MP100039

MITRE PRODUCT

Calculating Delay Propagation Multipliers for Cost-Benefit Analysis

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Sponsor: The Federal Aviation Administration
Dept. No.: F066
Project No.: 0210FB01-7A
Outcome No.: 1
PBWP Reference: Output 7; Titled “Demand Forecasting and Alternative Valuation”

For Release to all FAA
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1 Introduction

Delays that originate at one location in the National Airspace System (NAS) often propagate or result in delays at other locations. Given an infrastructure investment at an airport that is expected to reduce delay at that airport, it is reasonable to expect that the investment may also reduce delay at other airports through a reduction in propagated delay. This reduction in delay at other airports is a benefit of the investment and should be included in a cost-benefit analysis of that investment.

The Federal Aviation Administration's (FAA) guidance for airport cost-benefit analyses notes that if an enhancement reduces average delay per flight by five minutes or more at an airport, then the reduction in propagated delay is likely to be significant [FAA, 1999, p. 58]. To date, the FAA has not developed a general methodology to value reductions in propagated delay. The same FAA guidance indicates that, during the FAA's review of airport sponsor-provided benefit-cost analyses, the FAA allows benefits based on reduced propagated delay if such estimates are supported by a well-documented methodology. Given the complexity of developing such a methodology, appropriate documentation has not been forthcoming, creating the risk that benefits are being overlooked.

To fill this void, the FAA's Office of Aviation Policy and Planning (APO) asked The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) to develop a new approach for deriving delay propagation multipliers for use in airport cost-benefit studies. The approach was required to have the following characteristics:

1. Focused on computational simplicity and clarity of interpretation
2. Uses only publicly available NAS-wide data
3. Capable of producing delay propagation multipliers for individual airports or groups of airports rather than just a single, national multiplier

The FAA sought to create a consistent baseline estimate of delay propagation that could be used and compared across a wide range of locations and cost-benefit analyses (CBA). Economists may employ more detailed analyses tailored to a specific CBA to refine the estimated reductions in propagated delay as long as the reasons for the deviations from the baseline are understood.

In 2007, MITRE proposed an "accounting approach" methodology [Welman, 2007] that uses one full year of Airline Service Quality Performance[1] (ASQP) data in order to capture the effects of seasonal and day-of-week operational differences. In 2009, at the request of APO, MITRE implemented the proposed methodology with minor changes. In simplest terms, every minute of delay in ASQP is classified as either original or propagated. An original delay does not have an upstream source in ASQP while a propagated delay does. Each propagated delay is linked back to an original delay. From this mapping of original and propagated delay across the NAS, delay propagation multipliers are constructed for each airport based on the original delays that occur at each airport and the associated propagated arrival delays across the NAS.

[1] ASQP contains statistics on scheduled and actual domestic operations by aircraft tail number for airlines that carry at least one percent of all domestic passengers. ASQP covered twenty airlines in 2008. An analysis of one week of flight data concluded that ASQP captured approximately 72% of the scheduled domestic operations listed in the Official Airline Guide (OAG). This number somewhat underestimates the coverage of ASQP since OAG lists what was scheduled while ASQP captures what actually occurred.

This paper documents the multipliers obtained from 2008 ASQP data and provides a general explanation of how these are derived. Also included are discussions of how the multipliers could be used in a CBA and their limitations. Although the multipliers are calculated for specific airports and are influenced by infrastructure at those airports, delay propagation is a network phenomenon and is influenced by a wide range of factors across the network. The variation in the multipliers reflects the variation across the airports of these factors. For example, the propagation of delay is strongly influenced by the long-term operating decisions of airlines serving the airport and by the weather and delay patterns at airports served from the airport.

There are many ways to define delay propagation and many ways to construct metrics from available data on NAS activities. This approach is focused on calculating delay propagation multipliers for use in CBAs. Other approaches, or modifications of this approach, may be more appropriate for answering other questions about delay propagation. APO is implementing an approach to examine delay propagation in an operational context, such as the relationship to scheduling practices, and there are many university researchers working on related questions.

2 Aircraft Operational Day

The basic unit in this analysis is an "aircraft-operational day." An aircraft-operational day is defined as the period in which an aircraft, identified by tail number, does not have a scheduled turn time of more than a specified duration.

Delay propagation is predicated on the relationship between delays over time. However, reasonableness requires that the duration of that relationship be bounded. The question arises: how much time between flights must pass before those flights can be considered "independent"? In other words, what duration should be used to bound aircraft-operational days?

