Assessing Schedule Delay Propagation in the National Airspace System

William Baden, James DeArmon, Jacqueline Kee, Lorrie Smith
The MITRE Corporation
7515 Colshire Dr.
McLean VA 22102

ABSTRACT

Flight delay propagation or "ripple" is a well-known phenomenon in the National Airspace System (NAS). It is when delay on one flight leg carries forward to a future flight leg for the same aircraft due to the practice of airlines scheduling multiple flight legs per aircraft. The research investigates where delay propagation is occurring in the NAS by analyzing historical data. A backtracking algorithm is proposed to tally delay that is experienced on the ground and in the air for each flight leg, which later becomes observable schedule delay at downstream airports. Results are shown across different time periods, carriers, weather conditions, and airports.

INTRODUCTION

The National Airspace System (NAS) in the United States (US) is the collection of resources which make air travel possible: the airports, airspace, routes, radars, navigation points, sectors, etc. The NAS is quite complex, and contributing to the complexity is the interdependence of resources. One of the main airline practices that creates interdependency is the scheduling of aircraft to travel between multiple airports on a given day. Air carriers construct schedules with the intent of maximizing passenger movement and to do this they schedule the physical aircraft to make multiple (perhaps 4 to 9) legs of flight (or "hops") in a day. This sequence of flight legs creates high utilization of the expensive equipment and, as well, creates connectivity and potential propagation of delay effects. For example, if an aircraft is scheduled to visit Boston, Chicago, Atlanta, and then Los Angeles, delay experienced in departing Boston may carry forward to become delay at one or more future destination airports that day.

Understanding propagation of delay effects is important. The value of this study is to track the impact of changes that occur in the airline industry or in the air traffic control procedures on delay propagation. Air transportation is a key element of the national economy, but if service levels fall, passengers will avoid air travel, substituting other forms of travel, such as ground-based travel or not travel at all. Moreover, traffic levels are growing in this country, and congestion and delay are commensurately increasing. The Federal Aviation Administration's (FAA) goal of safe, expeditious air travel may be abetted through better understanding of the subtle effects of delay propagation.

This research was initially motivated by an analysis of unusually large delays experienced at several airports starting at the end of 2003. The authors set out to investigate the influence on the rest of the NAS caused by delays at individual airports. An algorithm was developed to track delay propagation for each aircraft and applied to historical data over an extended period. The results were then analyzed across different categories including air carrier, type of weather day, and airports.

PRIOR RESEARCH

Delay propagation in aviation is a topic that has engaged researchers over the years. The topic is broad and not well-defined, and studies have defined delay propagation in a number of ways and examined various aspects of the phenomenon.

DeArmon (1992) looked at delay propagation using conditional probabilities, and found evidence of pilots' expediting flights when departing late, likely in an attempt to reduce propagation. DeArmon (1993) also examined delay propagation in light of traffic flow problem interaction. In that study, multiple concurrent flow problems were investigated, via simulation modeling, looking for interaction effect, essentially a non-additivity of problem impacts. Delay propagation was the underlying mechanism creating downstream impacts.

Boswell and Evans (1997) examined delay propagation using Markov chains, and found an overall multiplier of 1.8, meaning that, in general, one minute of initial flight delay becomes an additional 0.8 minutes of delay when propagated downstream. In addition to that important result, the authors presented a methodology for estimating an air carrier's preference for flight cancellation in the face of mounting delays. Further, the authors cite published evidence from several air carriers on the "multiplier effect" of primary delays on downstream delays.

Amplifying that notion, Beatty, et. al., (1999) developed an elaborate table of delay multipliers. They used detailed company data (from American Airlines), to track causes for delay such as crew time-outs (by law, cockpit and cabin crews have restrictions on number of consecutive working hours) and developed delay multipliers as a function of primary delay and the time-of-day of that event.

Wang, et. al., (2003) developed a simple analytic model to separate the controllable factors from the uncontrollable factors that influence delay propagation. They presented results for three selected airports for a good weather day and a bad weather day and showed that the distributions based on the controllable and uncontrollable factors were unique to each airport.

Vigneau (2003) examined repeated aircraft itineraries through French airports and examined the relationships of arrival delay, departure delay, scheduled stop-over time, and passenger load factor. The author found that arrival delay could be predicted by departure delay plus passenger load factor. Delays on departure, given no prior-leg arrival delay, could be predicted using load factor alone. The importance of load factor highlights the effect of the local environment – different airports will produce varying load factors, contributing to delay and propagation.

PROBLEM DEFINITION

The intent of this research is to clearly define delay propagation, and then to detect where this phenomenon occurs in the NAS.

There are different definitions of delay. Delays can be determined by comparing actual performance against a published flight schedule, a flight plan which is filed by the pilot before the flight departure, or unimpeded/optimal operational times. Since the intent of this analysis is to evaluate the impact of delays on passengers, this analysis will focus on the delays taken against the flight schedule which is the schedule that is most visible to passengers.

An aircraft traverses multiple airports in a day, and the flights between the airports may be called "flight legs" or "hops." The sequence of flight legs for a specific aircraft over a day is called the aircraft itinerary. For each flight leg's scheduled arrival time, the difference between the actual and scheduled times, i.e., arrival delay is computed. If the arrival delay is positive, then a backtracking algorithm assesses earlier legs in the itinerary traversed by the same aircraft, and tallies the delay from prior legs as contributing to the current flight's arrival delay. This algorithm is explained in greater detail in a later section of this paper. Propagated delay, as defined in this study, is delay that has been transmitted over more than a single flight leg for a given aircraft itinerary.

This research did not look into the causes of the delay propagation. The focus of this research was to identify where the delay occurred and to allocate it back to the flight leg where it was originally experienced. Determining the causes would require more analysis and information than was available at the time of this study.

