with an empirical approach based on observation of historical capacity at delay-prone airports, Gilbo developed capacity curves for different runway configurations and weather conditions. Weather conditions were grouped into categories which reflect: visual conditions; marginal visual conditions; instrument conditions; and low instrument conditions.

The use of Gilbo's capacity coverage chart is illustrated in Figure A-1:

![Capacity Coverage Chart for New York LaGuardia Airport](source)

Source: FAA (2001)

Figure A-1. Capacity coverage chart for New York LaGuardia Airport

Gilbo introduced a new way to conceptualize the optimization of traffic flow at airports. Prior to this, airport capacity had generally been represented by separate capacities for departures and arrivals. Gilbo's capacity coverage chart has been widely
adopted. A limitation of the chart, however, is that it represents the ultimate capacity frontier for an airport, without regard to whether the levels of delay at the frontier are acceptable.

Gilbo (1997) formulated the problem of airport capacity utilization as one of optimizing the use of runways and terminal airspace. Gilbo (1997) considered the airport runways together with arrival and departure metering fixes as an integrated system resource. The paper addressed improvement in the efficiency of managing arrival and departure traffic at airports. Airport capacity and flows were allocated with regard to balancing constraints on interdependent arrivals and departures on both runways and arrival and departures fixes. Gilbo held that neglecting fix constraints affected utilization of runway capacity. Gilbo (1997) presented a model for allocating resources between arrivals and departure to avoid loss of available runway slots. Gilbo's model did not, however, deal with the relationship between delay and utilization of limited runway capacity, nor did Gilbo (1997) address uncertainty in airport arrivals and departures.

FAA (2008f) defines the procedure for calculating the airport arrival rate (AAR) for an airport's primary runway configuration. The AAR is defined as "a dynamic parameter specifying the number of arrival aircraft that an airport, in conjunction with terminal airspace, can accept under specific conditions throughout any consecutive 60 minute period." An airport's primary runway configuration is "an airport runway configuration which handles 3 percent or more of the annual operations."

The FAA (2008f) procedure requires calculation of AAR values for four weather conditions:

2. Marginal VMC: weather does not allow vectoring for visual approach, but visual separation on final is possible.

3. Instrument Meteorological Conditions (IMC): visual approaches and visual separation is not possible.

4. Low IMC: weather dictates Category II or III ILS operations, or 2.5 miles-in-trail (MIT) on final is not available.

The calculation of maximum runway arrival capacity is straightforward:

\[
\text{AAR} = \frac{\text{knots ground speed at runway threshold}}{\text{n.m. spacing at threshold}}
\]

FAA (2008f) notes that a number of factors may reduce the maximum AAR. These include close spacing between arrival runways, runways used for both arrivals and departures, availability of high speed exit taxiways, airspace constraints, taxiway layouts, severe weather, and intersecting arrival and departure runways. After adjustment for one or more of these factors, the AAR becomes the "optimum" AAR.

There is also a provision in FAA (2008f) for dynamic adjustment to the maximum AAR. Dynamic adjustments include aircraft type mix, runway conditions, runway and taxiway construction, equipment outages, and TRACON constraints.

The specification and computation of AAR considers only runway capacity. It does not consider uncertainty in arrival times and variable spacing between aircraft, and thus there is no consideration given to queuing delays as the actual arrival rate approaches the AAR. The effects of omitting consideration of volume-to-capacity ratio means that, under
FAA (2008f), AAR (like Gilbo's model) does not deal with the relationship between delay and utilization of limited runway capacity. This is no consideration of level of service or quality of service criteria in setting capacity limits. This will be addressed next.

Airport Volume-Capacity Relationship

The primary approach to increasing airport capacity has in the past been through building additional runways. For many airports and cities this is no longer possible. Operationally, capacity can be increased through simultaneous operations on closely spaced parallel runways and converging runways. The limitation is that aircraft separation risk cannot be relaxed. The established standard Target Level of Safety (TLS) is one fatal accident per 10 million operations (ICAO, 2001). However, given that a safety fence must be maintained, reduced landing time intervals and runway occupancy times will increase capacity, as will precision spacing on approach and landing (timing errors measured in single digits).

The two major causes of trip time variability and delay are airport delay and weather. Airport runway delay is a nonlinear function of airport demand as it relates to capacity. Runway delay tends to increase sharply when the volume to capacity ratio is close to 100 percent. This process can be viewed as a queuing process, with departing and arriving aircraft as customers waiting to be served by the airport and airspace surrounding the airport. In making best use of runway capacity (without compromising safety) there are two major strategies under development: (1) minimize stochasticity and create flows based on more shorter and more deterministic arrival and service times; and (2) reduce the gap between good weather (VMC) and instrument weather (IMC) runway capacity.
The relationship between delay, volume, and capacity can be illustrated using an example.

Assume that a runway is used exclusively for arrivals, that arrivals are random, that service times are stable, and that a steady-state equilibrium exists. Delay can then be computed from the following equation (Horonjeff and McKelvey, 1994):

\[
W_a = \frac{\lambda_a \left( \frac{\sigma_a^2 + 1}{\mu_a^2} \right)}{2 \left( 1 - \frac{\lambda_a}{\mu_a} \right)}
\]

where:

- \( W_a \) = mean delay to arriving aircraft in hours
- \( \lambda_a \) = mean arrival rate of aircraft (arriving aircraft per hour)
- \( \mu_a \) = mean service rate for arrivals (arrivals handled per hour), or reciprocal of mean service time (hours service time per arrival)
- \( \sigma_a \) = standard deviation of mean service time of arriving aircraft (hours, or seconds/3600)

With a mean service rate of 50 aircraft per hour, and 25 seconds standard deviation in service times, the chart in Figure A-2 illustrates the steep increase as mean arrival delays exceed 4 minutes (y axis) as the volume to capacity ratio (x axis) rises above 85 percent.

Credeur (1977) developed a similar formula taking into account weight category and approach speed differences between leading and trailing aircraft, as well as interarrival spacing differences. Credeur use a steady state queuing model to estimate the capacity benefits of reduced vortex separation minima.
Figure A-2. Illustration of runway delay as a function of volume

Welch and Lloyd (2001) used a steady state queuing approach to infer airport system capacity from FAA delay statistics. They compared delay reported at 26 airports with total annual delay predicted by a queuing model, with capacity estimates derived, with some adjustment, from FAA (2001). Their analysis found volume-to-capacity ratios at most of the 26 airports exceeded 50 percent, "indicating that further increases in demand will result in disproportionate increases in queuing delay" (Welch and Lloyd, 2001).

Peterson et al. (1995) questioned the use of queuing models based on steady-state assumptions. Traditional queuing analyses were not, in their view, appropriate for analysis of landing aircraft. For an airport, with three stations (a landing runway, a terminal gate and a departure runway), arrival rates are highly time-varying, and service
rates vary over time with weather. Service times depend on leading and following aircraft types, thus assumptions about independent, identically distributed (iid) service times are not valid. "A feature of the airport queuing problem which sets it apart from numerous other applications is the presence of substantial correlation between service rates in successive periods." (Peterson et al., 1995).

Peterson et al. suggested that the high degree of schedule peaking in airline hub operations is responsible for many day-to-day delays, and that moderate traffic smoothing policies would reduce delays and rationalize airline schedules.

Peterson et al. (1995) extended the analysis of airport delays with a model based on aircraft landings at a busy hub airport with variation in arrival rates throughout the day. Weather was used as the principal source of uncertainty. A Markovian process accounted for dependencies between capacity levels at successive time intervals. Peterson et al. considered landing aircraft as customers using a set of runways which operate as a single server. The paper explored the sensitivity of congestion delay to starting conditions and analyzed the effects of demand smoothing policies on queuing delay.

Hoffman et al. (2003) studied the ability of a following aircraft to maintain an exact 60 second constant time delay spacing behind a lead aircraft when the mix of arrivals included aircraft of different sizes and performance under different wind conditions. Turbulent winds severely degraded the stability of time based spacing under crosswind and headwind conditions.

Meyn and Erzberger (2005) used a stochastic simulation to evaluate the capacity benefits of improved delivery accuracy for a high-demand arrival period at Dallas-Fort
Worth International Airport (DFW). Both meter fix arrival and runway arrival accuracy are considered. Four configurations were evaluated:

1. A manual system as the base case, with voice communication from controllers to pilots (13 seconds standard deviation, 32 seconds buffer),
2. A system with decision support tools for controllers (such as Traffic Management Advisor), voice controller-to-pilot communications (10 seconds standard deviation to runway, 24 seconds buffer)
3. A highly automated system with trajectories sent via datalink to the aircraft (5 seconds standard deviation to runway, 12 seconds buffer), and
4. A system with perfect flight conformance to the ideal (zero standard deviation to runway, zero buffer).