In this analysis, we assumed an aircraft-operational day is defined as the time period in which an aircraft, identified by tail number, does not have a scheduled turn time of more than four hours. Delay can propagate through an aircraft's schedule within the same operational day, but cannot propagate from one operational day to another. Typically, an aircraft-operational day starts around 0600 and ends around 2300. However, our definition of an aircraft-operational day means that aircraft on overnight flights can propagate delay from one calendar day to another, something that cannot occur if the day is artificially cut at midnight. Overnight flights can also result in aircraft-operational days exceeding 24 hours. Alternatively, an aircraft could have two (or more) aircraft-operational days in a single calendar day if, for example, its morning and afternoon scheduled operations are separated by a scheduled turn time of more than four hours. After removing incomplete records in ASQP, the processing of the 2008 ASQP data produced 6,852,142 flights that were assembled into 1,599,408 aircraft-operational days.

Teleportation Events in the Data

After constructing the aircraft-operational days across the full year of ASQP data, there is one data-cleaning step before constructing the delay propagation multipliers. This step removes aircraft "teleportation" events. Teleportation occurs when, according to the ASQP data, an aircraft lands at one airport, but then departs from another airport. This can occur for several reasons, including data errors or repositioning flights, but a common cause is international flights, especially short international flights to Canada, Mexico and the Caribbean.[2] The affected aircraft-operational days are deleted out of concern that the artificial breaks in the data could distort the delay propagation multipliers because we cannot properly account for either delay that originates on international segments or the propagation of delay through an international segment. Of the 1,599,408 aircraft-operational days, 130,000 (or 8.1 percent) were deleted for teleportation reasons. These deletions had only a slight impact on the multipliers, producing a shift of 0.01 or less.

[2] ASQP data do not capture international flights, so a line of flight that includes at least two international flights, one from the United States (US) to another country, the other back to a different US airport, would appear as a teleportation in ASQP. If the return is to the same US airport, then there will not be a teleportation in ASQP, but there will likely appear to be a "turn time" in ASQP of more than 4 hours, in which case the day will be separated into two aircraft-operational days. The duration of this extended "turn time" is equal to the actual turn time after the domestic arrival into the US airport and prior to the international departure, plus the international outbound block time, plus the turn time at the international destination, plus the international inbound block time, plus the turn time prior to the next domestic departure. Only the initial domestic arrival and the final domestic departure at the US airport would appear in ASQP.

3 Classification of Delay

The next step is the classification of each minute of delay within each aircraft-operational day as either original or propagated. An original delay is not associated with an upstream delay, while a propagated delay is linked to an upstream original delay. For example, if the aircraft begins its operational day with a 45-minute late departure, that delay is classified as an original delay since it does not have an upstream source (within that operational day). If the aircraft arrives at its next stop 45 or fewer minutes late, those minutes are classified as propagated delay from the original late departure. If the aircraft arrives more than 45 minutes late, then 45 minutes are classified as propagated and the balance of the delay (e.g., 10 minutes of a 55-minute arrival delay) is classified as original delay from the inbound segment. If the aircraft has an on-time arrival or departure later in the day, then none of the morning delay can propagate further into the rest of the aircraft's operational day.

Every delay classified as propagated is linked back to an original delay. For example, if an aircraft has an original 30-minute delay in the morning and continues to run 30 minutes late for the rest of the operational day, then each of the downstream 30-minute arrival and departure delays is linked to the original 30-minute delay. If the aircraft slowly works its way back on schedule with arrivals and departures later in the day of less than 30 minutes, those remaining minutes of delay are linked to the original 30-minute delay.

Multiple original delays within a single aircraft-operational day result in multiple lines of delay propagation within that aircraft-operational day. As a result, downstream delays can have multiple sources. For example, a 75-minute arrival delay in the evening could be the result of propagated delay from several original delays in the morning combined with some original delay on that inbound segment to give the 75 minutes of delay observed.

One complication develops when an aircraft has multiple original delays in the morning but then gains time back during the operational day. From which of the original morning delays was the propagation reduced? To which original delays should the remaining propagated delays be linked? To solve this problem, the reduction in propagated delay linked to each original delay is made in proportion to the size of the original delay.

As an alternative, reductions in total delay during the operational day could be allocated based on either last-in-first-out (LIFO) or first-in-first-out (FIFO). LIFO would reduce the propagated delay associated with the most recent original delay (within the same aircraft-operational day) while FIFO would reduce the propagated delay associated with the earliest original delay. The proportional allocation was chosen as a reasonable compromise between these two extremes. Analysis of the LIFO, FIFO and proportional allocations using a full year of ASQP data concluded that the choice of allocation mechanism produces less than a 0.04 shift in the delay propagation multipliers, with the proportional allocation falling half-way between LIFO and FIFO.