DATA SOURCES

The data source used for the analysis is the Airline Service Quality Performance (ASQP) data, part of the Department of Transportation's On Time Reporting System. This dataset contains aircraft-specific information on a daily basis. The ASQP data contains only flight legs that both depart and land in the U.S. and are reported by air carriers that either have at least one percent of total domestic scheduled-service passenger revenues, or that choose voluntarily to report. The ASQP dataset contains both scheduled and actual departure and arrival times for each of the flight legs flown. In addition, the dataset contains information on actual taxi-in and taxi-out times for each flight leg.

Processing of the ASQP data was necessary, to remove aircrafts with incomplete or suspect itineraries. Examples of removed itineraries are those with missing tail numbers, missing departure or arrival times/taxi times, and itineraries where the first leg begins after 12:00 noon local time, raising a suspicion that the flight might have originated from an international airport. Since delays cannot be tracked to an international airport, this aircraft itinerary had to be discarded. The process of removing suspect itineraries eliminated approximately 10% to 15% of the ASQP records.

ASSUMPTIONS AND LOGIC

The algorithm used in this study tracks the delay experienced on the ground and in the air for each flight leg and then determines how much of this delay is propagated to downstream airports. Time lost by a late departure or airborne delay may result in not only a late arrival to the destination airport, but also late arrivals to airports further downstream as the aircraft follows its itinerary throughout the day.

The total delay propagated on each flight leg can be summarized across all itineraries for each day, and these daily totals can be further aggregated by month, quarter, or year for analysis purposes.

Figure 1 shows the different phases of a flight leg, where the arrows denote events and the intervals between events represent the flight phases where delay can be incurred.
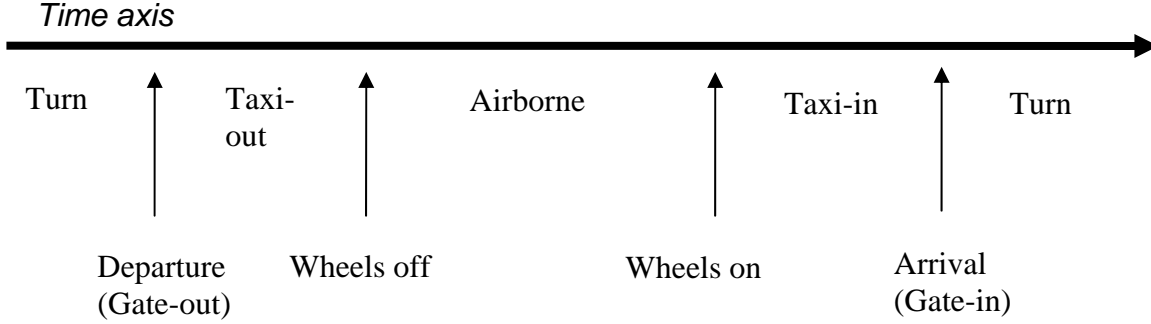
Figure 1: **Flight Phases that are Tracked by the Algorithm**

The delay definitions used in this study are defined as follows:

- *Departure delay*— this is determined as the *difference* between the actual and scheduled gate-out times.

- *Arrival delay*— this is determined as the *difference* between the actual and scheduled gate-in times.

- *Turn time delay*—this is associated with the interval between gate-in and gate-out times and is determined as the *difference* between actual and scheduled turn times. The exception is that for the first leg of each aircraft itinerary, the turn time delay is defined as the departure delay.

- *Taxi-out delay*—this is associated with the interval between the gate-out and wheels off times and is determined as the *difference* between actual and "scheduled" taxi-out times.

- *Airborne delay*— this is associated with the interval between the wheels off and wheels on times and is determined as the *difference* between the actual and "scheduled" airborne time.

- *Taxi-in delay*— this is associated with the interval between the wheels on and gate-in times and is determined as the *difference* between actual and "scheduled" taxi-in times.

The scheduled times for the taxi-out, airborne, and taxi-in delay phases are in quotes, since they are not formal, published times in the ASQP, but rather are computed by the algorithm as described in Appendix B. In general, the algorithm attributes arrival delay on the current leg by backtracking along the four flight phases (taxi-in, airborne, taxi-out, and turn time) prior to arriving at the destination of the current leg. If the summed delay on these four phases does not account for all of the arrival delay, the algorithm then proceeds to evaluate the four phases on the immediate upstream leg in the same order.

This process is repeated for further upstream legs until all of the arrival delay on the current leg is accounted for. Several assumptions are made:

- Negative delays are treated as zero delays, i.e., completing a flight phase early contributes nothing to accounting for arrival delay.

- Ground delay programs and ground stop actions imply no special accounting – since this algorithm is not concerned with causality, but rather the location where delay is taken, ground delay will show up as turn time delay or taxi-out delay at the departing airport.

An Example

The following hypothetical example illustrates the logic of the algorithm. Consider an itinerary where an aircraft originates from MIA, makes a first stop at BOS and then goes to ORD. The algorithm will perform an accounting of the arrival delay at ORD and then at BOS.