The results of the simulation were that, with delays held constant at existing levels, demand could be increased by 19 percent (decision support tools), 42 percent (highly automated system), and 69 percent (perfect conformance) relative to the base case. The implication of Meyn and Erzberger's research was that improved arrival time predictability (a capability of delivering an aircraft to a runway with 5 seconds standard deviation from the required time of arrival) had a significant effect on ability to manage the tradeoff between capacity and delay.

Balakrishnan and Chandran (2006) used dynamic programming to develop a shortest network path by grouping like-performing aircraft. This analysis built on earlier research by Neuman and Erzberger (1991). The arrival order of aircraft was rearranged through constrained position shifting. The problem analyzed was that a sequence of 10 alternating large and small aircraft will use runway capacity less efficiently than a sequence of five
small aircraft are followed by five large aircraft. The Balakrishnan-Chandran algorithm, using Poisson-distributed test data based on Denver International Airport experience, shortened the time necessary to handle 23 landing aircraft in a 30-minute period by five minutes, compared to a first-come, first served rule.

Holforty and Powell (2001) and Holforty (2003) report on research involving a predictive algorithm and synthetic vision to display predicted wake positions. The display also showed neighboring aircraft, including the wake-generating aircraft. Holforty demonstrated, through simulation and flight testing, that it was possible to display a wake danger zone well enough to help pilots act to avoid wake encounters. There was no sensor capable of real-time airborne wake vortex detection. The limitations of Holforty's prediction model were acknowledged, together with the situation in which sensor technology needed to catch up with synthetic vision display technology. Holforty's research showed that flight test pilots were able to fly close to the wake danger zone without encountering the wake, but were also able to locate the wake by intentionally flying into the wake danger zone.

Hahn and Schwarz (2006) analyzed the relationship between wake vortex avoidance separation standards and landing capacity, reporting on German Aerospace Center DLR Wake Vortex Prediction and Monitoring System project. Wake vortex separation is a limiting factor for runway capacity. The international standards of 2 or 3 minutes (non-radar) or 3, 4, 5, and 6 nautical miles (radar monitored) between aircraft in trail (depending on aircraft weight) were conservative, but had been shown to be operationally safe.
Hahn and Schwarz (2006) concluded that the ultimate limit on capacity was minimum runway occupancy time, assumed to be 45 to 50 seconds for a single runway. Wake vortex separation standards represented 90 seconds (3 nm spacing), 120 seconds (4 nm spacing) or more. Under crosswind conditions, the wake vortex hazard area from a leading aircraft will be blown laterally away from the path of a following aircraft. Possible safe wake vortex encounters range from (1) go-around upon wake encounter, to (2) undisturbed flight operation without adverse effects from wake vortices ("operationally safe"). Hahn and Schwarz (2006) used operationally safe wake vortex passage as the criterion. Their conclusion was that, with crosswind components of between 3 and 5 m/sec, operationally safe spacing wake vortex approach spacing may be able to approach the runway occupancy time value of 60 seconds. Thus wake vortex spacing theoretically could no longer be limiting.

However, in calm air or for headwinds or tailwinds with no crosswind component, the wake hazard area might remain in the flight path of the trail aircraft and there would be no reduction of current separation distances and therefore no capacity increase.

In his dissertation, Xie (2005) analyzed safety factors related to reducing airport arrival spacing. His research focused on the two aspects involved–simultaneous runway occupancy and wake vortex encounter. Xie used stochastic modeling to evaluate operational safety in the current system, then used the models to evaluate potential future changes. Xie relied in his research on the ICAO target level of safety for commercial aviation–one fatal accident per 10 million operations. Xie's research modeled wake vortex encounter probabilities under different conditions. A generalized conclusion of
Xie's results is that that current wake separation standards could be likely reduced by 20 percent without significant reduction in safety levels.

Mundra (2008) states that, under weather conditions during which visual conditions are in use, single runway separations over the runway threshold are nearly a mile better than radar-based separations.

Recent research sponsored by the National Research Council (2008) reported on a multi-year, Congressionally-mandated study of wake vortex research challenges. The report agreed with conclusions of earlier research that most aircraft can clear a runway in 60 seconds or less, and that wake vortex separation standards require a separation of two minutes or more, "leaving the runway used only half as much as it might be." Comparing wake vortex research in the United States and Europe, little work was underway in the United States, while European agencies were conducting research on a variety of wake vortex issues. The NASA budget could no longer support FAA short-term activities, nor was much funding available for more fundamental long-term research. The report concluded that: wake vortex encounters do occur and are safely tolerated in the current air transportation system; there was now no high-resolution wake vortex sensor capable of operating in inclement weather; reduction in wake vortex spacing standards could not be quantified, since there is no agreed definition or metric for hazard boundaries for wake encounters.

The National Research Council report, referring to Holforty (2003), found that onboard wake vortex visualization had been demonstrated in a proof-of-concept trial and could provide a safety net for dynamic wake vortex spacing procedures.
NextGen (2007b; 2008b) proposed consideration of revised wake separation standards for closely spaced parallel runways, together with new wind-based wake procedures on departure that would increase capacity.

Active research is underway in Europe and the United States (SESAR, 2008; NextGen, 2007b; FAA, 2008b) to increase runway and airport throughput per hour, as well as to reduce taxi delays during peak hours. Better airport processes, in the air and on the surface, promise to improve productivity. These processes include optimization of arrival, departure, and taxi scheduling. Continuing improvement is necessary in prediction of operational capacity, to allow the system to anticipate and adjust to weather and disrupted conditions, including system failures and emergency events.

As a basis for increasing airspace and airport capacity, NextGen (2007b) cited eight transformational capabilities, including, for airports, equivalent visual operations (EVO) and "super density" operations. Observing that airport capacity could be reduced by half under instrument conditions, when ceilings are low and visibility was poor, EVO would support the ability to regain much of the lost capacity. Super density airport arrival and departure operations would allow aircraft with the required navigational equipment to operate with reduced spacing and conformance to precise 4D flight paths.

SESAR (2008) set the following objectives for "best in class" runway VMC capacity in 2020 (with IMC capacity objectives set 20 percent below VMC levels):

- 60 movements per hour for a single runway airport
- 90 movements per hour for an airport with closely spaced dual runways
- 120 movements per hour for an airport with independent dual runways
The European SESAR initiative has also proposed to deal with the limitation that airport capacity is effectively halved in instrument weather. SESAR 2020 targets are based on developing operational the technology and procedures to reduce to the gap between IMC capacity and VMC capacity from 2008 level of 50 percent to a future level of 20 percent, while at the same time improving best-in-class VMC capacity by 20 percent above the 2008 level. In the EUROCONTROL capacity planning process, effective capacity is associated with a service quality, with a delay objective of "one minute per flight average en route ATFM delay (2.1 minutes including airport delay)" (EUROCONTROL, 2007b).

Airport Arrival Delay Standards

The FAA Advisory Circular on airport master planning (FAA, 2005a) adopts a traditional definition of acceptable delay for airport planning purposes. Delay is typically expressed in minutes per aircraft operation, which can be translated into hours of annual delay and easily converted into dollar estimates to be used as a basis for comparison. Traditionally, four to six minutes of average delay per aircraft operation has been used in the calculation of annual service volume for airport planning. This has, in the past, been considered as an acceptable level of delay. When the average annual delays per aircraft operation reached four to six minutes, an airport was considered to be approaching its practical capacity, and was regarded as congested (FAA, 2005a).

FAA (1976) begins with a statement that there was lack of agreement on what constituted acceptable delay applicable to airports and their airfield components. The textbook view of practical airfield capacity was that stated in Horonjeff and McKelvey
Horonjeff and McKelvey (1983) held that tolerable average delays were as follows:

1. For departing aircraft, 4 minutes for mixed runway operations in VFR conditions when more than 10 percent of the aircraft population was large and heavy jet aircraft.
2. For departing aircraft, 3 minutes or less for mixed runway operations in VFR conditions when 10 percent or less of the aircraft population was large and heavy jet aircraft.
3. For departing aircraft, 4 minutes for mixed runway operations in VFR conditions when there was less than 1 percent large and heavy jet aircraft in the aircraft population.
4. For departing aircraft, 4 minutes for mixed runway operations in IFR conditions, regardless of aircraft class.
5. For arriving aircraft, 4 minutes for mixed runway operations in IFR conditions regardless of the aircraft class.
6. For all arrivals, 1 minute in VFR conditions.

Horonjeff and McKelvey (1983) noted that since these were averages, some aircraft would be delayed more than the specified levels and some less.

