Project Report
ATC-257

Analysis of Downstream Impacts of Air Traffic Delay

S. B. Boswell
J. E. Evans

3 March 1997

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Prepared for the Federal Aviation Administration,
Washington, D.C. 20591

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
ATC-257		

4. Title and Subtitle	5. Report Date
Analysis of Downstream Impacts of Air Traffic Delay	3 March 1997
	6. Performing Organization Code
7. Author(s) S.B. Boswell, J.E. Evans	8. Performing Organization Report No. ATC-257
9. Performing Organization Name and Address MIT Lincoln Laboratory 244 Wood Street Lexington, MA 02173-9108	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTFA01-91-Z-02036
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Washington, DC 20591	13. Type of Report and Period Covered Project Report
	14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, under Air Force Contract F19628-95-C-0002.

16. Abstract

Reduction of air carrier flight delay in the U.S. National Airspace System (NAS) has been a major objective of the Federal Aviation Administration (FAA) for many years. Much of the current delay arises from weather-induced delays at airports. When a plane is delayed on one of the day's flights, there can be a carryover delay that affects later flights by that aircraft. In this report, we develop statistical models to predict:

1. The "downstream" delays that occur when a flight experiences an initial delay, and
2. The likelihood of flight cancellation as a function of the initial delay.

Using historical airline-reported delays for December 1993, we conclude that the mean "downstream" delay is approximately 80 percent of the initial delay, i.e., the net delay for an aircraft due to an initial flight delay is approximately 1.8 × the initial delay.

17. Key Words		18. Distribution Statement
Air Carrier Delay	ASQP	This document is available to the public through the National Technical Information Service, Springfield, VA 22161.
Downstream Delay	ITWS	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

ABSTRACT

Reduction of air carrier flight delay in the U.S. National Airspace System (NAS) has been a major objective of the Federal Aviation Administration (FAA) for many years. Much of the current delay arises from weather-induced delays at airports. When a plane is delayed on one of the day's flights, there can be a carryover delay that affects later flights by that aircraft. In this report, we develop statistical models to predict:

1. The "downstream" delays that occur when a flight experiences an initial delay, and

2. The likelihood of flight cancellation as a function of the initial delay.

Using historical airline-reported delays for December 1993, we conclude that the mean "downstream" delay is approximately 80 percent of the initial delay, i.e., the net delay for an aircraft due to an initial flight delay is approximately 1.8 x the initial delay.

TABLE OF CONTENTS

Section	Page
Abstract	iii
1. INTRODUCTION	1
2. ESTIMATION OF DOWNSTREAM DELAYS THAT FOLLOW FROM AN INITIAL PRIMARY DELAY	5
2.1 Formulation of Downstream Model	6
2.2 Estimation of Parameters	11
3. DOWNSTREAM MULTIPLIER FOR DOMESTIC SCHEDULED OPERATIONS	15
4. COST OF DOWNSTREAM DELAY	19
5. PROBABILITY OF CANCELLATION AS A FUNCTION OF INCOMING DELAY	21
6. DISCUSSION	25
REFERENCES	27
APPENDIX A: Examples of Testimony, Anecdotal and Published Evidence Regarding Downstream Delay	A-1

LIST OF ILLUSTRATIONS

Figure		Page
1.	Four illustrative direct delay distributions. Horizontal axis is delay in minutes, grouped in 10-minute intervals. Vertical axis is the probability of delay falling in each category.	16
2.	Relationship between arrival delay on one flight leg and probability of cancellation on the subsequent leg.	22

LIST OF TABLES

Table		Page
1	Notation	3
2	Aggregation Table for Arrival Delay	3
3	Arrival Delay Distributions. First Two Legs of Multi-leg Flights. ASQP System, December 1993	7
4	Observed Relative Frequencies of Arrival Delay on the Second Leg Given Arrival Delay on the First Leg. ASQP System Data, December 1993	8
5	Four-parameter Downstream Transition Matrix	10
6	Fit of Forecast Delay Distribution ($\tilde{\mathbf{d}}_2$) to the Measured Delay Distribution ($\mathbf{d}_2$) Arrival Delay on the Second Leg of Multi-leg Flights. ASQP System, December 1993	13
7	Downstream Delay Impacts (delay in minutes) Four Direct Delay Distributions	17
8	Observed Probability of Cancellation on Second Leg vs. Arrival Delay on the First Leg. ASQP System, December 1993	21
9	Cancellation Model Parameters	23

1. INTRODUCTION

Travel delay is an important consideration in evaluating the performance of the National Airspace System. Frequently, analyses of the benefits of proposed improvements to the NAS include an estimate of operational delay savings, often explicitly in the form of "Delay hours saved per annum" times "Unit cost of delay." What is meant by an "operational delay" is a delay incurred in the process of conducting an operation, once an intention has been expressed to initiate the operation. In FAA benefits analyses, operational delays are likely to be assigned a fleet-weighted unit Direct Operating Cost (DOC), sometimes broken down by phase of flight (e.g., gate vs. taxi vs. airborne). The value of passenger time may be included in the analyses, though its treatment varies. Frequently, no ancillary cost of delay, beyond these direct costs, is considered.

However, in addition to its immediate costs, an operational delay may generate carryover or "downstream" impacts that affect later flights. Evidence from a variety of sources, cited in Appendix A, indicates that scheduled air carriers consider downstream impacts to be a major, and sometimes dominant factor, in assessing the total costs of air traffic delay. The purpose of the work described here is to quantify some of these downstream impacts in a way that permits their true costs to be incorporated in the A-109 process [1] recommended by the U.S. Office of Management and Budget.

Historically, the FAA has quantitatively considered downstream delay by modeling individual flights in an overall aviation system simulation using the NASPAC model [2, 3]. In this study, we seek to develop a straightforward analytical model which is derived from actual reported delay statistics. The approach taken here yields an end result that is much easier to utilize for typical delay studies: a simple multiplicative constant versus a relatively expensive simulation.

At least three types of downstream impacts should be recognized. These are:

- Cancellations
- Missed connections
- Downstream delays.

In many cases, airlines can expedite ground operations[1] to help put a delayed flight back on schedule. It is also common to build some slack into operating schedules to accommodate typical variations in block time and to absorb modest operating delays. Nevertheless, if the first leg of a multi-leg flight is delayed one hour, for example, it is probable that the second and third legs of that flight will remain behind schedule, assuming that they are not canceled, even in the absence of subsequent operational delays. Delays in the subsequent flight legs, defined with respect to schedule and not attributable to operational delays on these legs, are what is meant by "downstream" delays.

---

[1] A brief discussion of ground servicing, schedule padding ("siesta turns"), downstream impact upon on-time departures, and indirect or lost opportunity costs (discussed elsewhere in this memo) occurs in a Wall Street Journal article on USAir's High Ground program, "New Airline Fad: Faster Airport Turnaround," 4 August 1994.