Figure 2 shows the logic for accounting of the arrival delay at ORD. Starting on the far right (Step 0), the algorithm computes the gate-in arrival delay at ORD as (actual – scheduled) = 16:59-16:34 = 25 minutes. The backtracking logic needs to account for the 25 minutes of delay by successively examining the flight phases on the BOS to ORD flight leg, followed by the MIA and BOS leg.
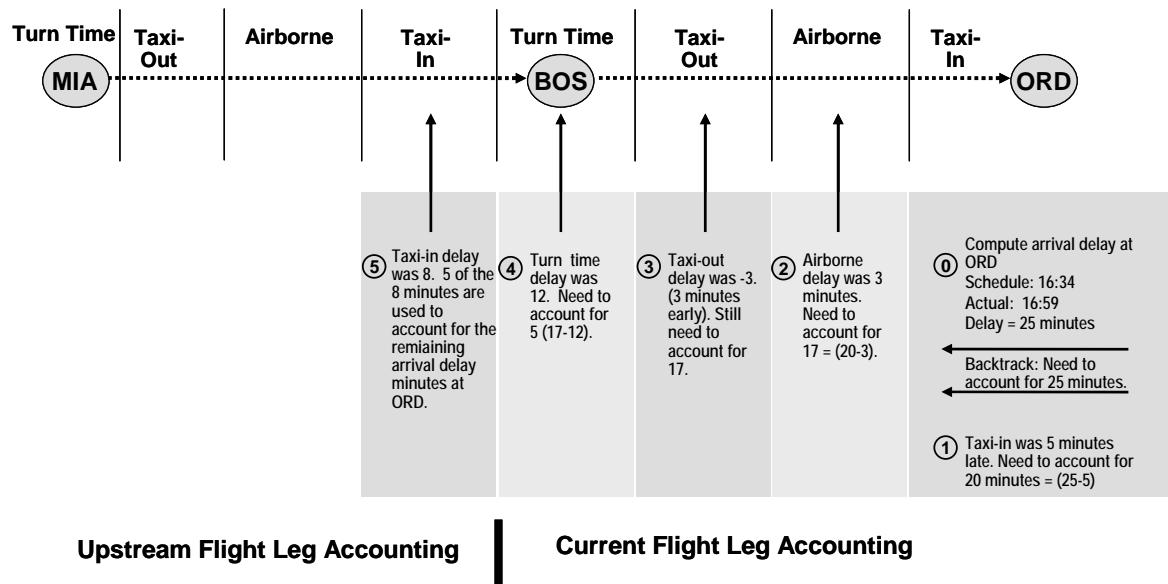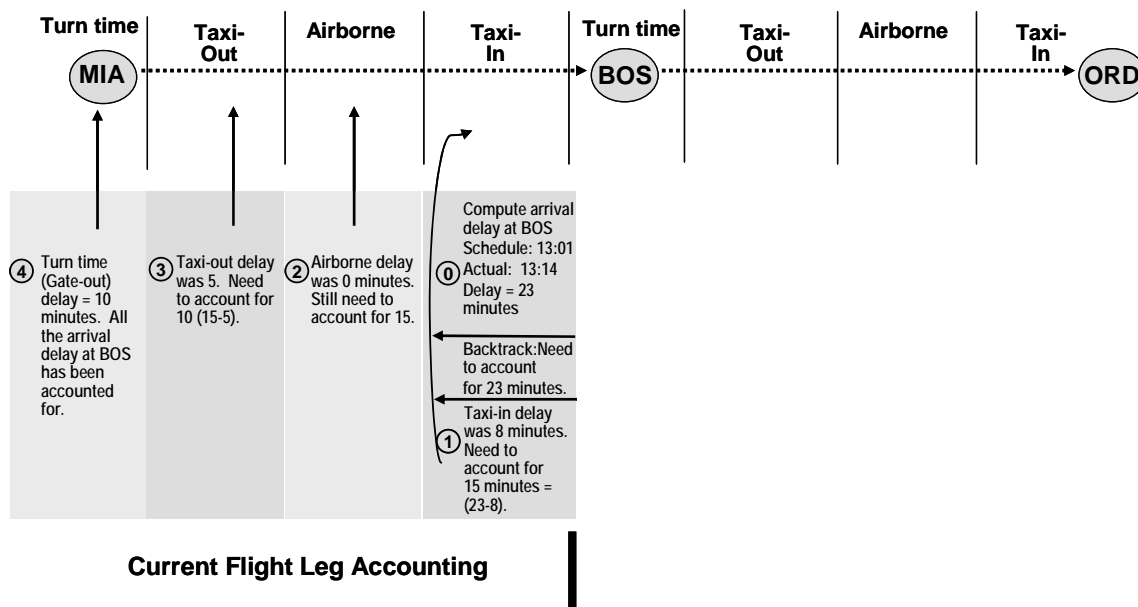

Figure 2: Accounting for Arrival Delay at ORD

In Step 1, the taxi-in time on the BOS to ORD leg is assessed. There was 5 minutes of taxi-in delay, leaving 20 (=25-5) of arrival delay minutes still to be accounted for.

Step 2 shows airborne delay as 3 minutes, leaving 17 (=20-3) of the arrival delay minutes still to be accounted for. Step 3 examines the taxi-out delay on the BOS to ORD leg. As it happened, taxi-out activity was 3 minutes *early*. Early events have no ameliorative impact on the accounting for delay, so 17 minutes remains to be accounted for. Step 4 examines turn time delay, shown as 12 minutes, leaving 5 minutes (=17-12) of the arrival delay minutes still to be accounted for.

At this point, one complete flight leg (BOS to ORD) has been examined and not all of the arrival delay experienced at ORD has been fully accounted for, and so the next upstream leg, MIA to BOS, is considered. The fifth step in Figure 2 is the assessment of taxi-in delay for the MIA-BOS leg. This taxi-in delay was 8 minutes, which satisfies the 5 minute deficit, and accounts for the last 5 minutes of the 25 minutes of arrival delay experienced by the BOS-ORD flight. Based on the definition of propagated delay, this taxi-in delay of 5 minutes on the MIA to BOS leg is the amount of delay that has been propagated to the BOS to ORD leg.