The FAA (1981) report contains an discussion of airfield and en route delay and capacity. The discussion includes the concept of acceptable delay. Determination of acceptable delay is a policy decision. In economic terms, if delay reduction required an investment, then the investment in delay reduction should continue to be made until the
benefits associated with delay reduction equaled the cost of undertaking them (FAA, 1981).

FAA (1983) contains detailed worksheets for calculating throughput capacity and annual service volumes for airport elements. In its treatment of average delay, FAA (1983) noted that "delays 5 to 10 times the average could be experienced by individual aircraft."

FAA (1995) used a measure of delays of 15 minutes or more per thousand operations, using 20,000 hours of annual delay at an airport as a criterion for designating high-delay airports, reporting that 23 airports each exceeded 20,000 hours of annual flight delays.

FAA (1999) stated that average delay per operation of 10 minutes or more may be considered severe. FAA (2001) used a significant passenger delay measure of three percent or more of the operations experiencing delays in excess of 15 minutes, stating that "airports can achieve maximum capacity only at a reduced quality of service."

FAA (2002) stated that:

"Experience shows that delay increases gradually with rising levels of traffic until the practical capacity of an airport is reached, at which point the average delay per aircraft operation is in the range of 3 to 5 minutes. Delays increase rapidly once traffic demand increases beyond this level. An airport is considered to be congested when average delay exceeds 5 minutes per operation. Beyond this point delays are extremely volatile, and a small increase in traffic, adverse weather conditions, or other disruptions can result in lengthy delays that upset flight schedules and impose a heavy workload on the air traffic control system."
FAA (2004a) stated that, for the purpose of its analysis, "average arrival delay estimated at 12 minutes per flight or above was an indication that an airport may need additional capacity." FAA (2004b) noted that "some amount of congestion and delay is not inconsistent with efficient and affordable air transportation."

FAA (2007a) discussed annual service volume and reasons for using 7 minutes as a measure, noting that this level of average delay is higher than the 4 minutes average delay per flight that is used in airport planning. ASVs were based on an estimate of 7 minutes of delay per flight, on average. "The higher level was selected because the analysis is intended to identify airports with excessive delay levels" (FAA, 2007a).

Delay Distribution in Transportation Literature

The probability distribution of delays in scheduled airline service has not been extensively investigated. Delay distributions are generally not symmetrical. While delays can be negative (as in the case of early flight arrivals), delays can also be extended to extremes (as in the case of arrivals 12 or more hours late). The distribution of delay is thus positively skewed, with mode, median and mean values in ascending order. It is inappropriate to use the well-understood normal distribution (which, as a symmetrical distribution, has an identical mode, median, and mean value) in the analysis of delays. Care must be taken in the use of average, or arithmetic mean, delays as a measure of delay, since the mean is heavily influenced by extreme values of delay. A characteristic of extreme value distributions is that the standard deviation is large compared to the mean.

In the transportation literature, bus and train delays have been more extensively studied than scheduled airline delays. The literature contains research that attempts to fit
known positively skewed distributions to observed travel times departure delay and arrival delay. Dessouky et al. (1997) surveyed 14 prior studies for bus transit arrival time, lateness, or delay to summarize probability distributions for random bus times. Their finding was that two earlier studies used an exponential distribution, 4 studies used Gamma distributions, 3 used lognormal distributions, one used a Gumbel distribution, 5 used the normal distribution, and one used a truncated exponential distribution. Two of the studies used two different distributions. Liu and Wirasinghe (2001) modeled bus departure times from the starting terminal, assuming Gamma or lognormal distribution of starting times, with the Gamma distribution for link times.

Yuan and Hansen (2002) modeled train arrival delays for a Dutch railway station, concluding that train delays follow an exponential distribution, and excess dwell times (greater than scheduled time at the station platform) for late-arriving trains follow a normal distribution. Nie and Hansen (2005) reviewed past studies of train running times in Germany, reporting that Weibull and Chi-square distributions. However, Nie and Hansen concluded that little research had been published on train speed, blocking and buffer times, and that the research had been limited mainly to "experiments and analysis applying assumed distributions of primary delays and deterministic running and minimum headway times of trains." Nie and Hansen, based on observed data, concluded that they could not reject normally-distributed train running times, but that neither the departure delay nor the arrival delay fit a known distribution using the Kolmogorov-Smirnov goodness-of-fit test. They attributed this lack of fit to multiple knock-on effects (delay propagation). Huisman et al. (2005) surveyed operations research in passenger railway transportation. Huisman et al. acknowledged that deviations in delays were
important, but simplified the analysis by using arrival punctuality as the objective measure of reliability. Their definition of punctuality is "the percentage of trains that arrive less than x minutes late." The European margin was stated to be 5 minutes, with a 3-minute margin used in the Netherlands.

Yuan and Hansen (2007) developed an analytical model of the propagation of train delays at a station as a convolution of several individual distributions: (1) the arrival time of the approach train and the conflicting train at the approach signal under several different conditions; (2) the running times of both trains on relevant track sections; and (3) the distribution of the platform track clearance time of the clearance train when it departed the station. In addition, departure delays were modeled under conditions in which a feeder train caused a departure to be delayed to accept transfer passengers. Yuan and Hansen (2007) used an Erlang distribution to model the arrival time distribution of a train, and an exponential distribution to model train dwell time. In their paper, Yuan and Hansen (2007) reserved estimation of propagated delays for the station as a whole for future research.


Mueller and Chatterji (2002) evaluated aircraft arrivals and departures at 10 airports over a 21-day period, using data from the FAA POET (Post Operations Evaluation Tool) database. Mueller and Chatterji concluded that departure delay was better modeled using a Poisson distribution, and arrival delay modeled using a normal distribution.
Welch and Ahmed (2003) analyzed patterns of throughput and delay for U.S. airports that operate near capacity. They defined a delay occurrence spectrum for each of these airports, "roughly analogous to the Fourier transform of the arrival time series." In their paper, they related the distribution of delays to the spectra for throughput delay.

Welch and Ahmed (2003) presented two diagrams as illustrations, representing probability density functions for arrival delay at DFW International Airport for April 2000. The first figure graphs arrival delay in terms of actual gate arrival time versus scheduled gate arrival time (delay distribution mode -5 minutes, mean 2.05 minutes, standard deviation 23.6 minutes). The second figure graphs actual arrival time versus the airline's flight plan estimated time en route (delay distribution mean 0.78 minutes, standard deviation 9.2 minutes). These distributions show a pattern similar to distributions charted in Yuan and Hansen (2002). The shape of the distributions suggested that the literature review in this research extend to extreme value distributions. This will be covered in the next section.

Welch and Ahmed (2003) concluded that delay relative to predicted flight time (airborne delay) was nearly invariant to arrival throughput at all but the lowest arrival rates. This suggested two implications for the current research. The first was that airborne times at the lowest arrival rates represented the unimpeded times. The second was that the probability distribution of airborne times was of lesser relevance than the probability distribution of departure delay, taxi-out time and block times. This second implication followed directly from the conclusion that "delay relative to schedule (arrival delay) varied significantly with arrival throughput" (Welch and Ahmed, 2003).
Welch and Ahmed (2003) made the following observation: "at airports with well-metered flow, arrival delay generally increased at the high end of the spectrum. It is likely that the highest throughput occurred at these airports when delayed flights arrived in bunches by chance. On the other hand, at hub airports, arrival delay decreased at the high end of the spectrum, probably because instances of high peak throughput occurred more frequently when aircraft arrived on schedule during hubbing rushes."

Levy et al. (2004) studied the distributions of landing speeds and inter-arrival distance spacing of Memphis International Airport arrivals. Their conclusion was that arrival spacing between aircraft followed a Johnson $S_B$ distribution (Johnson, 1949), with a finite lower bound as a result of the application of minimum safe separation standards for arriving aircraft.

Xie (2004; 2005) and Haynie (2002) analyzed stochastic interaction of landing time intervals and runway occupancy times. Xie also analyzed the effect of reduced times on safety, as measured by the probability of simultaneous runway occupancy by two aircraft. Xie assumed that runway occupancy time followed a normal distribution. For part of his analysis, Xie also used the normal mixture distribution to approximate landing time intervals, but later obtained a distribution through a simulation using queuing model and a Poisson aircraft arrival process, ending with an Erlang distribution as an approximation to the normal distribution. Xie found that a shortcoming in the approach of Levy et al. was that a Johnson $S_B$ curve approach might fit satisfactorily, the approach could not reveal the physical fundamentals of the process. For his purposes (determination of the joint distribution of landing time interval and runway occupancy time), Xie needed to
forecast landing time intervals, and he concluded that curve-fitting methods were unable to do this.