Lacking a comprehensive data source regarding missed connections, this study will concentrate on cancellations and downstream delays. Comprehensive, nationwide data on cancellations and arrival and departure delays, taken with respect to schedule, are available from the Airline Service Quality Performance (ASQP) files. The ASQP system is administered by the Policy Analysis Division (P-35), Office of Economics, Office of the Secretary, Department of Transportation, as authorized in 14 CFR Part 234. Each U.S. airline that accounts for one percent or more of total U.S. domestic scheduled passenger revenues is required to report a detailed record for every scheduled movement in its domestic system (apart from flights that are delayed or canceled because of mechanical problems). Each record identifies the flight and date and includes scheduled and actual gate departure time (by minute) and scheduled and actual gate arrival time (by minute), as well as delays (calculated as deviations from the schedule). The ASQP-reporting carriers account for over 95 percent of domestic scheduled passenger revenues, and the ASQP database provides comprehensive coverage of U.S. domestic scheduled operations. For December 1993, for example, the database contains over 425,000 individual flight records.

The linkage necessary to establish an relationship between primary and downstream events may be obtained from the ASQP data by linking the successive movements of flights having one or more intermediate stops. In the December 1993 data set, which will be used throughout this discussion, there are 10845 flight designations, most operating for the full month, though some are active for periods as short as one day. Of these flight designations, almost 6000 contain at least two flight legs with an intermediate stop; over 950 have three or more flight legs. Over the course of the month, the ASQP file contains 162524 daily flight histories for flights with two or more legs.

Using the ASQP linked flight data, it has been possible to derive estimates of the following two probability relationships:

1. Given that an incoming flight leg arrives at the gate late by an amount **d**, what is the probability that the outbound leg arrives late by an amount **d′** (in the absence of operational delays on the outbound leg)?

2. Given that an incoming flight leg arrives at the gate late by an amount **d**, what is the probability that the outbound leg will be canceled?

The estimates have been shown to give an excellent fit to the patterns of delay accumulation that are recorded nationwide in the ASQP system. The estimation methods and their results are discussed in Section 2 (downstream delay) and Section 5 (cancellations).

In Section 3, the ensemble of probabilities discussed in Section 2 are combined to provide a delay "multiplier" that can be applied generically to "scale up" operational delay savings in the various payoff areas defined for the delay reduction system under study, and so reflect their downstream costs as well. The multiplier is adapted to a broad average delay distribution in the NAS, tabulated from ASQP-reporting flights at all sites and in all weather and traffic conditions. It might be desirable to supplement the omnibus multiplier with multipliers tailored for application to individual sites with exceptional traffic conditions (e.g., large hubs) or to particular payoff areas or types of weather events that generate worse-than-average operational delays. Tailored multipliers of this nature are not provided in this report, though they could be constructed. In Section 4, methods of ascribing cost to the downstream impacts will be considered.

Throughout the report, the notation given in Table 1 will be used.

Table 1
Notation

$\mathbf{D}$	the random variable, arrival delay. (Arrival delay is Actual time of arrival at the destination gate minus Scheduled time of arrival at the destination gate.)
$\mathbf{d}$	an instance of $\mathbf{D}$, that is an observation of the arrival delay of a single flight leg
$\left.\begin{matrix}\mathbf{D_i}\\ \mathbf{d_i}\end{matrix}\right\}$	values of $\mathbf{D}$ and d occurring on the $\mathbf{i}$-th leg of a multi-leg flight, $\mathbf{i}$ =1,2,3,....
$\left.\begin{matrix}\Omega_i\\ \omega_i\end{matrix}\right\}$	the part of $\mathbf{D_i}$ and $\mathbf{d_i}$,respectively, that arises from operational delays incurred in conducting the i-th leg of a multi-leg flight.
$\left.\begin{matrix}\Delta_i\\ \delta_i\end{matrix}\right\}$	the "downstream" portion of $\mathbf{D_i}$ and $\mathbf{d_i}$, respectively, that persists from operational delays on earlier flight legs.
X_i	Indicator of cancellation of the $\mathbf{i}$-th leg.
$P[X_i \mid d_i]$	probability of cancellation of the $\mathbf{j}$-th leg, given that the $\mathbf{i}$-th leg arrival delay is $\mathbf{d_i}$.

Note that for convenience in plotting and tabulating results as well as facilitating computations, values of delay will often be aggregated into sixteen discrete groups as shown in Table 2. When aggregated in this way, delay is treated as a discrete random variable, taking on index values, as indicated in the right-hand column of Table 2. In terms of notation, no distinction is made between the original delay measurements (one-minute resolution) and the aggregated versions. However, as an aid to clarity, a quoted equality symbol will often be used when dealing with the aggregated delays. For example, an arrival delay equaling 23 minutes may alternately be written $\mathbf{D} = 23$ or, in the aggregated form, $\mathbf{D}$ '=' 3, 3 being the index value assigned to delays of 21 to 30 minutes, inclusive.

Table 2
Aggregation Table for Arrival Delay

Delay Range (min)	Index Value
LE Zero	0
1-10	1
11-20	2
21-30	3
31-40	4
41-50	5
51-60	6
61-70	7
71-80	8
81-90	9
91-100	10
101-110	11
111-120	12
2hr-3hr *	13 *
3hr-4hr	14
GT 4hr	15

* For purposes of modeling downstream delay propagation, the high-end groups in Table 2 will be further aggregated into a single group (index value 13) consisting of all arrival delays of two hours or more.

2. ESTIMATION OF DOWNSTREAM DELAYS THAT FOLLOW FROM AN INITIAL PRIMARY DELAY

Example

To introduce notation and the manner in which downstream delay will be modeled, let us begin with a single concrete example. Suppose that the first of two flight legs arrives at the destination gate 35 minutes behind schedule, that is,

$$d_1 = 35. \tag{1}$$

Suppose that the airline is able to expedite ground servicing of the aircraft, or swap in a different aircraft, so that turnaround is 10 minutes faster than nominally allotted in constructing the flight schedule. Also, the undelayed flight time of the second leg, given prevailing winds, is expected to be five minutes less than the amount provided for in the flight schedule. Then, despite the absorption of 15 minutes of the incoming delay, the expectation is that the second leg cannot be completed less than 20 minutes behind schedule; that is, the downstream delay on the second leg is 20 minutes:

$$\delta_2 = 20 \tag{2}$$

Finally, suppose that the second leg experiences a slower than average taxi-out and some airborne vectoring, for a total of 10 minutes of operational delay on that leg. Thus,

$$\omega_2 = 10 \tag{3}$$

$$d_2 = 30 \tag{4}$$

and we may write

$$d_2 = \delta_2 + \omega_2 \text{, or} \tag{5}$$

$$d_2 = (\delta_2 | d_1) + \omega_2 \text{,}$$

recognizing that the downstream delay is a function of the initial delay.

On the other hand, operational delays on the second leg are determined by weather, traffic patterns and controller decisions on the second leg (in large part at the destination airport), and to a great extent they will occur independently of whether the flight ran late or early on the first leg. In the study reported here, the assumption will be made that second leg operational delays are independent of carryover delay from a previous leg.

Naturally, there are circumstances in which this assumption is questionable. For example, at airports where a low cloud deck requires a change in runway configuration or usage, such as in the running of parallels at San Francisco International Airport (SFO), both arrival and departure capacity suffer, and delays on inbound and outbound legs may be correlated. Similar correlations may arise when thunderstorms interfere with both arrival and departure operations. In a subsequent phase, this study can be extended to exclude or to provide separate models for airports and/or weather in which arrival and departure capacity are closely coupled.