Figure 3 depicts the same itinerary as Figure 2, except the logic is shown to account for the arrival delay at BOS. The arrival delay of 23 minutes at BOS is accounted for by tallying the delay on the MIA to BOS leg, via backtracking, to obtain: taxi-in delay = 8 minutes, airborne delay = 0 minutes, taxi-out delay = 5 minutes, and turn time delay = 10 minutes, for an overall total of 23 minutes. Note that as this is the first leg of the itinerary, the original departure delay is used for the turn-time delay on the MIA to BOS leg. There can be no propagated delay on this leg, as this is the first leg of the itinerary.


Figure 3: Accounting for the Arrival Delay at BOS

ANALYSIS AND RESULTS

The algorithm was run with data for all weekdays in 2000 and 2004 and the results were analyzed for different categories including air carrier, type of weather day, and airports.

Analysis By Carrier

The amount of propagated delay shown as a proportion of the average arrival delay per flight segment was analyzed using the 2000 and 2004 ASQP data. The average arrival delays are shown for each reporting air carrier in Figures 4 and 5.
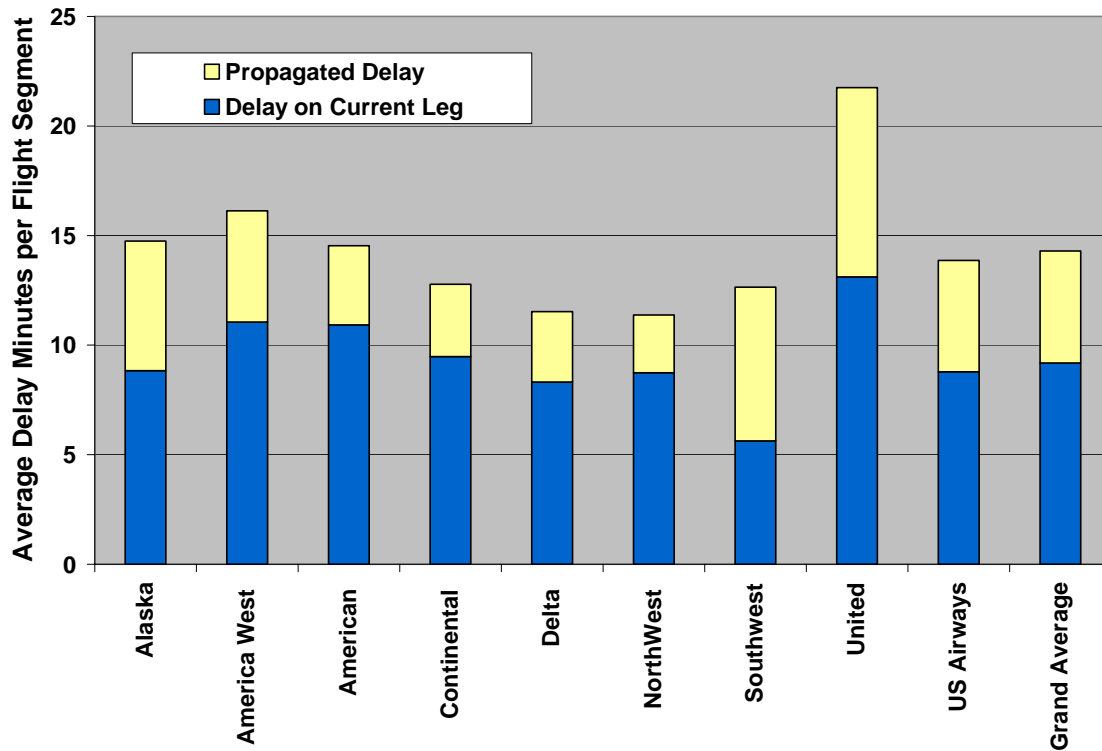
Figure 4: Average Propagated Delay per Flight Segment in 2000 (using ASQP data)
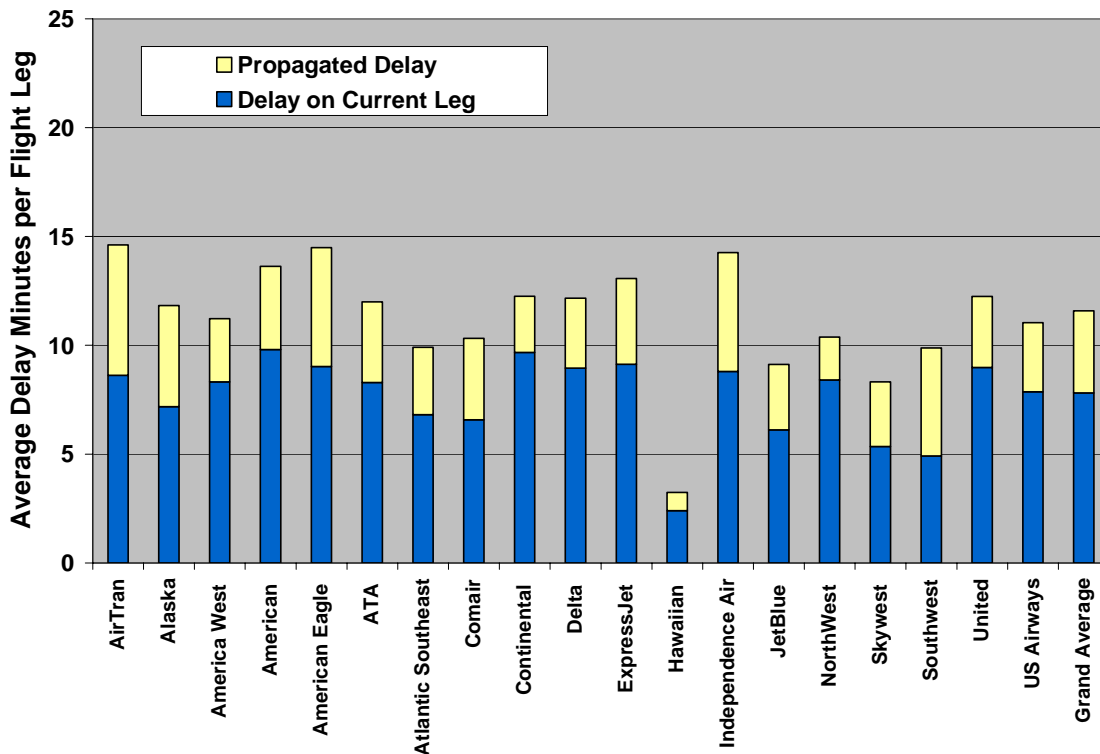
Figure 5: Average Propagated Delay per Flight Segment in 2004 (using ASQP data)