Tu et al. (2008) noted that most prior studies of airspace delays typically have provided only average delay statistics and do not focus on estimates of distribution functions. Tu et al. (2008) focused their research on pushback delay, the time difference between the time that an aircraft actually leaves the gate and the time the aircraft was scheduled to leave the gate. Their research used 2000 data from nearly 93,000 United Airlines flight departures at Denver International Airport as the basis for training and validating a model that was then used to forecast 2001. To model delays produced by different random variables, Tu et al. employed a mixture of several probability density functions. Their justification was that "many of the underlying mechanisms of delay suggest the use of an error model that comprises different components." Their process combined expectation maximization and genetic algorithm to minimize the value of residuals. In order for this approach to be workable, Tu et al. first needed to adjust for daily and monthly seasonality. The daily seasonality, representing an increasing delay trend through the afternoon and early evening hours, was referred to by the authors as "the daily propagation pattern." The components they suggested include a component for early flight departures, another for the majority of flights "that depart right around the scheduled time," and one or more components that account for flights that have extremely long delays. Tu et al. actually selected a 4-component mixture model with two components forming the center of the distribution, a third component capturing medium delays, and a fourth component accounting for extremely long delays. Tu et al. concluded that the actual and estimated delay distributions "are very similar (at least visually)."
et al. explain their methodology, but their approach, limited to one airline's departures at a single airport, does not seem to be scalable. Their approach would have been stronger had they focused on modeling the combination of pushback delay and taxi-out delay.

Wanke et al. (2005) addressed the problem of improving the ability to predict uncertain demand and capacity up to several hours in advance for en route air traffic control sectors. The main variables were look-ahead time, predicted peak traffic count, active flights already in the system, and sector type. The research performed by Wanke et al. covered look-ahead times of up to 4 hours, over 171 days in the first half of 2004 for 754 ATC sectors. Wanke et al. selected Binomial and Poisson probability distributions to characterize uncertainty, based on the application of Chi-square goodness-of-fit tests.

In summary, the literature appears underdeveloped in guidance for selection of probability distributions for use in delay studies for ground and air transportation modes. The most methodologically rigorous work appears to have been performed by Dutch researchers (Yuan and Hansen, 2002; Nie and Hansen, 2005; Huisman et al., 2005) in studies of rail operations. What appears missing in the research is discussion of appropriate positively-skewed probability distributions that model delay behavior in the relevant range. For arrival delay, the relevant range is that above the 85th percentile. The decision as to how much buffer time to allocate in a flight schedule depends on accurate modeling probability for the long tail of the distribution. The results are sensitive to the distribution's shape in the upper tail. The need to focus on good fit over a specific, but limited, region of a distribution implies that general goodness-of-fit tests such as the Kolmogorov-Smirnov test are not appropriate. This point seems rarely recognized in the surveyed literature.
There are three foundational elements missing in the transportation literature. There is no foundational work for replacing the arbitrary "scheduled" times (which include buffers) with appropriate "reference" times (which exclude buffers). The second is that the lack of research into the probability distributions that shape delays. The third is missing ability to associate values with changes in trip time delay and variability.

Delay Distribution in Civil and Environmental Engineering Literature

Gumbel (1958) wrote that the statistics of extremes are in opposition to the empirical methods favored by many engineers and practical statisticians, "who are inclined to believe that, after all, nearly everything should be normal, and whatever turns out not to be so can be made normal by a logarithmic transformation. This is neither practical nor true" (Gumbel, 1958).

In reviewing the literature on delays, it became evident that the empirical shape of several distributions presented in graphs and figures could be characterized as extreme value distributions. However, except for Levy et al. (2004), the literature search for this dissertation revealed no mention of application of extreme value distributions relating to scheduled air transportation delay.

The search in this literature review looked to references drawn from the civil engineering literature. However, extreme value distributions are found in many fields, and it was useful to refer also to financial engineering and econometric sources.

The publication of Gumbel (1958) represented an engineer's development of the theory of extreme values. Castillo (1988) points out that "there exists a very long list of engineering areas where the extreme value theory plays a decisive role." in many cases, the design engineer is often more interested in design values based on the extremes rather
than on the overall distribution of operating conditions and capacities. Castillo provides an examples of the interest that engineering studies take in extreme values, among which are the critical values of sea wave height, flood amount, or wind speed that lead to damages, demonstrating that often the only interest is centered on the frequencies of exceedance of such values. Castillo also provides examples of engineering areas in which extremes need to be understood–structural engineering, ocean engineering, hydrology, pollution studies, meteorology, strength of materials, fatigue strength, highway traffic, and corrosion resistance. The relevance of extreme value theory to the analysis of delays is apparent.

Metcalfe (1997) comments in reference to extreme value and related distributions that design decisions will be made by extrapolating into the tails of the theoretical distributions, so it is important to make an appropriate choice of a distribution and then to estimate the parameters in an efficient way. Metcalfe suggests using probability plots as a useful means for assessing goodness-of-fit. He also suggests equating the sample mean, standard deviation and skewness to the theoretical distribution, but cautions that sample skewness is based on cubed deviations from the mean, which may allow outlying values to have disproportionate effects.

Metcalfe (1997) extends his treatment of extreme value distributions to bivariate and multivariate extreme value distributions. He uses, as an example, offshore structures such as oil rigs that can fail under conditions of extreme waves and violent winds. Metcalfe notes that a common approach to multivariate data analysis is to use a transformation (such as a logarithmic transformation) that makes it plausible to assume that the transformed data come from a multivariate normal distribution. This cannot be done for
prediction of extreme values. Metcalfe (1997) cautions on simulation of bivariate distributions from conditional distributions, citing the drawback the result is an empirical distribution rather than an algebraic function.

Chao et al. (1988) consider that when stochastic processes, which evolve in a manner that is partly predictable and partly random, have characteristics such that the random variability of the process is large compared to its predictability, then an analyst can be justified in treating the process as purely random. Chao et al. also consider that "statistical methods are based on mathematical principles that describe the random variation of a set of observations of a process, and they focus attention on the observations themselves rather than the physical processes that produced them. Statistics is a science of description, not causality."

Rao and Hamed (2000) relate the approach used in hydrologic frequency analysis, which is paraphrased here. The objective is to associate the magnitude of extreme events with the frequency of their occurrence. Data observed over an extended period of time are analyzed. The data are assumed to be independent and identically distributed. The data are assumed to be stochastic and may, in some cases, be assumed to be space and time independent. In practice, the true probability distribution is not known. More than one type of cause may contribute to extreme events. However, for the analysis to be of practical use, simpler distributions are used to characterize the relation between the event magnitudes and their frequencies. The performance of the distributions is evaluated by using different statistical tests. In the analytical process, the assumptions may often be invalid. The assumptions need to be questioned and discussed extensively.
Embrechts et al. (1997) start with a justification for addressing their book to the financial and insurance industries. They reason that this audience has been less exposed to extreme value theory (EVT), in contrast to hydrologists and engineers, for whom EVT has for a long time belonged to the standard toolkit. Embrechts et al. state, that in the context of extreme events, the following are important:

- Subexponential distributions as realistic models of heavy-tailed random variables.
- Fréchet, Weibull, and Gumbel distributions as limit laws for maxima of independent and identically distributed random variables (iid).
- The normal distribution as limit law for sums of iid, finite-variance random variables.
- The Poisson distribution as limit law of binomial distributions which represent a counting measure of rare events.

A review of the data suggests that several extreme value distributions may provide a fit to the empirical distributions in the research dataset. These are the loglogistic distribution, the Burr III (or Dagum) distribution, the Burr XII distribution, the Johnson $S_U$ distribution, and the Generalized Extreme Value (GEV) distribution. These distributions are described below.

Ahmad et al. (1988) suggest that an ideal for distributions useful for flood frequency analysis. Adapting Ahmad et al. (1988) recommendations to extend them to other extreme value data, the ideal distribution should meet all of the following criteria:

1. it must reproduce at least as much variability as observed in empirical data sets;
2. it must be insensitive to extreme outliers especially in the upper tail;
3. it must have a cumulative distribution function and an inverse distribution
   function that can be explicitly expressed in a closed form; and
4. it must not be computationally complex nor involve the estimation of a large
   number of parameters.

Loglogistic Distribution

Ahmad et al. (1988) evaluated the loglogistic distribution as a replacement for other
distributions used in flood frequency analysis. An advantage of the loglogistic
distribution is that its probability density function (PDF), cumulative distribution function
(CDF), and inverse CDF can be explicitly specified, and its parameters can be estimated
from empirical data. The loglogistic distribution relates to the logistic distribution as the
log-normal distribution does to the normal distribution (Ahmad et al., 1988).