Another possibility is that the delays experienced at one airport due to insufficient capacity "interact" with the delays at another airport which has insufficient capacity such that the net delay experienced by a flight going between the pair of airports is not the sum of the individual delays. This was addressed in a NASPAC simulation [4] where it was concluded that flight delays among several airports generally do equate to:

$$\sum_{i}(\text{Delay due to insufficient capacity at the } \mathbf{i}-\text{th airport}).$$

2.1 Formulation of Downstream Model

In general, even when $\mathbf{d_1}$ is a specific known value, the downstream carryover and the next-leg operational delay will vary from flight to flight and day to day, and of course the incoming delay is a random variable as well. With each of the quantities regarded as a random variable, Equation 5 is written

$$D_2 = \Delta_2 + \Omega_2, \text{ or} \qquad \textbf{(6)}$$

$$D_2 = (\Delta_2 | d_1) + \Omega_2.$$

If delays are aggregated as indicated in Table 2 (with all delays exceeding two hours combined into a single high-end category), the distribution of any of these random variables is described by a probability mass function, which will be denoted by the same symbol as the delay type, but in boldface. For example,

$$\mathbf{d_2}(\,i\,) = \Pr[\,D_2 \text{ `='} \, i\,], \quad i = 0,1,...,13.$$

Also, the boldface symbol written without an argument will denote the vector of probabilities associated with each category, such as:

$$\mathbf{d_2} = \begin{pmatrix} \mathbf{d_2}\ (0) \\ \mathbf{d_2}\ (1) \\ \bullet\bullet\bullet \\ \mathbf{d_2}\ (13) \end{pmatrix} = \begin{pmatrix} \Pr[D_2 \le 0] \\ \Pr[1 \le D_2 \le 10] \\ \bullet\bullet\bullet \\ \Pr[2\text{hr} < D_2] \end{pmatrix}$$

Overall among multi-leg flights in the December 1993 ASQP data, the empirically observed delay distributions on the first two legs, expressed as percentages, are as given in Table 3.

The transition matrix listed in Table 4 gives more detailed information about how first leg delays lead into second leg delays. Note that the delay distributions $\mathbf{d_1}$ and $\mathbf{d_2}$ of Table 3 reappear as marginal distributions along the bottom and right-hand margins of Table 4, respectively. The internal entries in the table are conditional probabilities (symbolically, $\Pr[D_2 \text{ `='} \, i \mid D_1 \text{ `='} \, j]$) of having arrival delay in a certain range on the second leg, given the amount of arrival delay experienced on the first leg. The numerical values are calculated empirically from the December 1993 ASQP data and given as percentages. For example, there were 14788 first leg operations during the month that arrived at the gate between 11 and 20 minutes late. On the corresponding second leg, 4210 or 28.47 percent of these arrived on time or early. To help accentuate the patterns that exist in the table, the percentages are given just to integer precision, and elements along the diagonal are printed in an outline font.

Table 3
Arrival Delay Distributions.
First Two Legs of Multi-leg Flights.
ASQP System, December 1993

Delay Range (min)	d_1 (%)	d_2 (%)
LE Zero	49.02	45.23
1-10	27.48	25.46
11-20	11.68	13.30
21-30	4.83	6.34
31-40	2.39	3.33
41-50	1.40	1.96
51-60	0.88	1.27
61-70	0.62	0.81
71-80	0.44	0.61
81-90	0.34	0.45
91-100	0.22	0.35
101-110	0.15	0.23
111-120	0.12	0.16
GT 2hr	0.43	0.50

The banded pattern that exists in Table 4 gives an indication as to how the second leg delay may be resolved into downstream and operational components. In each column the bulk of the probability lies between three positions above the diagonal (indicating that the second leg is on schedule or 30 minutes closer to schedule than the first leg) and one position below (indicating that the second leg is delayed about 10 minutes more than the first). There appears to be a fairly constant probability of being able to shave off 10 minutes of delay on the second leg, irrespective of the amount of delay on the first. Similarly, there are fairly constant probabilities of being able to reduce the delay on the second leg by 20 minutes, or by 30 minutes. There is also a finite probability of having the second leg arrive on time even when the first leg is severely delayed, and the size of that probability appears roughly constant for first leg delays of any amount from 40 minutes to two hours or more. Obviously, if a first leg is two hours late and the second leg is on time, there is either a very long layover scheduled or the second leg embarks with a different aircraft and crew before the first leg arrives.

Table 4
Observed Relative Frequencies of Arrival Delay on the Second Leg Given Arrival Delay on the First Leg ASQP System Data, December 1993

		Arrival Delay on 1st Leg															
		LE Zero	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-110	111-120	GE 2hr	%	N
	LE Zero	59	44	28	14	8	5	3	3	4	5	6	5	3	8	45.23	57259
	1-10	25	30	29	20	12	7	3	3	2	3	2	4	6	8	25.46	32229
	11-20	10	15	22	25	19	11	7	3	2	2	2	3	3	4	13.30	16838
	21-30	3	6	11	19	22	18	12	6	3	2	3	2	1	3	6.34	8029
	31-40	1	2	5	10	17	20	18	12	7	2	2	3	3	3	3.33	4210
Arrival	41-50	1	1	2	5	10	17	20	17	9	7	3	2	2	4	1.96	2476
Delay	51-60	0	1	1	2	6	10	16	21	16	13	3	3	3	2	1.27	1609
on	61-70	0	0	1	1	3	5	9	13	17	13	7	2	5	2	0.81	1026
2nd Leg	71-80	0	0	0	1	1	3	5	10	21	18	15	12	4	2	0.61	772
	81-90	0	0	0	0	1	2	3	5	9	15	19	15	11	2	0.45	573
	91-100	0	0	0	0	1	1	1	3	5	8	19	18	15	3	0.35	437
	101-110	0	0	0	0	0	1	1	1	2	6	9	9	13	6	0.23	286
	111-120	0	0	0	0	0	0	0	1	1	2	4	10	11	8	0.16	207
	GE 2hr	0	0	0	0	1	1	1	2	2	4	6	13	19	45	0.50	635
	Marginal %, 1st Leg	49.02	27.48	11.68	4.83	2.39	1.40	0.88	0.62	0.44	0.34	0.22	0.15	0.12	0.42		
	Marginal N, 1st Leg	62050	34791	14788	6115	3027	1774	1117	789	563	432	273	187	150	530		126586 (Total)
	Pr[Leg 2 Lower]	N/A	44	58	60	61	61	62	65	60	65	62	68	75	55		
	Pr[Leg 2 Higher]	41	26	21	21	22	22	21	22	19	20	19	22	20	N/A		

The patterns in Table 4 suggest that, taken as a broad average over all scheduled domestic operations, the way that delays on an incoming leg are partially absorbed and partially carried forward as downstream delays, before the second leg operation commences, may be well described by the matrix-vector multiplication

$$\delta_2 = \mathbf{P}\mathbf{d}_1\,, \tag{7}$$

where **P** is a transition matrix with four parameters, pictured in Table 5. The free parameters in Table 5 are (ϕ_1, ϕ_2, ϕ_3, ϕ_4). All columns in **P** must sum to one, and the symbol "π" is just a notational shorthand for "$1 - (\phi_1+\phi_2+\phi_3+\phi_4)$." The parameters will require an estimation procedure as described later.