On average, in 2000 the airlines experienced slightly less than 15 minutes of arrival delay per flight leg, of which about 5 minutes (36%) are termed as propagated delay, i.e., the delay that was experienced at flight legs that were more than a single hop away from the current flight leg. The average arrival delay dropped to less than 12 minutes of arrival delay in 2004, of which about 4 minutes (33%) was propagated delay.

In both 2000 and 2004, Southwest Airlines had the highest proportion of propagated delay (55% and 50% respectively) compared to the other carriers. The authors hypothesize that this is due to Southwest's scheduling of short turn times and high utilization of its aircraft fleet, where, over the course of a day, Southwest might schedule an average of seven to eight flight legs in an itinerary (compared to other carriers who schedule an average of five legs or less).

Although Southwest has the highest proportion of propagated delay, its overall delay levels in 2000 and 2004 are lower than the NAS-wide averages. In 2004, Southwest's average arrival delay is similar to that for Northwest Airlines, which had the lowest proportion of propagated delay (19%). This observation implies that there are other factors that play a more important role in influencing arrival delay than delay propagation.

Analysis by Weather Day

The authors also looked at the proportion of propagated delay that is experienced on good weather versus bad weather days. An index, called the Misery Index, was used to characterize the weather experienced on each day and this metric is based on the number of cancellations, diversions and departure delays greater than 30 minutes (see Callaham

et al. (2001)). There is a strong relationship between the proportion of propagated delay and the Misery Index for both 2000 and 2004 as shown in Figure 6.
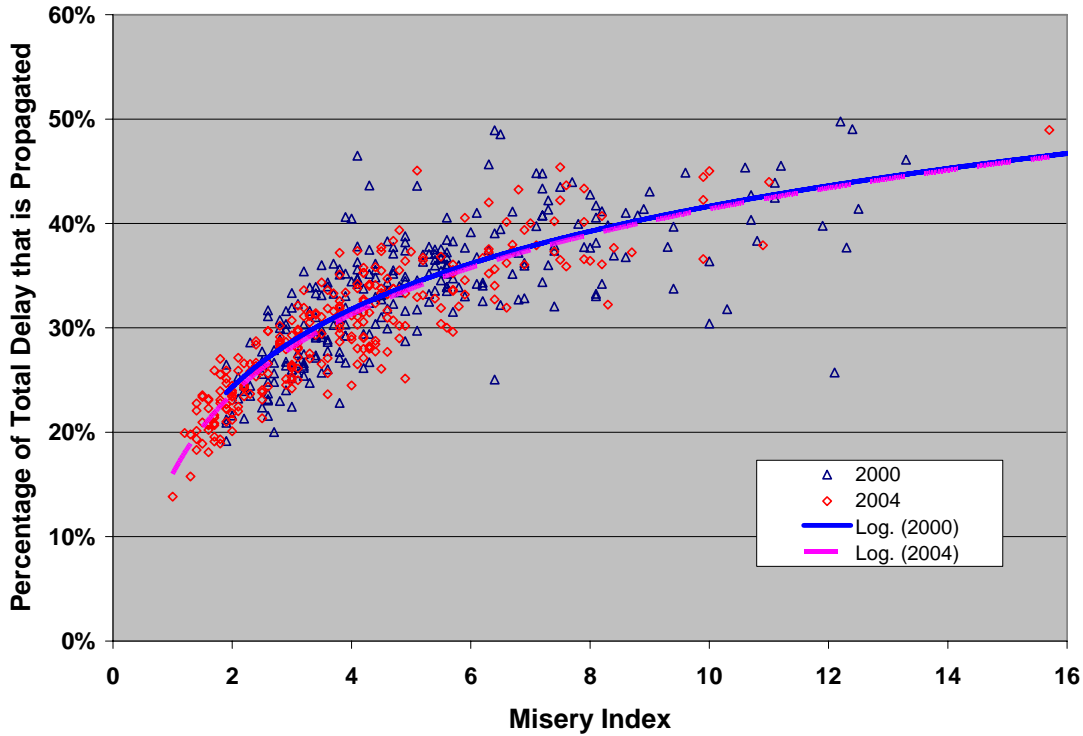
Figure 6: Relationship between Weather and Propagated Delay

For the top ten percent good weather days, the average proportion of all delay in 2004 that was propagated was 21%. In contrast, for the bottom ten percent bad weather days, the proportion of propagated delays was 40%. In general, on very bad weather days, the amount of propagated delay is around twice that experienced on very good weather days.