Ahmad et al. provide a formula for the loglogistic cumulative distribution function,
with 3 parameters, essentially the same as that shown below.

Parameters

\[ \begin{align*}
\alpha & \quad \text{continuous shape parameter} \quad (\alpha > 0) \\
\beta & \quad \text{continuous scale parameter} \quad (\beta > 0) \\
\gamma & \quad \text{continuous location parameter} \quad (\gamma > 0)
\end{align*} \]

Cumulative Distribution Function

\[
F(x) = \left(1 + \left(\frac{\beta}{x - \gamma}\right)^\alpha\right)^{-1}
\]

Probability Density Function

\[
f(x) = \frac{\alpha}{\beta} \left(\frac{x - \gamma}{\beta}\right)^{\alpha-1} \left(1 + \left(\frac{x - \gamma}{\beta}\right)^\alpha\right)^{-2}
\]
Burr III or Dagum Distribution

Burr (1942) developed a family of distributions with closed forms for the cumulative distribution function (Kleiber and Kotz, 2003). Dagum (1977) derived a probability function to describe the distribution of personal income. Dagum classified personal income probability functions according to three categories: those driven by a stochastic process; those proposed solely as representing a good fit to empirical data; and those based on differential equations that purport to capture the regularity and permanence observed in empirical distributions of income.

Dagum concluded that among the most frequently applied models, the Pareto distribution, was only useful in describing the high income upper tail of the distribution, and the lognormal and Gamma fit the whole range of income distributions, but were quite poor in describing the upper and lower tails of the actual distributions (Dagum, 1977).

Dagum's model for income distribution provided a better fit over the whole range of incomes for four dissimilar countries (Argentina, Canada, Sri Lanka, and the United States) and refuted the received wisdom at the time among economists that empirical distributions would never be accurately described by a single function. Dagum's model represents a variation on the loglogistic model, and has an explicit mathematical solution for its CDF, and for both the mode and the quantiles of the density function (Dagum, 1977).
Dagum's original paper (1977) derives a 4-parameter model. The equations shown here represent a 3-parameter model, with the value of Dagum's location parameter set to zero.

Parameters

\[
\begin{align*}
  k & \text{ continuous shape parameter} \quad (k > 0) \\
  \alpha & \text{ continuous shape parameter} \quad (\alpha > 0) \\
  \beta & \text{ continuous scale parameter} \quad (\beta > 0)
\end{align*}
\]

Cumulative Distribution Function

\[
F(x) = \left( 1 + \left( \frac{x}{\beta} \right)^{-\alpha} \right)^{-k}
\]

Probability Density Function

\[
f(x) = \frac{\alpha k \left( \frac{x}{\beta} \right)^{\alpha k - 1}}{\beta \left( 1 + \left( \frac{x}{\beta} \right)^{\alpha} \right)^{k+1}}
\]

Source for formulas: MathWave (2008)
Burr XII Distribution

The Burr XII distribution (also known as the Burr distribution) is a member of the family of distributions with closed forms for the cumulative distribution function, developed by Burr (1949).

Parameters

- $k$  continuous shape parameter #1 ($k > 0$)
- $\alpha$ continuous shape parameter #2 ($\alpha > 0$)
- $\beta$ continuous scale parameter ($\beta > 0$)
- $\gamma$ continuous location parameter

Domain $\gamma \leq x < +\infty$

Cumulative Distribution Function

\[ F(x) = 1 - \left( 1 + \left( \frac{x - \gamma}{\beta} \right)^\alpha \right)^{-k} \]

Probability Density Function

\[ f(x) = \frac{\alpha k \left( \frac{x - \gamma}{\beta} \right)^{\alpha-1}}{\beta \left( 1 + \left( \frac{x - \gamma}{\beta} \right)^\alpha \right)^{k+1}} \]

Source for formulas: MathWave (2008)

Johnson SU Distribution

Johnson (1949) showed an interest in ways in which variables could be transformed such that the transformed variables could be considered to have a normal distribution. Normal distributions cannot adequately represent distributions encountered in practice. The most obvious departure from normality is skewness. Johnson (1949) proposed a
system of curves derived by his method for translating variables. Johnson introduced the symbols $S_L$ for 'log-normal system,' $S_B$ for 'bounded system,' and $S_U$ for 'unbounded system.' The term 'bounded' or 'unbounded' referred to whether the distribution's range was bounded at both extremities, or was unbounded at either extremity (Johnson, 1949).

The parameterization of the Johnson SU distribution shown below corresponds to Johnson (1949), equation (22).

Parameters

- $\gamma$ continuous shape parameter
- $\delta$ continuous shape parameter ($\delta > 0$)
- $\lambda$ continuous scale parameter ($\lambda > 0$)
- $\zeta$ continuous location parameter

Cumulative Distribution Function

$$F(x) = \Phi\left(\gamma + \delta \ln \left(z + \sqrt{z^2 + 1}\right)\right)$$

Probability Density Function

$$f(x) = \frac{\delta}{\lambda \sqrt{2\pi z^2 + 1}} \exp\left(-\frac{1}{2}\left(\gamma + \delta \ln \left(z + \sqrt{z^2 + 1}\right)\right)^2\right)$$

where:

$$z = \frac{x - \mu}{\mu}$$

$\Phi$ is the Laplace integral

Source for formulas: MathWave (2008)
Generalized Extreme Value Distribution

Extreme value distributions are obtained as limiting distributions (as \( n \) becomes very large) of the greatest value among \( n \) independent random variables each having the same continuous distribution (Kotz and Nadarajah, 2000). The Generalized Extreme Value (GEV) distribution is useful in estimating the likelihood that certain threshold values will be exceeded. The GEV Model was first introduced by Jenkinson (Kotz and Nadarajah, 2000). The problem, as stated by Jenkinson (1955), was the prediction of maximum values of a meteorological element to be expected once every 50 or 100 years, given the recorded maximum values over a relatively short number of years. Jenkinson found a general solution that described the types of extreme value distribution actually found in meteorological data. The GEV is applicable to other data developed from maximum (or minimum) values of the underlying distributions. The three types of extreme value distributions are based on whether the shape parameter \( (k) \) takes on a positive, zero or negative value. GEV type 1 distributions are known as Gumbel-type distributions; GEV type 2 distributions are Fréchet-type; and GEV type 3 distributions are Weibull-type (Kotz and Nadarajah, 2000).

Parameters

\[
k \quad \text{continuous shape parameter} \\
\sigma \quad \text{continuous scale parameter} \quad (\sigma > 0) \\
\mu \quad \text{continuous location parameter}
\]

Cumulative Distribution Function

\[
F(x) = \exp \left( -\left(1 + kx\right)^{-1/k} \right)
\]
Probability Density Function

\[ f(x) = \frac{1}{\sigma} \exp \left(-\left(1 + k z\right)^{-1/k}\right) \left(1 + k z\right)^{-1-1/k} \]

where:

\[ z = \frac{x - \mu}{\mu} \]

Source for formulas: MathWave (2008)

This section on possible distributions for characterizing delay ends with a discussion of the use of distributions that are not grounded in theory. Johnson (1949) quotes Pretorius (1930): "The superiority of one frequency function over another depends rather on the success with which that function can be applied to graduate data than on the manner in which it originated." Johnson comments that this point of view has much to recommend it and, if accepted, would make it unnecessary to provide a plausible probability theory basis for any proposed system of frequency curves. Johnson (1949) does, however, in his paper relates his method of translation to probability theory.

Flight Delays and Flight Efficiency

Solomos et al. (2003, 2005) reported on limited analyses of excess, or wasted, flying time in the National Airspace System in 2001 and 2002. A sample of fifteen of the best weather days in each year were used as the reference. Using the “best observed flying time as a standard,” four to five minutes of excess flying time could be detected.

Yakovchuk (2003) analyzed “estimated time en route” airline flight plan differences to develop factors influencing flight plan times—origin airport, destination airport, month, day of week, hour of day, aircraft type and carrier. Route, month, hour of day and carrier
were all found to have statistically significant influences on estimated time en route. The analysis, however, compared only flight plans as filed with the FAA, and not actual operational performance.

Mayer and Sinai (2003) reviewed scheduled trip times and actual trip times between 1988 and 2000, concluding that average trip times were about eight minutes less than scheduled trip times. This difference, or “buffer,” increased in 1999 and 2000 as flight delays increased and airlines attempted to maintain their on-time performance ratings.