The downstream delays are then compounded by operational delays in the process of conducting second leg aircraft movements. The distribution of these operational delays is denoted by the symbol ω_2. This distribution cannot be measured explicitly using the ASQP data. However, there is support in Table 4 (and in knowledge of the way that air traffic control systems function) for the supposition that second leg operational delays are independent of the incoming and downstream delays, specifically that Ω_2 and Δ_2 are statistically independent random variables.[2] When a random variable results from or is equivalent to the sum of two other independent random variables, its distribution function is the convolution of the distributions of the two summands. As noted in Equation 6, arrival delay on the second leg is such a sum, and thus one can expect $\mathbf{d}_2$ to be close to an estimate of the form

$$\tilde{\mathbf{d}}_2 = \delta_2 * \omega_2 = \mathbf{P}\mathbf{d}_1 * \omega_2, \tag{8}$$

where "*" denotes convolution. If Equation 8 does adequately describe second leg arrival delays, then the same technique should propagate forward to describe later leg arrival delays, namely

$$\tilde{\mathbf{d}}_3 = \mathbf{P}\mathbf{d}_2 * \omega_3 = \mathbf{P}\,(\mathbf{P}\mathbf{d}_1 * \omega_2) * \omega_3, \tag{9}$$

and so forth. Unless there is a reason to anticipate that operational delays will differ systematically from one leg to the next, then the indices can be dropped and Equation 9 simplifies to

$$\tilde{\mathbf{d}}_3 = \mathbf{P}\mathbf{d}_2 * \omega = \mathbf{P}\,(\mathbf{P}\mathbf{d}_1 * \omega) * \omega, \tag{10}$$

with ω denoting a generic distribution of delay for a single aircraft movement. Once values for **P** and ω are estimated, as discussed below, Equation 11 is proposed as a forecast equation for subsequent leg schedule delays, given $\mathbf{d}_1$ as a starting delay distribution.

2 Though, as discussed in the example above, one might elect to examine the independence (or possible dependence) of incoming and downstream delays more carefully in a subsequent phase of this study.

Table 5
Four-Parameter Downstream Transition Matrix

Arrival Delay on First Leg (min)

Downstream Delay on 2nd Leg (min)	LE 0	1-10	11-20	21-30	31-40	41-50	51-60	...	110-120	GE 2hr
LE 0	1	$\phi_1+...+\phi_4$	$\phi_2+\phi_3+\phi_4$	$\phi_3+\phi_4$	ϕ_4	ϕ_4	ϕ_4		ϕ_4	ϕ_4
1-10		π	ϕ_1	ϕ_2	ϕ_3					
11-20			π	ϕ_1	ϕ_2	ϕ_3				
21-30				π	ϕ_1	ϕ_2	ϕ_3			
31-40					π	ϕ_1	ϕ_2			
41-50						π	ϕ_1			
51-60							π			
61-70										
71-80										
81-90								...	ϕ_3	
91-100									ϕ_2	ϕ_3
101-110									ϕ_1	ϕ_2
111-120									π	ϕ_1
GE 2hr										π

$(\pi = 1 - \phi_1 - \phi_2 - \phi_3 - \phi_4)$

Further, given any initial delay distribution $\mathbf{d_1}$, assuming that the delay-absorbing properties of carrier operations are a fairly consistent concomitant of scheduling practices, the downstream delay remaining for the j-th additional flight leg would have a distribution

$$\delta_j = \mathbf{P}^j \mathbf{d}_1 \,, \tag{11}$$

and the total downstream delay accumulated over k additional flight legs would have the distribution

$$\sum_{j=1}^{k} \delta_j = \left(\sum_{j=1}^{k} \mathbf{P}^J \right) \mathbf{d}_1 \tag{12}$$

Equations 11 and 12 are proposed as estimators of downstream delay, given $\mathbf{d_1}$ as a starting point.

2.2 Estimation of parameters

Included in Table 4, in the left-most column, is a record of second leg arrival delays for flights that have no delay at all at the conclusion of the first leg and thus no downstream delay. Therefore, the column labeled "LE Zero" in Table 4 provides an estimate of ω, the distribution of operational delays on a single aircraft movement. The estimate is based upon 62050 aircraft movements spread over a month and across the domestic air transportation system, and while the distribution might change slightly with the seasons or with changes in traffic volume, the estimate for ω should be reliable. Thus we have an interim conclusion that 59 percent of aircraft movements in the NAS experience no operational delay, 25 percent experience between one and ten minutes, and so forth.

Note that the level of delay captured in ω is substantially smaller than the level reported by many systems that monitor operational delay such as the former Standardized Delay Reporting System (SDRS) of the FAA or the Consolidated Operations and Delay Analysis System (CODAS) which is being developed out of APO-130. The reason is that ω captures only delays above the threshold at which they begin to impact the published flight schedule. The quantity ω figures in this enquiry as a quantity that must be factored out to extract a downstream delay component from the on-time performance data. It is not intended as a proper estimate of operating delay in the NAS. Parenthetically, it may be noted that systems like CODAS seek to identify small-scale congestion-related delays whether they explicitly affect on-time performance or not. Taxi-out, for example, may be considered to be delayed if it is slower than some historical percentile (often the 10-th percentile) of similar operations. Carrier operating schedules are set to a fairly high percentile, probably somewhere between the 60-th and 90-th, in order to keep them stable. Much of the true cost of operating delays lies in "lost productivity"[3] resulting from the need to stretch out schedules in this manner.

[3] Air Transport Association. "Air Traffic Management in the Future Air Navigation System," April 29, 1994. See Attachment A-1.

Using the estimate of ω, it is possible to develop initial estimates of ϕ_1, ϕ_2, ϕ_3, and ϕ_4. Table 4 indicates that 44 percent of the flights that finish the first leg with delays of between 1 and 10 minutes (15287 of 34791 such flights) continue to finish the second leg on time. The estimate for ω indicates that 59 percent of movements that are in a position to begin on time do finish on time. Thus, the count of 15287 should represent about 59 percent of what originally was a larger proportion of the 34791, all effectively put back on schedule before commencing the second leg. This proportion is the first row, second column entry in Table 7, or $\phi_1+\phi_2+\phi_3+\phi_4$. Thus we have

$$\begin{aligned}\phi_1+\phi_2+\phi_3+\phi_4 &= (15287/34791) / 0.59 \\ &= \Pr[D_2' = 0 \mid D_1' = 1] / \Pr[D_2' = 0 \mid D_1' = 0] \\ &= 0.745\,.\end{aligned} \tag{13a}$$

Similarly,

$$\phi_2+\phi_3+\phi_4 = \Pr[D_2' = 0 \mid D_1' = 2] / \Pr[D_2' = 0 \mid D_1' = 0] = 0.483\,, \tag{13b}$$

$$\phi_3+\phi_4 = \Pr[D_2' = 0 \mid D_1' = 3] / \Pr[D_2' = 0 \mid D_1' = 0] = 0.238\,, \tag{13c}$$

$$\phi_4 = \Pr[D_2' = 0 \mid D_1' = 4] / \Pr[D_2' = 0 \mid D_1' = 0] = 0.096\,. \tag{13d}$$

Thus, initial estimates based upon the December 1993 ASQP file are

$$\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{pmatrix} = \begin{pmatrix}0.262\\ 0.245\\ 0.142\\ 0.096\end{pmatrix} \approx \begin{pmatrix}0.25\\ 0.25\\ 0.15\\ 0.1\end{pmatrix}. \tag{14}$$

Also, $\pi = 0.25$.