Calendar Year 2004
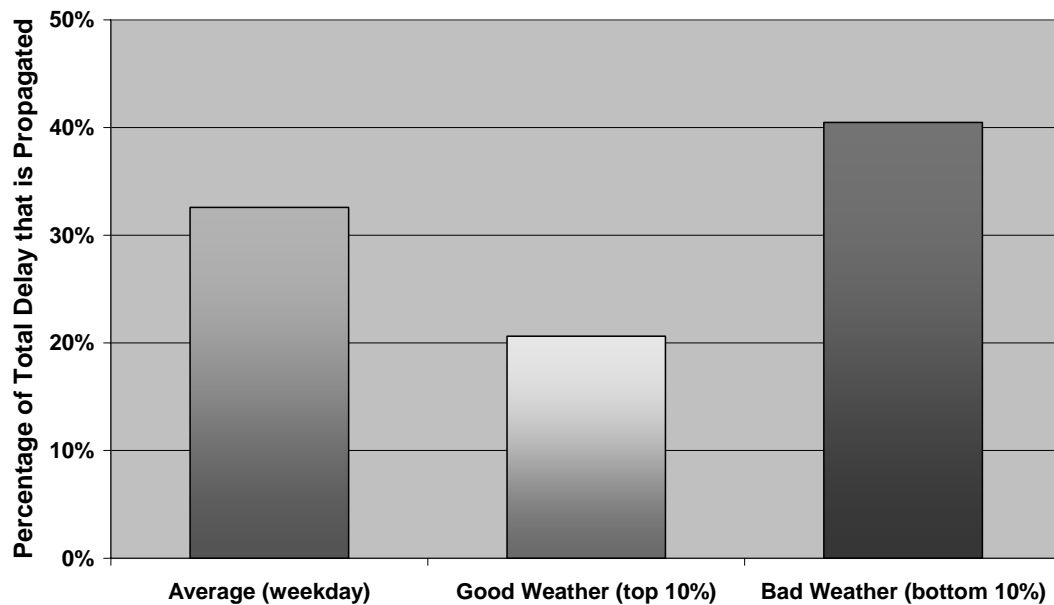
Figure 7: Propagated Delay Across Different Weather Days

Analysis by Airport

Table 1 shows the amount of delay that is propagated for every minute of arrival delay experienced at the subject airport. This metric is calculated as the total propagated delay attributed to flight segments that arrived at the subject airport divided by total arrival delay experienced at that airport. It is a measure of the propensity of an airport to propagate the delay it experiences.

The airports shown are the 35 major airports and these are sorted by the highest to lowest amount of propagated delay. MDW (Chicago Midway International) has the highest proportion of propagated delay – for one minute of arrival delay experienced at MDW, 28 seconds of that delay propagates to other downstream airports in the NAS. The major air carrier operating at MDW is Southwest Airlines, which tends to have a higher proportion of propagated delay compared to the other air carriers. Southwest also has the highest share of operations at LAS (Las Vegas McCarran International) and BWI (Baltimore-Washington International Thurgood Marshall Airport) which are near the top of the list in Table 1.

Table 1: Average Propagated Delay in 2004 for Each Minute of Arrival Delay

Arrival Airport	Propagated Delay (seconds)	Arrival Airport	Propagated Delay (seconds)
MDW	28	EWR	17
LAS	27	DCA	17
ORD	25	DEN	16
BWI	25	PDX	16
ATL	23	CLT	16
FLL	22	PIT	15
PHL	22	CVG	15
SFO	21	SLC	15
SAN	20	BOS	15
MCO	20	SEA	15
IAD	19	LAX	15
LGA	19	CLE	14
PHX	19	DTW	14
STL	19	IAH	13
MEM	18	JFK	13
TPA	17	MIA	11
DFW	17	MSP	11
		HNL	8

In order to gain a perspective of the impact of delay propagation to the NAS, the above metric was applied to the total arrival delay minutes experienced at the 35 major airports in 2004. The results are shown in Table 2. Using data from the FAA's Aviation System Performance Metrics (ASPM) database, the average arrival delay minutes were multiplied by the number of scheduled arrivals (defined as the arrivals for metric computation) to obtain the total arrival delay minutes. The total amount of propagated delay is determined by applying the proportion of arrival delay that is propagated to the total minutes of arrival delay. Not surprisingly, this new traffic and delay-weighted metric pushes the large hub airports, ORD, ATL, and PHL to the top of the list.

Table 2: Total Propagated Delay Minutes in 2004

Arrival Airport	ASPM Average Arrival Delay Minutes	ASPM Scheduled Arrivals	Pct Propagated Delay*	Total Propagated Delay Minutes	Arrival Airport	ASPM Average Arrival Delay Minutes	ASPM Scheduled Arrivals	Pct Propagated Delay*	Total Propagated Delay Mintues
ORD	19.2	484,859	42%	3,911,613	MCO	11.9	150,352	33%	585,333
ATL	15.3	473,249	38%	2,750,148	FLL	14.4	106,749	37%	563,640
PHL	16.4	224,381	37%	1,345,203	DTW	9.8	250,939	23%	555,750
DFW	11.4	394,112	29%	1,294,103	CLT	9.7	210,977	26%	528,629
LAS	13.3	196,144	45%	1,183,197	JFK	14.9	148,127	22%	488,959
EWR	18.5	209,575	28%	1,098,554	MSP	10.3	253,293	18%	456,738
IAD	15.1	215,986	32%	1,050,112	SEA	10.3	175,080	25%	445,662
LGA	15.5	196,310	32%	967,149	SLC	10.2	160,765	25%	418,443
PHX	11.6	239,521	32%	876,248	PIT	10.7	150,689	26%	412,613
LAX	10.5	307,061	25%	794,003	MIA	14.6	144,138	19%	400,046
MDW	12.2	135,948	47%	773,976	STL	9.8	130,684	31%	395,323
SFO	13.3	166,132	35%	762,805	DCA	10.0	134,342	28%	370,277
DEN	9.7	273,449	27%	725,543	SAN	11.1	95,914	34%	357,245
CVG	11.0	251,102	25%	702,810	CLE	11.9	121,774	24%	344,230
BWI	12.1	131,476	41%	660,631	TPA	11.3	100,312	29%	329,102
IAH	11.2	246,368	22%	612,099	PDX	9.7	107,597	26%	274,516
BOS	13.0	184,869	25%	603,554	HNL	10.7	91,206	13%	126,655
MEM	11.5	169,818	30%	590,694					