Chew (1997) dealt with ATM system performance and standards for evaluating ATM performance. The presentation included the following “target concepts of outcome,” which are a subset of the eleven key performance areas later adopted by ICAO (2007):

1. Delay
2. Predictability
3. Flexibility
4. Efficiency
5. Access
6. Cost of Service

Chew noted that ATM system saturation critically affects the flight schedule, the core airline product. Delay, a by-product of airspace congestion and ATC inefficiency, impacts airline costs in operating a scheduled business. Wasting of airline assets (aircraft) was a primary airline concern. Chew defined such waste as the cost “from operating delays and the revenue loss from reduced scheduling opportunities.”
APPENDIX B

AIRLINE SERVICE QUALITY PERFORMANCE REPORTS
U.S. Department of Transportation Data Sources

Airline data filed under Code of Federal Regulations, Title 14, Part 234, Airline Service Quality Performance Reports

§234.3 Applicability.

This part applies to certain domestic scheduled passenger flights that are held out to the public by certificated air carriers that account for at least 1 percent of domestic scheduled passenger revenues. Certain provisions also apply to voluntary reporting to on-time performance by carriers.

§ 234.4 Reporting of on-time performance.

(a) Each reporting carrier shall file BTS Form 234 “On-Time Flight Performance Report” with the Office of Airline Information on a monthly basis, setting forth the information for each of its reportable flights held out in the Official Airline Guide (OAG), in the computer reservations systems (CRS), or in other schedule publications. The reportable flights include, but are not limited to, cancelled flights, mechanically cancelled flights, diverted flights, new flights and wet-leased flights. The report shall be
made in the form and manner set forth in accounting and reporting directives issued by
the Director, Office of Airline Statistics, and shall contain the following information:

(1) Carrier and flight number.

(2) Aircraft tail number.

(3) Origin and Destination airport codes.

(4) Published OAG departure and arrival times for each scheduled operation of the
flight.

(5) CRS scheduled arrival and departure time for each scheduled operation of the
flight.

(6) Actual departure and arrival time for each operation of the flight.

(7) Difference in minutes between OAG and CRS scheduled arrival times.

(8) Difference in minutes between OAG and CRS scheduled departure times.

(9) Actual wheels-off and wheels-on times for each operation of the flight.

(10) Date and day of week of scheduled flight operation.

(11) Scheduled elapsed time, according to CRS schedule.

(12) Actual elapsed time.

(13) Amount of departure delay, if any.

(14) Amount of arrival delay, if any.

(15) Amount of elapsed time difference, if any.

(16) Causal code for cancellation, if any.

(17) Minutes of delay attributed to the air carrier, if any.

(18) Minutes of delay attributed to extreme weather, if any.

(19) Minutes of delay attributed to the national aviation system, if any.
(20) Minutes of delay attributed to security, if any.

(21) Minutes of delay attributed to a previous late arriving aircraft, if any.

(b) When reporting the information specified in paragraph (a) of this section for a diverted flight, a reporting carrier shall use the original scheduled flight number and the original scheduled origin and destination airport codes. Carriers are not required to report causal information for diverted flights.

(c) A reporting carrier shall report the information specified in paragraph (a) of this section for a new flight beginning with the first day of the new scheduled operation.

(d) A reporting carrier shall not report the information specified in paragraph (a) of this section for any discontinued or extra-section flight.

(e) Actual arrival, departure and elapsed times shall be measured by the times at which the aircraft arrived at and departed from the gate or passenger loading area.

(f) The published arrival time and departure time of a flight shall be, respectively, the scheduled arrival and departure times in effect on the date of the scheduled operation of the flight, as shown in the most recent Official Airline Guide, and in computer reservations systems. Each carrier shall designate a single computer reservations system in addition to the Official Airline Guide as the sources of scheduled arrival time and departure time data in its reports to the Department and shall report the scheduled arrival times and departure times listed in those sources for each flight. Scheduled elapsed times, amount of departure and/or arrival delay, and elapsed time difference shall be calculated using the scheduled times shown in the designated CRS source.

(g) Reporting carriers should use the following codes to identify causes for cancelled flights:
(1) Air Carrier cancellations are due to circumstances that were within the control of the air carrier (e.g. lack of flight crew, maintenance, etc.).

(2) Extreme weather cancellations are caused by weather conditions (e.g. significant meteorological conditions), actual or forecasted at the point of departure, en route, or point of arrival that, in accordance with applicable regulatory standards and/or in the judgment of the air carrier, prevents operation of that flight and/or prevents operations of subsequent flights due to the intended aircraft being out of position as a result of a prior cancellation or delay attributable to weather.

(3) NAS cancellations are caused by circumstances within the National Aviation System. This term is used to refer to a broad set of conditions–weather-non-extreme, airport operations, heavy traffic volume, air traffic control, etc.

(4) Security cancellations may be the result of malfunctioning screening or other security equipment or a breach of security that causes the evacuation of the airport or individual concourses, or the need to re-screen passengers.

(h) Reporting carriers should use the following causes to identify the reasons for delayed flights:

<table>
<thead>
<tr>
<th>CAUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Carrier</td>
</tr>
</tbody>
</table>
Extreme weather

NAS

Security

Late arriving aircraft

(1) Air carrier delays are due to circumstances within the control of the air carrier.

(2) Extreme weather delays are caused by weather conditions (e.g. significant meteorological conditions, actual or forecasted at the point of departure, en route, or point of arrival that, in accordance with applicable regulatory standards and/or in the judgment of the air carrier, prevents operation of that flight and/or prevents operations of subsequent flights due to the intended aircraft being out of position as a result of a prior cancellation or delay attributable to weather.

(3) NAS delays are caused by circumstances within the National Aviation System. This term is used to refer to a broad set of conditions–weather-non-extreme, airport operations, heavy traffic volume, air traffic control, etc.

(4) Security delays may be the result of malfunctioning screening or other security equipment or a breach of security that causes the evacuation of the airport or individual concourses or the need to re-screen passengers.

(5) Late arriving aircraft delays are the result of a late incoming aircraft from the previous flight.

(i) When reporting causal codes in paragraph (a) of this section, reporting carriers are required to code delays only when the arrival delay is 15 minutes or greater; and reporting carriers must report each causal component of the reportable delay when the causal component is 5 minutes or greater.
§ 234.5  Form of reports.

Except where otherwise noted, all reports required by this part shall be filed within 15 days of the end of the month for which data are reported. The reports must be submitted to the Office of Airline Information in a format specified in accounting and reporting directives issued by the Bureau of Transportation Statistics' Assistant Director for Airline Information.
APPENDIX C

AIR TRAFFIC MANAGEMENT GLOSSARY OF TERMS

4D Trajectory. Aircraft trajectory defined by three space dimensions and one time dimension.

AAR Airport Acceptance Rate or Airport Arrival Rate. The number of arrivals an airport is capable of accepting each hour. FAA (2008f) defines the procedure for calculating AAR for an airport's primary runway configurations.

ACARS Aircraft Communication Addressing and Reporting System. A datalink system which supports the exchange of information between an aircraft and a ground network. ACARS was initially designed to transmit OOOI times.

ADS-B Automatic Dependent Surveillance-Broadcast.

AC, A/C or ACFT Aircraft

ANS Air Navigation System.

ANSP Air Navigation System Provider.

ARPT Airport

AFP An AFP is a traffic management (TM) process administered by the ATCSCC. Aircraft are assigned specific airspace arrival slots utilizing flight schedule monitor (FSM) to manage capacity and demand for a specific area of the National
Airspace System (NAS). AFPs support the TM mission and mitigate the effects of en route constraints.

AMAN Arrival manager.

AMASS Airport Movement Area Safety System.

ARSR Air Route Surveillance Radar. Air Route Traffic Control Center (ARTCC) radar used primarily to detect and display an aircraft’s position while en route between terminal areas. The ARSR enables controllers to provide radar air traffic control service when aircraft are within the ARSR coverage. In some instances, ARSR may enable an ARTCC to provide terminal radar services similar to but usually more limited than those provided by a radar approach control.

ARTCC Air Route Traffic Control Center. A facility established to provide air traffic control service to aircraft operating on IFR flight plans within controlled airspace and principally during the en route phase of flight. When equipment capabilities and controller workload permit, certain advisory/assistance services may be provided to VFR aircraft. There are 20 ARTCCs in the continental U.S.

ASDE Airport Surface Detection Equipment.

ASQP The Airline Service Quality Performance System (ASQP) contains individual flight data submitted by airlines that carry at least 1 percent of all domestic passengers. The number of airlines providing data has varied from 10 to 20. Actual and scheduled time is available for gate departure and gate arrival. Also available is actual wheels-off time so that taxi-out time can be computed and wheels-on time so that taxi-in time can be computed. Since June 2003, airlines have supplied causal data for all flights arriving 15 minutes past their scheduled
arrival time. The causes of delay categories are airline, extreme weather, National Aviation System, security, and late arriving flight.