For general application it will be necessary to revise initial estimates derived in the manner of Equations 13a-d in order to minimize a measure of discrepancy between the forecast second leg delays using the estimates, or $\tilde{\mathbf{d}}_2$, and the empirically observed delay distribution, $\mathbf{d}_2$. One desirable measure of discrepancy is an information-based quantity,

$$\langle \mathbf{d}_2, \tilde{\mathbf{d}}_2 \rangle = -\sum_{k=0}^{13} \mathbf{d}_2(k)\ \log \tilde{\mathbf{d}}_2(k)\,. \tag{15}$$

The discrepancy may be minimized by an iterative optimization procedure. However, the fit to $\mathbf{d}_2$ obtained with the initial estimates in (14) is reasonably good, and in the interest of time, further optimization will not be discussed here. The fit is indicated in Table 6.

Table 6

Fit of Forecast Delay Distribution ($\tilde{d}_2$) to the Measured Delay Distribution (d_2) Arrival Delay on the Second Leg of Multi-leg Flights. ASQP System, December 1993

Delay Range (min)	d_2 (%)	$\tilde{d}_2$ (%)
LE Zero	45.23	45.40
1-10	25.46	26.02
11-20	13.30	13.22
21-30	6.34	6.25
31-40	3.33	3.15
41-50	1.96	1.80
51-60	1.27	1.14
61-70	0.81	0.78
71-80	0.61	0.55
81-90	0.45	0.41
91-100	0.35	0.33
101-110	0.23	0.28
111-120	0.16	0.23
GT 2hr	0.50	0.28

3. DOWNSTREAM MULTIPLIER FOR DOMESTIC SCHEDULED OPERATIONS

A downstream multiplier is a constant of proportionality that, on average, expresses the ratio between an initial delay and its total downstream impacts. That is, if the downstream multiplier is denoted by μ, then on average over the scope of operations for which the multiplier is intended to apply, one minute of seed delay produces μ minutes of concomitant downstream delay. Similarly, to first approximation,[4] each minute of direct delay savings produces an additional μ minutes of downstream delay savings. It could be appropriate to have separate multipliers for different sites (e.g., hub vs. non-hub airports) or delay causes (e.g., ceiling and visibility vs. thunderstorms). However, consideration of such tailored multipliers is left for future work. In the discussion here, the intent is to develop a general-purpose multiplier to be applied across the board to all scheduled domestic operations.

In calculating a downstream multiplier it is necessary to establish an appropriate candidate for the distribution of primary delays. It is also necessary to determine how many downstream legs, on average, are impacted by a primary delay.

In selecting a representative "seed" delay distribution, four candidate distributions will be considered. The sensitivity of the multiplier calculation to the seed delay will be examined, and a multiplier that lies in the middle of the range of responses will be suggested for use. The four candidate seed delay distributions are:

- ω — As extracted from Table 4 and discussed in Section 2, this is an estimate of operational delay obtained from the December 1993 ASQP file, based upon a large number of operations, but biased in that it represents only delays exceeding a threshold.

- AAS C/BA — This is an estimate of operational delay derived from appendices to the Benefit/Cost and Risk Analysis for the Advanced Automation System.[5]

---

[4] Downstream delay impacts depend on the initial delay in a nonlinear way. For example, by Equation 12, the impact of a five-minute delay over three successive legs is 1.64 minutes (for a ratio of 0.33), while a 25-minute delay produces a 17-minute downstream accumulation (ratio = 0.69), and a 55-minute delay leads to 73 minutes downstream (ratio 1.33). The downstream multiplier is in effect a weighted average of these varying ratios, adapted to match typical delay patterns in the set of operations to which it applies. (For present purposes, that set is all domestic scheduled operations.) A change in the typical delay patterns, which is what a delay savings implies, would also lead to a change in the multiplier. However, examples given in this section indicate that, practically speaking, operationally feasible delay savings would cause only a modest shift in the ratio of downstream to direct delay. Therefore, for practical purposes it is sufficient to scale direct delay savings by the constant multiplier to calculate downstream delay savings.

[5] It is obtained by combining the distributions of Gate Hold Delay, Taxi-Out, Airborne and Taxi-In delay pictured in Figures D-3, D-4, D-5 and D-6 of The Advanced Automation System: A Benefit/Cost and Risk Analysis, Volume IV, The MITRE Corporation, MTR-87W00235-04, sponsored by the FAA Office of Aviation Policy and Plans, Contract No. DTFA01-84-C-00001. The delay measurements in these figures are obtained from the FAA's Standardized Delay Reporting System (SDRS). They were combined by convolution, as if delays on each phase of flight are independent. The actual distribution of total delay per movement, which was not available in the AAS report, would differ slightly from this reconstruction.

- Uniform 0-60 This is a hypothetical distribution, describing a delay episode in which direct delays have a uniform distribution between 0 and 60 minutes; that is, all delay amounts within this range are equally likely.

- ATL 4/27/94 This delay distribution is obtained from the ASQP system and describes the experience at Atlanta Hartsfield International Airport between 4:00 PM LCL, April 27, 1994, and 2:00 AM the following morning, during which time airport operations were impacted by thunderstorm activity, peaking around 7:45 PM. This is an example of locally severe weather and delay accumulation.

The four seed distributions are pictured in Figure 1. In this figure, the horizontal axis of each plot is direct delay in minutes. Delays are grouped into 10-minute intervals (LE Zero, 1-10, 11-20, etc.), and the vertical axis gives the probability that a flight leg incurs each of the possible categories of delay.