CONCLUSION

The goal of this analysis was to investigate how delay propagates in the NAS. There are several main findings from this study. First, on the average, roughly one third of the delay experienced in 2004 and 2000 can be attributed to delay that occurred upstream from the flight leg that experienced the arrival delay, i.e., the delay was propagated. On very bad weather days, the amount of propagated delay doubles compared to that experienced on very good weather days. In general, airports that tend to pass on a higher proportion of their delay are mostly served by air carriers that have higher proportions of delay propagation. This does not mean, however, that these airports experience large amounts of delay. Finally, in 2004, the flights that arrived at large hub airports ORD, ATL, and PHL, propagated the highest number of minutes of delay in the NAS.

It is important to note that the results presented in this paper are based on an analysis of historical data and are only valid if the underlying assumptions, such as schedule connectivity and presence of hub operations, do not change. If the underlying assumptions change, such as an airport is no longer operating as a hub, then the analysis should be revised with the updated information.

REFERENCES

Beatty, R., R. Hsu, L. Berry, and J. Rome, (1999), "Preliminary Evaluation of Flight Delay Propagation Through an Airline Schedule," Air Traffic Control Quarterly, Vol. 7, pp 259-270.

Boswell, S. and J. Evans, (1997), Analysis of Downstream Impacts of Air Traffic Delay, Project Report ATC-257, MIT Lincoln Laboratory, Cambridge, MA.

Callaham, M. et al., 2001, "Assessing NAS Performance: Normalizing for the Effects of Weather," Fourth USA/Europe Air Traffic Management R&D Symposium, Santa Fe, NM.

DeArmon, J. (1992), "Analysis and research for traffic flow management," Proceedings of the ATCA Conference, Atlantic City, NJ, pp 423-429.

DeArmon, J. (1993), "Do air traffic flow problems interact? A preliminary analysis," IEEE Transactions on Control Systems Technology, 1(3), pp 195-203.

Vigneau, W., (2003) "Flight Delay Propagation: Synthesis of the Study", EEC Note No. 18/03, Eurocontrol Agency, Brussels, Belgium.

Wang, P., L. Schaefer, and L. Wojcik, (2003), "Flight Connections and Their Impacts on Delay Propagation," Proceedings of the 22nd DASC, Vol. 1 pp 5.B.4-1 to 5.B.4-9.

APPENDIX A: Location Identifiers

ATL   Hartsfield - Jackson Atlanta International
BOS   Boston Logan International
BWI   Baltimore-Washington International Thurgood Marshall Airport
CLE   Cleveland Hopkins International
CLT   Charlotte Douglas International
CVG   Cincinnati/Northern Kentucky International
DCA   Ronald Reagan Washington National
DEN   Denver International
DFW   Dallas-Fort Worth International
DTW   Detroit Metropolitan Wayne County
EWR   Newark Liberty International
FLL   Fort Lauderdale-Hollywood International
HNL   Honolulu International
IAD   Washington Dulles International
IAH   George Bush Intercontinental/Houston
JFK   John F Kennedy International
LAS   Las Vegas McCarran International
LAX   Los Angeles International
LGA   LaGuardia
MCO   Orlando International
MDW   Chicago Midway International
MEM   Memphis International
MIA   Miami International
MSP   Minneapolis-St Paul International
ORD   Chicago O'hare International
PDX   Portland International
PHL   Philadelphia International
PHX   Phoenix Sky Harbor International
PIT   Pittsburgh International
SAN   San Diego International
SEA   Seattle-Tacoma International
SFO   San Francisco International
SLC   Salt Lake City International
STL   Lambert-St Louis International
TPA   Tampa International

Appendix B: Determination of the Schedule Times for the Taxi-out, Airborne, and Taxi-in Phases

In the algorithm used in this study, assumptions are made of the scheduled times for the taxi-out, airborne, and taxi-in phases of the flight. Unlike the flight arrival, departure and turn times which are published by the air carriers, the planned or scheduled taxi and airborne times for each flight are not publicly available. The authors developed a method for determining the scheduled times, by allocating the block time, which is the elapsed time between the gate departure to the gate arrival times, into two components: an unimpeded component and a schedule slack component. The unimpeded component is the amount of time it would take to perform the flight if there were no delays in the NAS. The schedule slack is the buffer allocated to the block time so that the flight can meet its on-time arrival performance goal.