ASR  Airport Surveillance Radar. Approach control radar used to detect and display an aircraft’s position in the terminal area. ASR provides range and azimuth information but does not provide elevation data. Coverage of the ASR can extend up to 60 miles.

ATC  Air Traffic Control. A service operated by appropriate authority to promote the safe, orderly and expeditious flow of air traffic.

ATCSCC Air Traffic Control System Command Center.

ATCT  Airport Traffic Control Tower. A terminal facility that uses air/ground communications, visual signaling, and other devices to provide ATC services to aircraft operating in the vicinity of an airport or on the movement area. Authorizes aircraft to land or takeoff at the airport controlled by the tower or to transit the Class D airspace area regardless of flight plan or weather conditions (IFR or VFR). A tower may also provide approach control services (radar or nonradar).

ATFM Air Traffic Flow Management.

ATM  Air Traffic Management.

BLOCK TIME  Block time is defined as the sum of taxi-out, airborne and taxi-in times. Block time starts when the pilot releases the aircraft parking brake after passengers have been loaded and aircraft doors have been closed. Block time ends when the pilot sets the aircraft parking brake after arriving at the airport gate or passenger unloading area (BTS, 2008g)

CAVS CDTI-Aided Visual Separation.
CBA  Cost-Benefit Analysis

CDM  Collaborative Decision Making. Cooperative effort between the various components of aviation transportation, both government and industry, to exchange information for better decision making.

CDR  Coded Departure Routes. Predefined routes used to route air traffic around areas of severe weather.

CDTI  Cockpit Display of Traffic Information.

CFIT  Controlled Flight Into Terrain

CIGS  Ceilings. The height above the ground of the base of the lowest layer of clouds when over half of the sky is obscured.

CLSD  Closed.

CNS/ATM Communications, Navigation, and Surveillance/Air Traffic Management (in ICAO usage CNS/ATM replaced FANS.)

CI  Cost Index. An index set by an airline that allows an aircraft FMS to calculate minimum cost per unit of distance traveled.

CPDLC  Controller Pilot Datalink Communication.

CRS  Computer Reservation System.

CSBT  Coordinated Shared Business Trajectory (SESAR, 2007). See ISBT.

EATM  European Air Traffic Management.

EC  European Commission.

EDCT  Expect Departure Clearance Time. The time issued to a flight to indicate when it can expect to receive departure clearance. EDCTs are issued as part of Traffic Management Programs, such as a Ground Delay Program (GDP).
EMERG Emergency.

EQUIP Equipment.

ETMS Enhanced Air Traffic Management System.

EUROCONTROL European Organization for the safety of Air Navigation.

EVO Equivalent Visual Operations.

EVS Enhanced Vision System.

FAA Federal Aviation Administration.

FAB Functional Airspace Block.

FANS Future Air Navigation System (ICAO term which was replaced by CNS/ATM.).

FEA/FCA Flow Evaluation Area (FEA) / Flow Constrained Area (FCA) - FEA/FCAs provide reroutes using the Create Reroute capability and are published through a reroute advisory with an optional flight list attached. Stakeholders can monitor FEA/FCAs through reroute monitor in traffic situation display (TSD), web situation display (WSD) or collaborative constraint situation display (CCSD).

FMS Flight Management System. The FMS represents an aircraft computer system that manages navigation functions and can compute the most efficient flight trajectory.

FSM Flight Schedule Monitor. A tool used by Air Traffic Management Specialists to monitor air traffic demand at airports.

FSS Flight Service Station. Air traffic facilities which provide pilot briefing, en route communications and VFR search and rescue services, assist lost aircraft and aircraft in emergency situations, relay ATC clearances, originate Notices to Airmen, broadcast aviation weather and NAS information, receive and process IFR flight plans, and monitor NAVAIDs. In addition, at selected locations, FSSs
provide En Route Flight Advisory Service (Flight Watch), take weather observations, issue airport advisories, and advise Customs and Immigration of transborder flights.

GA CDR General Aviation Coded Departure Routes (GA CDR) - The CDR program provides a rapid means to reroute aircraft when the filed flight plan route is constrained by either weather or congestion. Historically, abbreviated CDR clearances have only been issued to airline customers who have signed a Memorandum of Agreement (MOA) with the facilities that issue abbreviated CDR clearances. Recently, general aviation customers have requested use of this reroute capability. This change permits general aviation customers to communicate to Air Traffic Control (ATC) facilities their ability and willingness to accept CDRs and their capability to accept abbreviated clearances associated with CDRs.

GDP Ground Delay Program. Ground Delay Programs are implemented to control air traffic volume to airports where the projected traffic demand is expected to exceed the airport’s acceptance rate for a lengthy period of time. Lengthy periods of demand exceeding acceptance rate are normally a result of the airport’s acceptance rate being reduced for some reason. The most common reason for a reduction in acceptance rate is adverse weather such as low ceilings and visibility. How GDP works:

Flights that are destined to the affected airport are issued Expect Departure Clearance Times (EDCT) at their point of departure. Flights that have been issued EDCTs are not permitted to depart until their Expect Departure Clearance Time.
These EDCTs are calculated in such a way as to meter the rate that traffic arrives at the affected airport; ensuring that demand is equal to acceptance rate. The length of delays that result from the implementation of a Ground Delay Program is a factor of two things; how much greater than the acceptance rate the original demand was, and for what length of time the original demand was expected to exceed the acceptance rate.

**GNSS** Global Navigation Satellite System, the generic term for any satellite-based global navigation system.

**GPS** Global Positioning System. GPS usually refers to the U.S. Navstar GNSS.

**GS** Ground Stop. Flights that are destined to the affected airport are held at their departure point for the duration of a Ground Stop. Ground Stops are implemented for a number of reasons. The most common reasons are:

- To control air traffic volume to airports when the projected traffic demand is expected to exceed the airport’s acceptance rate for a short period of time.
- To temporarily stop traffic allowing for the implementation of a longer-term solution, such as a Ground Delay Program.
- The affected airport’s acceptance rate has been reduced to zero.

**HDTA** High Density Traffic Airport. The FAA has designated five airports (DCA, EWR, JFK, LGA, and ORD) as high density airports and has prescribed air traffic rules and requirements for operating aircraft to and from these airports. Arrival and departure slot reservations are currently required at DCA and LGA between 0600 and 2359 local time, and at JFK between 1500 and 1959 local time.
The ICR process requires that a constraint is identified early. Traffic management may issue a planning (PLN) advisory describing the system constraint and providing route guidance. System stakeholders are allowed an opportunity to consider the area of concern, and provide early intent (EI) messages that communicate their decisions in response to the constraint. EI messages update enhanced traffic management system (ETMS) flight trajectories, monitor alert values and routing intentions. At the expiration of the EI window, traffic management can then analyze the customer responses and decide if the actions taken have resolved the issue, or if recommended routes, required routes, airspace flow programs (AFP) and/or other traffic management initiatives (TMIs) will be necessary to further reduce demand.

ICR allows system stakeholders flexibility in managing their flights based on an identified NAS constraint, reducing the possibility of more restrictive initiatives. Traffic flow management (TFM) tools benefit from enhanced flight information and collaborative responses to system capacity actions.

Instrument Flight Rules. A set of rules governing the conduct of flight under instrument meteorological conditions (IMC).

Instrument Landing System. A ground based precision approach system that provides course and vertical guidance to landing aircraft.
IMC  Instrument Meteorological Conditions.

IRBT  Initial Reference Business trajectory (IRBT) (SESAR, 2007). See ISBT.

ISBT  Initial Shared Business Trajectory (SESAR, 2007). For a scheduled flight, an ISBT exists at least one day before the day of operation. As the flight time approaches, the ISBT continues through several life cycle steps. The ISBT represents an advance user optimum trajectory in the presence of fixed and known (non-negotiable) constraints, under nominal conditions, and without considering traffic congestion, including:

• Airport characteristics and surrounding terrain
• Airport curfews
• Noise abatement procedures
• Prohibited or restricted areas
• Airport slot restrictions
• Statistical weather data

The ISBT turns into the Mature SBT (MSBT) when it takes into account all factors applicable on the day of operation. The MSBT is integrated into the traffic flow and becomes a Coordinated SBT (CSBT) about one hour prior to departure. When the CSBT is uploaded in the aircraft FMS or otherwise given to the flight crew, it becomes the Initial Reference Business trajectory (IRBT).

JPDO  Joint Program Development Office for NextGen

LAADR Low Altitude Arrival/Departure Routing.

LAHSO  Land and Hold Short Operations. Operations which include simultaneous takeoffs and landings and/or simultaneous landings when a landing aircraft is able
and is instructed by the controller to hold short of the intersecting runway/taxiway
or designated hold-short point. Pilots are expected to promptly inform the
controller if the hold short clearance cannot be accepted.