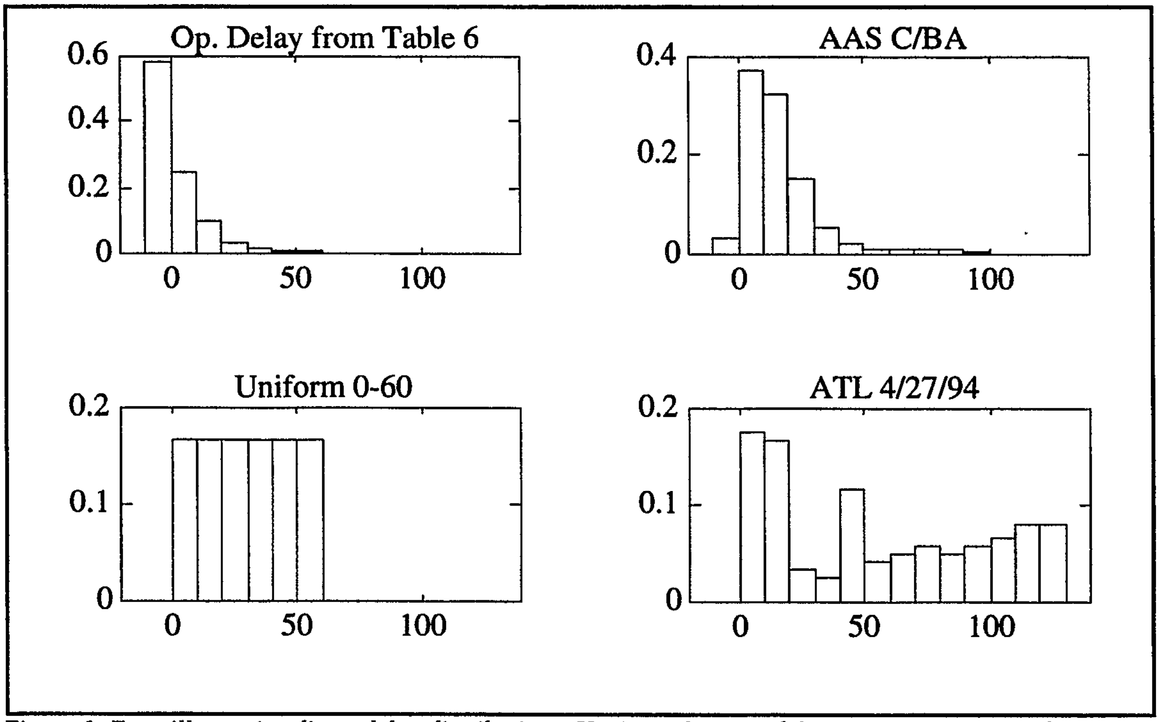

Figure 1. Four illustrative direct delay distributions. Horizontal axis is delay in minutes, grouped in 10-minute intervals. Vertical axis is the probability of delay falling in each category.

A tabulation of the December 1993 ASQP file indicates that among all first legs of multiple leg flights, the average scheduled gate-to-gate flight duration is 110.4 minutes. Also, the average scheduled layover, i.e., the time elapsed between completion of the first leg and departure from the gate for the second leg, is 48.6 minutes. Together these suggest that each flight leg requires about 2 hours and 40 minutes on average, except for the last leg (or first) which has no turnaround levy. Thus, five flight legs appear to require around 12 hours and 30 minutes on average, and six flight legs require just over 15 hours. This suggests that six flight legs is an average utilization factor for major scheduled air carriers. Thus, if a flight delay occurs on the first leg, there will be an average of approximately five additional legs remaining on the same day that may sustain downstream delay. After the second leg, there are four downstream legs remaining on average, and so on. While weather impacts are not uniformly distributed throughout the day (fog prevalent in the morning, thunderstorms in the afternoon), it is useful for the present to suppose that direct delays are uniformly distributed among flight legs. In this case the average number of downstream legs that are impacted by a direct delay, taken at random times during the day, would be close to (5+4+3+2+1)/6, or 2.5.

One quick way of calculating a multiplier would be to approximate what it means to accumulate downstream delays over 2.5 flight legs. To do so, one can calculate the average accumulation over two downstream legs, and the average accumulation over three downstream legs, and split the difference between them. Such a technique is used in constructing Table 7 which provides a partial tabulation of the downstream impacts that follow from each of the seed delay distributions in Figure 1. Table 7 gives the average direct delay implied by each seed delay distribution as well as the average downstream delay remaining for the first, second and third successive flight legs. A multiplier for each seed distribution is obtained by summing the first two downstream legs and half of the third and then presenting this sum as a percentage of the average direct delay. In future work it may be desirable to look more closely at the distribution of number of flight legs among scheduled air carriers, and at the timing of weather impacts, in constructing a general purpose multiplier.

Table 7
Downstream Delay Impacts (delay in minutes)
Four Direct Delay Distributions

	Table 4[6]	AAS C/BA	Uniform 0-60	ATL 4/27/94[7]
Direct Delay	5.45	16.68	30.00	59.78
Downstream				
Leg 1	2.45	7.87	17.17	41.79
Leg 2	1.20	3.78	9.00	29.62
Leg 3	0.63	1.86	4.34	20.76
multiplier	0.76	0.75	0.94	1.37

While the distinctive results for ATL on 4/27/94 suggest that special circumstances may warrant a suitably adapted multiplier, the multipliers for the other test cases lie in a fairly narrow range, between 0.75 and 0.94. These seed distributions account for a fairly wide variation in delay patterns, and it seems reasonable that a general-purpose multiplier for downstream delay should lie in that range. In the absence of further information, a value for the general-purpose multiplier of

$$\mu = 0.8 \quad \textbf{(16)}$$

is suggested here, in particular for winter weather.

[6] The quantity ω, representing direct delay that is sufficient to impact the published flight schedule, derived from Table 6.

[7] Note that the second and third downstream legs, starting from the distribution that occurred at Atlanta on 27 April 1994, are comparable to the "Uniform 0-60" distribution, which still has a peak delay of one hour.

The multiplier in (16) is derived on the basis of only one month of traffic, and that month (December 1993) is entirely winter weather. Aside from the variation in weather impact that occurs in the same month from year to year, there are a number of seasonal characteristics that might cause the downstream multiplying effect to be different in summer and winter months. For example, ceiling and visibility is more of a morning problem and may affect more downstream legs than an afternoon thunderstorm. The different schedules that airlines employ during summer and winter may themselves generate differences in downstream accumulation. For these reasons, it will be desirable in subsequent work to look at summer period ASQP data and recalibrate the multiplier given in (16) if summer delay patterns differ significantly from those that have been examined so far.

4. COST OF DOWNSTREAM DELAY

As formulated in Section 3, and estimated in Equation 16, the multiplier μ represents an incremental amount of delay occurring downstream for each unit of direct delay. A multiplier that translated direct delay into total delay would be formulated as $(1+\mu)$. The incremental form has been used here to allow cost to be charged differently to downstream delay than it is to direct delay.

The direct operating costs that are properly applied to direct operating delay such as fuel, maintenance, and labor are already charged and should not apply to the downstream delay which is simply the continued presence of a portion of the direct delay.

Indirect costs such as redundant staffing, baggage handling for missed connections, and the "lost productivity" discussed in Appendix A do constitute real costs of downstream delay that should be considered eligible for benefit/cost analyses. They will not be considered here because of lack of time but could be investigated in future work.