Figure B-1 illustrates the process of creating the "scheduled" taxi-in, airborne, and taxi-out times. In Step 1, the unimpeded component for each of the three flight phases (taxi-in, airborne, and taxi-out) is first determined based on the tenth percentile of the historical distribution, with stratification on air carrier, equipment type, and airport (or airport pair for airborne). For example, there would be a specific distribution for air carrier ABC flying an Airbus 320 from ORD to DFW. The tenth percentile is used, as opposed to the minimum of the distribution, in order to avoid outliers and extreme values.
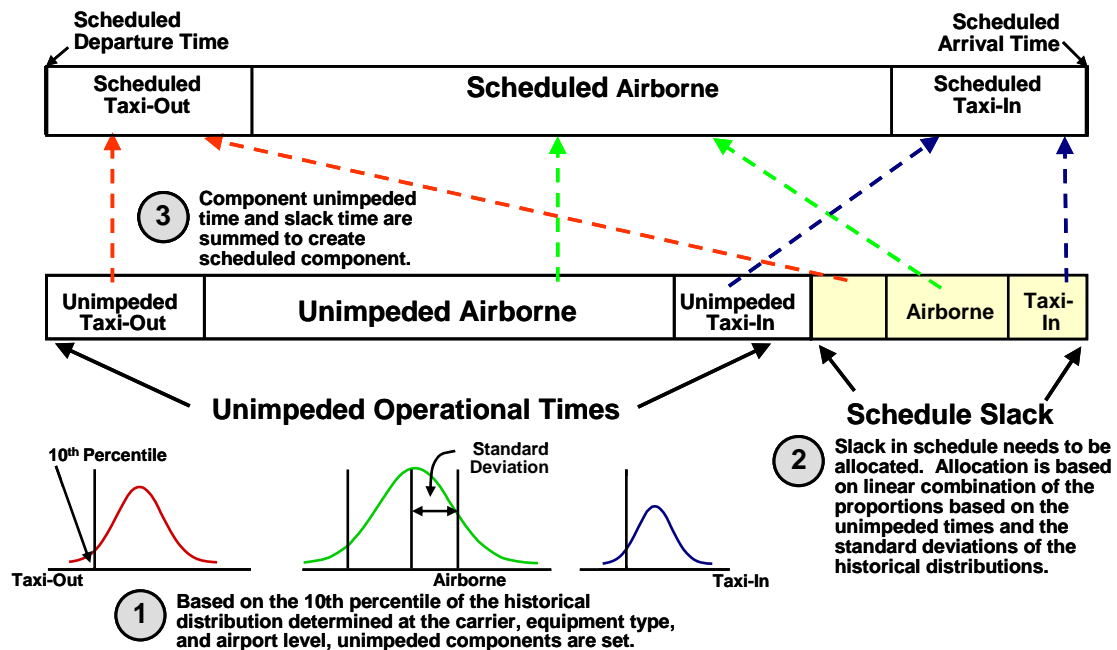

Figure B-1. Compute "Scheduled" Times for Taxi-Out, Airborne, and Taxi-In

Once the unimpeded components are determined for the three flight phases and summed up, the difference between the block time and the sum of the unimpeded times is called the schedule slack. The allocation of the schedule slack to the three flight phases is

shown in Step 2 and is based on information from the stratified historical distributions of the individual flight phases. The method uses proportions based on the unimpeded times and the standard deviation of the historical distributions. Using sample unpublished schedule data from several air carriers, which showed the scheduled times for taxi-out, airborne, and taxi-in flight phases, the authors determined that using a 50% weighting for both the unimpeded times proportion and the standard deviation proportion provided the best match to the air carriers' schedules. A numerical example is shown below:

For the example flight leg, the historical unimpeded times and standard deviation of the three flight phases are shown in the first two rows of Table B-1.

Table B-1: Schedule Slack Allocation Example

	Taxi-Out (minutes)	Airborne (minutes)	Taxi-In (minutes)
Unimpeded Times	10	80	10
Standard Deviation	10	10	5
Proportion Allocated to Schedule Slack	0.5*(10/100) + 0.5(10/25) = 0.25	0.5*(80/100) + 0.5(10/25) = 0.6	0.5*(10/100) + 0.5(5/25) = 0.15

The third row shows the calculation of the proportion of schedule slack allocated to three flight phases. In the allocation to the taxi-out phase, the proportion of the unimpeded taxi-out to the sum of the three individual unimpeded times, 10 out of 100 minutes, is multiplied by the 50% weighting and added to the proportion of the standard deviation of the taxi-out phase to the sum of the three standard deviations, 10 out of the total 25 minutes, multiplied by the 50% weighting. The resulting proportion of the schedule slack that is allocated to taxi-out is 0.25. Similarly, the proportion allocated to airborne and taxi-in are 0.6 and 0.15 respectively. If the schedule slack in this example is 10 minutes, then

Schedule slack allocated to taxi-out = 0.25 * 10 = 2.5 minutes

Schedule slack allocated to airborne = 0.6 * 10 = 6 minutes

Schedule slack allocated to taxi-out = 0.15 * 10 = 1.5 minutes

Finally in Step 3 of Figure B-1, the unimpeded and schedule slack times are summed, in turn, for the three phases, taxi-out, airborne, and taxi-in, to create the "scheduled" times. So for the above example,

Schedule taxi-out time = 10 + 2.5 = 12.5 minutes

Schedule airborne time = 80 + 6 = 86 minutes

Schedule taxi-in time = 10 + 1.5 = 11.5 minutes

Author Biographical Information

William Baden is a Senior Economics/Business Analyst with The MITRE Corporation's Center for Advanced Aviation System Development (CAASD). He has experience modeling the operational impact of proposed improvements and schedule changes on both the National Airspace System (NAS) and individual airports. Mr. Baden holds a B.A. in Economics from Towson University.

James DeArmon is a Principal Engineer with The MITRE Corporation. He has worked for the last several years in research and modeling of air traffic flow dynamics. He holds a Master's degree in Operations Research, and has taught graduate courses at the University of Maryland. He has written numerous papers in aviation and applied math. He is a member of the Editorial Advisory Board of the journal *Computers and Operations Research.*

Jacqueline Kee is a Project Team Manager with The MITRE Corporation. She has worked on projects analyzing air transportation performance, conducting benefits assessment, and forecasting passenger demand. She holds an M.S. degree in Operations Research from the Massachusetts Institute of Technology and has worked previously in the Operations Research Groups at American Airlines and U.S. Airways.

Lorrie Smith is a Senior Staff Member in the Center for Advanced Aviation System Development (CAASD), System Assessment and Implementation Department, Simulation and Analysis group. Her projects have included developing programs for modeling the NAS and the analysis of flight plan and operational data. Ms. Smith holds a B.S. in Computer Science from Drexel University