LO CIGS  Low Ceilings. Low clouds.
LOC    Localizer. The component of an ILS that provides course guidance to the runway.
MINIT Minutes in Trail. A specified interval between aircraft expressed in time.
MIT    Miles in Trail. A specified interval between aircraft expressed in nautical miles.
MSBT Mature Shared Business Trajectory (SESAR, 2007). See ISBT.
MULTI-TAXI Many aircraft trying to taxi at once, creating congestion.
N90    New York TRACON.
NAS    National Airspace System. The common network of U.S. airspace; air navigation
facilities, equipment and services, airports or landing areas.
NAVAID Navigational Aid. Any visual or electronic device, airborne or on the surface,
which provides point-to-point guidance information or position data to aircraft in
flight.
NEXTGEN Next Generation Air Transportation System
NM     Nautical Mile. International unit equal to 6076.115 feet (1852 meters).
NOTAM Notice to Airmen. A notice containing information (not known sufficiently in
advance to publicize by other means) concerning the establishment, condition, or
change in any component (facility, service, or procedure of, or hazard in the
National Airspace System) the timely knowledge of which is essential to
personnel concerned with flight operations.
NRP  North American Route Program. The NRP is a set of rules and procedures which are designed to increase the flexibility of user flight planning within published guidelines.

OEP  Operational Evolution Partnership (FAA designation for the transition to NextGen)

OEP1 and OEP2 Airports. Airports included in the OEP. For the purposes of this research, these airports were classified as OEP1 (2005 combined inbound and outbound delay generally under 5,000 hours) and OEP2 (2005 combined inbound and outbound delay generally above 5,000 hours). According to the FAA, "the 35 airports included in the OEP account for about 75 percent of all passenger enplanements. Much of the current delay to air traffic can be traced to inadequate throughput (measured as arrival and departure rates) at these airports. The construction of new airfield infrastructure such as new runways and taxiways and major runway extensions are currently the most effective method of increasing throughput at these airports." Retrieved November 28, 2008 from:

http://www.faa.gov/about/office_org/headquarters_offices/ato/publications/oep/version1/solutionsets/oep35/

OOOI  OUT-OFF-ON-IN times (OUT from the gate, OFF the ground, ON the ground, IN to the gate)

OTS  Out of service.

RBT  Reference Business Trajectory (SESAR, 2007). See ISBT.

RCP  Required Communication Performance.

RLSD  Released.

RNAV  Area Navigation.
RNP  Required Navigation Performance.

RRTES Reroutes.

RTSP  Required Total System Performance.

RVSM Reduced Vertical Separation Minimum.

RWY  Runway.

RWY CONFIG Runway Configuration.

RY  Runway.

SBT Shared Business Trajectory.

SESAR Single European Sky ATM Research Programme.

SID  Standard Instrument Departure.

SPO Strategic Plan of Operation. See SPT.

SPT Strategic Planning Team. The Strategic Planning Team acts as a focal point for the development of collaborative Strategic Plans of Operation. Their goal is to provide advanced planning information for system users and air traffic facilities in order to maximize the utilization of the NAS in an organized and equitable manner.


SARPS Standards and Recommended practices (ICAO).

STAR Standard Terminal Arrival.

STMP Special Traffic Management Program. Reservation program implemented to regulate arrivals and/or departures at airports that are in areas hosting special events such as the Masters Golf Tournament and Indianapolis 500.

SVRWX Severe Weather.
SVS  Synthetic Vision System.

SWAP  Severe Weather Avoidance Plan. An approved plan to minimize the effect of severe weather on traffic flows in impacted terminal and/or ARTCC areas. SWAP is normally implemented to provide the least disruption to the ATC system when flight through portions of airspace is difficult or impossible due to severe weather.

TACAN  Tactical Air Navigation Aid. An ultra-high frequency electronic rho-theta air navigation aid which provides suitably equipped aircraft with a continuous indication of bearing and distance to the TACAN station.

TERPS  Terminal Instrument Procedures.

TFC  Traffic.

TLS  Target Level of Safety. ICAO (2001) establishes a standard TLS of one fatal accident per 10 million operations.

TMA  Terminal Area

TMA  Traffic Management Advisor, an automated decision support tool for air traffic controllers to optimize the sequence of aircraft arriving at an airport through time-based metering.

TRACON  Terminal Radar Control Facility. A terminal ATC facility that uses radar and nonradar capabilities to provide approach control services to aircraft arriving, departing, or transiting airspace controlled by the facility.

TSD  Traffic Situation Display. A tool used by Traffic Management Specialists to monitor the position of air traffic and to determine the traffic demand on airports and sectors.

TSTMS  Thunderstorms.
TWR  Airport Control Tower

URET  User Request Tool

UTC  Coordinated Universal Time (abbreviated as UTC, and therefore often spelled out as Universal Time Coordinated, and sometimes as Universal Coordinated Time) is the standard time common to every place in the world. Formerly and still widely called Greenwich Mean Time (GMT) and also World Time, UTC nominally reflects the mean solar time along the Earth’s prime meridian.

VAPS  Visual Approaches. An approach conducted under Instrument Flight Rules that authorizes the pilot to proceed visually and clear of clouds to the airport. Usually this will be used in conjunction with Visual Separation. When using Visual Separation, a pilot sees the other aircraft involved, and upon instructions from the controller, provides his own separation by maneuvering his aircraft as necessary to avoid it. Visual Separation requires less spacing between aircraft than radar separation allowing more aircraft to land in a given period of time.

VFR  Visual Flight Rules. Rules that govern the procedures for conducting flight under visual conditions. The term "VFR" is also used in the United States to indicate weather conditions that are equal to or greater than minimum VFR requirements. In addition, it is used by pilots and controllers to indicate type of flight plan.

VHF  Very High Frequency

VMC  Visual Meteorological Conditions.

VOL  Volume. Usually used to indicate that the volume of aircraft exceeds an airport’s capacity.
VOR  Very High Frequency Omni Directional Range. A ground-based electronic
navigation aid transmitting very high frequency navigation signals, 360 degrees in
azimuth, oriented from magnetic north. Used as the basis for navigation in the
National Airspace System. The VOR periodically identifies itself by Morse Code
and may have an additional voice identification feature. Voice features may be
used by ATC or FSS for transmitting instructions/information to pilots.

VORTAC A navigation aid providing VOR azimuth, TACAN azimuth, and TACAN
distance measuring equipment (DME) at one site.

VSBY Visibility. The ability, as determined by atmospheric conditions and expressed in
units of distance, to see and identify prominent unlighted objects by day and
prominent lighted objects by night.

WAAS Wide Area Augmentation Service, a satellite navigation system consisting of
equipment and software which augments the GPS Standard Positioning Service
(SPS). The WAAS provides enhanced integrity, accuracy, availability, and
continuity over and above GPS SPS. The differential correction function provides
improved accuracy required for precision approach.

WND  Wind.

WX  Weather.

WX DEV Weather Deviation.

Z  Zulu Time. Another term used to designate Coordinated Universal Time (UTC),
the standard time common to every place in the world. Formerly called
Greenwich Mean Time (GMT), "Zulu" refers to the time zone of the prime
(Greenwich) meridian as expressed in the ICAO phonetic alphabet.
Source: Based on FAA, Air Traffic Control System Command Center, Air Traffic Management Glossary of Terms, with additional terms from other sources.
REFERENCES


Civil Aeronautics Board. (1974). Domestic Passenger Fare Investigation, Phase 9--Fare Structure, Docket 21866, Order 74-3-82, Washington, D.C.


FAA. (2008f). Facility operation and administration, section 7, airport arrival rates (AAR). Order JO 7210.3V, Federal Aviation Administration, Washington, D.C.


VITA

Graduate College
University of Nevada, Las Vegas

Raymond A. Young III

Local Address:
P.O. Box 19920
Jean, Nevada 89019-1920

Degrees:
Bachelor of Science in Engineering, 1964
Princeton University

Master of Business Administration, with distinction, 1970
Harvard University

Special Honors and Awards:
Harding Doctoral Fellowship, 1970-1972, Harvard University
U.S. DOT Gold Medal, 1976
Tau Beta Pi, 2004
Phi Kappa Phi, 2006

Dissertation Title: Examination of Air Transportation Trip Time Variability

Dissertation Examination Committee:
Chairman and Research Advisor: Shashi S. Nambisan, Ph.D., P.E.
Co-Chairman: Mohamed S. Kaseko, Ph.D.
Committee Member: Edward S. Neumann, Ph.D., P.E.
Committee Member: Hualiang Teng, Ph.D.
Graduate Faculty Representative: Alan Schlottmann, Ph.D.