Passenger time losses do represent a tangible cost of downstream delay and a tangible value of delay savings. The point at which a passenger makes a final accounting of delay is the point of deplanement at the end of the passenger's terminating flight leg. The average number of deplanements of this sort is the same as the average number of revenue enplanements per aircraft movement. Therefore, it is recommended that the downstream value of passenger time be attached to the direct delay savings estimated for any program payoff area, using the following formula:

Downstream passenger time savings =

$$\begin{pmatrix}\text{Payoff area}\\ \text{delay savings}\end{pmatrix} \times (\text{multiplier}) \times \begin{pmatrix}\$\,/\,\text{hr}\\ \text{Passenger time}\end{pmatrix} \times \begin{pmatrix}\text{Average \# revenue passenger}\\ \text{Enplanements / movement}\end{pmatrix}. \quad \textbf{(17)}$$

To give a feel for the size of the savings described in Equation 17, one example calculation will be performed using the multiplier $\mu = 0.8$ suggested in (16). For this calculation assume that passenger time is valued at \$40/hr and assume 63.6 revenue enplanements per departure.[8] Then each hour of direct delay savings for any ITWS payoff area is calculated by (17) to produce a savings of \$2035 in passenger time on downstream legs, in addition to any direct operating cost (DOC) reductions attributable to the delay savings.

In some circumstances the Operations Research Service (AOR) of the FAA has used a rule that only passenger delays exceeding 15 minutes should be counted in calculating the value of passenger time. If such a rule is to be applied, the modeling technique discussed in Section 2 may still be applied because at each downstream leg it generates a delay distribution from which the frequency and size of delays exceeding 15 minutes may be determined. The construction of a multiplier in Section 3 and cost determination as in Section 4 could then be redone, but such a revision is left for subsequent work.

---

[8] The average number of revenue departures per flight was estimated from the figure captioned "U.S. Air Carrier Domestic Traffic Trends," p.34 in FAA Aviation Forecasts, Fiscal Years 1992-2003, FAA-APO92-1, February 1992. The figure indicates that there were about 35 million revenue passenger enplanements per month during 1991, and approximately 550 thousand aircraft departures per month.

5. PROBABILITY OF CANCELLATION AS A FUNCTION OF INCOMING DELAY

As stated previously, in all the ASQP data available at the time of this report, airlines are exempted from reporting flight cancellations (delays similarly) when the cancellations result from mechanical problems. If a cancellation occurs for other reasons, including weather or inadequate passenger volume, it is manifest in the ASQP. Given the tight coupling that exists in airline operating schedules, it is to be expected that operating delays during aircraft movements increase the difficulty of assembling the resources (aircraft, gates, flight crews) to field later movements and thus increase the likelihood of cancellation. Also, large delays may push a flight beyond noise abatement or other statutory limits or may make it economically unattractive. Data on cancellations from the December 1993 ASQP data file, summarized in Table 8, confirm these general expectations.

Table 8
Observed Probability of Cancellation on Second Leg vs. Arrival Delay on the First Leg
ASQP System, December 1993

Delay Range (min)	Percent Canceled	Number of Flight-Days	Ave. Delay in the group
LE Zero	0.99	61934	-6.76
1-10	0.51	35021	4.95
11-20	0.66	14913	14.70
21-30	0.87	6182	24.86
31-40	0.79	3056	34.99
41-50	1.17	1800	45.04
51-60	1.23	1134	55.20
61-70	1.74	805	65.23
71-80	1.40	573	75.32
81-90	2.04	442	85.25
91-100	5.50	291	95.34
101-110	1.58	190	105.25
111-120	4.46	157	115.08
2hr-3hr	7.40	419	141.20
3hr-4hr	14.02	107	204.79
GT 4hr	16.92	65	321.25

To have a basis for calculating the cancellation rates appearing in the second column of Table 8, flight operations were aggregated according to the categories of Table 2, depending upon the arrival delay observed on the first leg. The third column in Table 8 gives the sample size or number of data points in each delay category. A "flight-day" is just a shorthand for the conduct of a listed flight on a single day. The fourth column gives the average delay among the group of movements falling into each delay category. For example, in December 1993 there were 14913 occurrences of a multi-leg flight on which the first leg arrived between 11 and 20 minutes behind schedule, averaging among them 14.70 minutes behind schedule. Of these, 98 (or 0.66 percent) had the second leg canceled for reasons other than mechanical concerns.

The small circles in Figure 2 plot the empirical probability of cancellation (percent divided by 100) for each delay category against the average delay for that category. There appears to be a prevailing monotonic trend with some sampling noise in the individual cancellation probabilities.

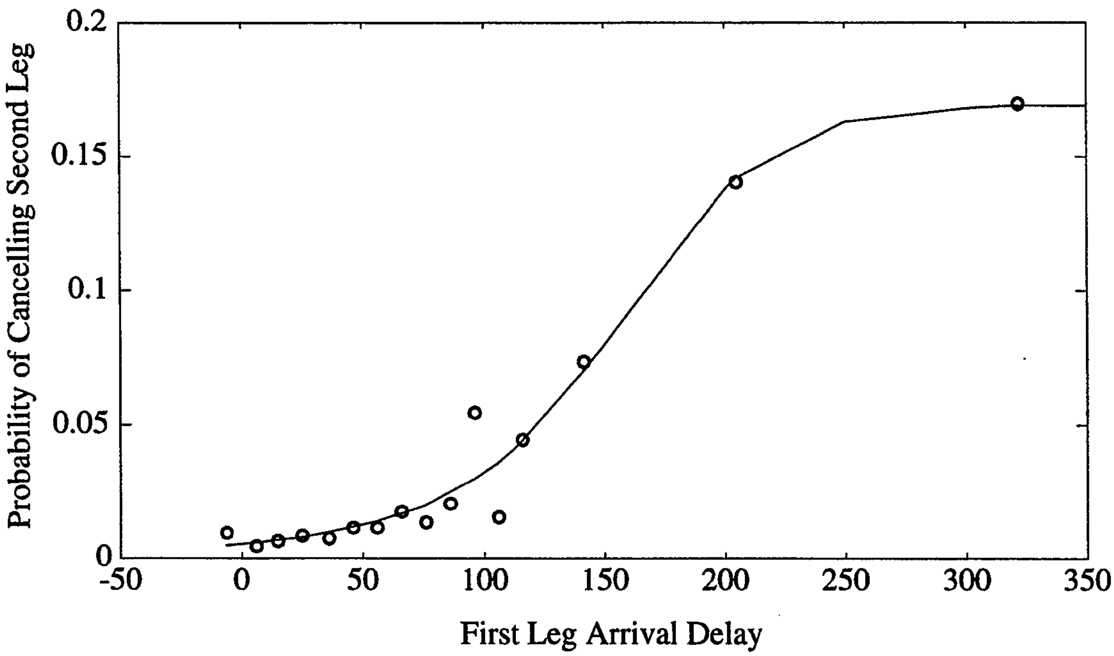

Figure 2. Relationship between arrival delay on one flight leg and probability of cancellation on the subsequent leg.

In order to smooth out the sampling noise and to extract a concise description of the relationship between arrival delay and subsequent cancellation, a sigmoidal curve, also pictured in Figure 2, was fitted to the observed probabilities. The curve is derived using a modification of the linear logistic model which is widely used for modeling the dependence of event probabilities upon external factors:

$$P\left[X_2 \middle| d_1\right] = c \bullet \frac{\exp(a + bd_1 + gd_1^2)}{1 + \exp(a + bd_1 + gd_1^2)} . \quad (18)$$

The model is less complicated than it may appear symbolically. The parameter c represents an asymptotic maximal probability of cancellation, given an arbitrarily large arrival delay on the first leg. Then, letting

$$\pi = P\left[X_2 \middle| d_1\right] / c \quad (19)$$

represent how close the conditional probability of cancellation is to this asymptote, Equation 18 is equivalent to:

$$\log\left(\frac{\pi}{1-\pi}\right) = a + bd_1 + gd_1^2 . \qquad \textbf{(20)}$$

The model was fitted by nonlinear least squares[9] and yielded parameter values as indicated in Table 9.

Table 9
Cancellation Model Parameters

Parameter	Est'd Value	Std. Error
c	0.169	0.010
a	-3.398	0.696
b	0.0150	0.0117
g	0.0000472	0.0000502

The standard error given in the table is an estimate of the level of sampling error that exists in the estimate of the parameter value. An interval of twice the standard error on either side of the estimated parameter value is often used as an approximate 95 percent confidence interval for the parameter. Thus the confidence intervals for parameters b ($-0.0106 \leq b \leq 0.0405$) and g ($-0.00006 \leq g \leq 0.00016$) are wide compared to the numerical value of the parameter, and both include zero. If both parameters were zero, the incoming arrival delay would have no effect on next-leg cancellation.

Also, the specification of an asymptote in Equation 18 is slightly arbitrary. Though it is suggested by and consistent with the flattening trend observed in Figure 2, it will take further investigation to determine whether the formulation in Equation 18 provides a reliable predictor of probability of cancellation, particularly with large incoming delays.

For these two reasons it may be best to regard the model based on Equation 18 and the parameter values in Table 9 as provisional and subject to revision. Nevertheless, the model fits the observed probabilities well and any method of formulating the problem, if it is required to fit the observational data of December 1993, will produce a response curve for $\mathbf{P}\,[X_2 \mid \mathbf{d}_1]$ that lies close to what is produced by substituting the values in Table 9 into Equation 18, namely

$$\mathbf{P}\left[X_2 \middle| \mathbf{d}_1\right] = 0.169 \bullet \backslash F\left(\exp\left(-3.398 + 0.0150\mathbf{d}_1 + 0.0000472\mathbf{d}_1^2\right),\ 1 + \exp\left(-3.398 + 0.0150\mathbf{d}_1 + 0.0000472\mathbf{d}_1^2\right)\right) . \qquad \textbf{(21)}$$

---

[9] Using PROC NLIN in the commercial statistical package SAS.

6. DISCUSSION

The study described above has been targeted toward meeting the schedule for the Integrated Terminal Weather System (ITWS) full-scale production decision document. While the analysis and the conclusions presented above are thought to be trustworthy, there are a number of topics that could be pursued at greater length in future work. These include:

- A broader base of ASQP data, including summer months in particular;
- Separate consideration of different kinds of weather events and of airports with distinctive characteristics;
- Further examination of the techniques and assumptions employed in estimating downstream delay, including the assumption of independence preceding Equation 8 and the form of the absorption matrix depicted in Table 5; and
- The manner of assigning value to downstream delay savings and to reduced cancellation rates.

REFERENCES

1. Executive Office of the President, "Major Systems Acquisitions," April 5, 1976.

2. Weiss, W.E. and E. Lacher, 1988: "Simulating the National Airspace System," in *Proceedings of the 1988 Winter Simulation Conference*, San Diego, CA, December 12-14 1988. New York: IEEE.

3. Frolow, I. and J.H. Sinnott, 1989: "National Airspace System Demand and Capacity Modeling," in *Proceedings of the IEEE*, Vol. 77, No. 11, pp. 1618-1624.

4. DeArmon, J.S., 1992: "Analysis and Research for Traffic Flow Management," *Proceedings of the 37th Annual Conference of the Air Traffic Control Association*, Nov. 1-5, 1992, Atlantic City NJ, Air Traffic Control Association, pp. 423-429.

APPENDIX A

Examples of Testimony, Anecdotal and Published Evidence Regarding Downstream Delay Impacts in the National Airspace System (NAS)

Evidence from a variety of sources indicates that airlines consider downstream impacts to be a major factor, and sometimes a dominant factor, in assessing the true costs of NAS delay. A few such examples are given here:

1. In a journal article[10] on the slot allocation program that American Airlines uses to assign aircraft to landing slots during Central Flow-imposed ground delay programs, the "down-line" delay savings from the program are estimated to be at least twice ($10.4 million) the direct cost savings ($5.2 million); in other words, the author states that direct cost savings should be multiplied by at least three to obtain a total delay cost savings to the airline.

2. The senior vice president for operations at Horizon Air, a short-haul feeder to Alaska Airlines that operates "1.2 flights per hour per airplane" indicates[11] that "each flight canceled or diverted affects five other flights down line, and we have been able to substantiate that." Another study of the economic value of head-up guidance systems[12] describes several types of downstream impacts, basing its report on "in-depth analyses" of route structures, schedules, weather and costs for several airlines. One example is given in which four hours of fog at Chicago O'Hare are stated to cause delay of 15 minutes or more on 449 departures and 529 arrivals at other airports. Also, 1334 passengers delayed in excess of 15 minutes at the affected airport compares with 36,121 passengers delayed down line on 352 flights.

3. In an attachment[13] to a letter dated May 9, 1994 from J. Landry, President, Air Transport Association (ATA), to D. Hinson, FAA Administrator, the cost to twelve member airlines of weather-related cancellations, that is, cancellations not caused by mechanical problems, is estimated to be $222 million/year. This is secondary, but not wholly negligible compared to the estimated cost of taxi-out and flow control gate delays, totaling $1317 million annually, particularly if

---

[10] Vasquez-Marquez, A. "American Airlines Arrival Slot Allocation System (ASAS)," INTERFACES 21: Jan-Feb 1991, p. 42-61. In this article, down-line delays are defined as "the delays imposed on later flights that relate to the flights affected by ground delays because of shared resources: aircraft, crew members, or gates."

[11] Esler, D. "Justifying the Head-Up Display in Dollars and Sense," Business and Commercial Aviation, September 1993, p.C6-C12. Also, "one airline told us that at one of its major hubs, it takes one day to recover from one hour of fog."

[12] Hartman, B. "The Future of Head-Up Guidance," IEEE Aerospace and Electronic Systems Magazine, March 1993, p.31-33.

[13] Air Transport Association. "Air Traffic Management in the Future Air Navigation System," April 29, 1994.

cancellations affect a large number of subsequent operations, as suggested in item (2) above.

4. In the same attachment described in item (3), the "lost productivity," that is the revenue foregone by a single ATA member airline, owing to constraints that ATC delay impose on the number of daily revenue departures per aircraft, is reported to be $1.2 billion per year. This compares to direct costs estimated by the airline to be $670 million per year. If accurate, this indirect cost exceeds the direct cost of operating delay, reported at $3.5 billion total for 12 member airlines.

Citation of the above sources is not meant to suggest that the dollar amounts, the methodologies, or the political statements in the sources be taken at face value as a basis for FAA policy. However, it does seem appropriate for cost and benefit assessments to recognize the major cost factors as they are perceived by NAS users, and the above sources suggest that downstream impacts should be considered in the valuation of NAS delay.