A Mapping of Original and Propagated Delays

The 1,469,408 aircraft-operational days used in this analysis encompass 6,470,602 flights. Taken together, these create a picture of original and propagated delay for domestic operations for an entire year (as captured by ASQP). Every minute of delay in ASQP is classified as either original or propagated and each propagated delay is linked to an original delay. This mapping of original and propagated delay allows delays to be examined in two ways that are important for constructing delay propagation multipliers.

These two ways of examining the data are illustrated in Figures 3-1 and 3-2 using a single, hypothetical aircraft-operational day. The aircraft follows a routing of Washington Dulles International Airport (IAD) to General Edward Lawrence Logan International Airport (BOS) to Chicago O'Hare International Airport (ORD) to Dallas/Fort Worth International Airport (DFW) to Denver International Airport (DEN). The arrival and departure delays as recorded in ASQP are in the first row of data, highlighted in blue. The block of data below the ASQP row shows the disaggregation of the ASQP delays into original (yellow) and propagated (green) delays, with the propagated delays placed in rows that identify the original delay source. In each column, the original and propagated delays sum to the delay recorded in ASQP in the top row (within the rounding error introduced by the proportional allocation of propagated delay).

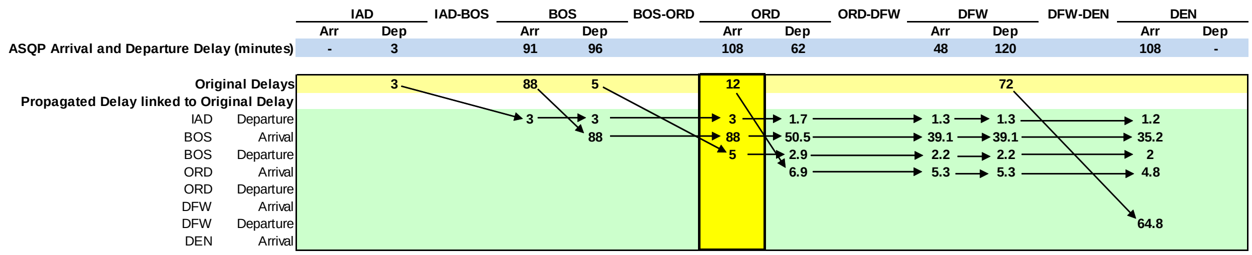

Figure 3-1. Decomposition of an ASQP Delay into Original and Propagated Delay

The first way of examining the data focuses on the source of a delay recorded in ASQP. Any single arrival or departure delay in ASQP can now be decomposed into its original and propagated delay components. In Figure 3-1, the 108-minute late arrival at ORD (see the highlighted column) can now be decomposed into 12 minutes of original delay on arrival at ORD combined with 3 minutes from the late departure from IAD, 88 minutes from the late arrival at BOS, and 5 minutes from a late departure from BOS. The 108-minute departure delay in ASQP can be seen as 12 minutes of original delay at ORD and 96 minutes of delay propagated into ORD. This ability to identify the original delay component of an ASQP delay is required for constructing the delay propagation multipliers.

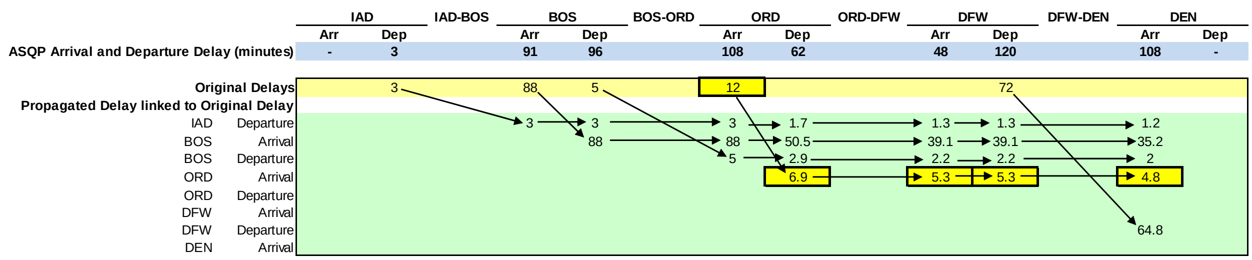

Figure 3-2. Propagated Delay Associated with an Original Delay

The second way of examining the data starts with an original delay and identifies the propagated delays (if any) that result from that original delay (see Figure 3-2). For example, for the 108-minute arrival delay in ASQP just described, the 12 minutes that are original delay at ORD can be seen to be the source of 6.9 minutes of departure delay at ORD, 5.3 minutes of arrival and departure delay at DFW, and 4.8 minutes of arrival delay at DEN. The 12 minutes of original arrival delay at ORD resulted in 22.3 minutes of propagated delay. This ability to identify the propagated delays linked to an original delay is also required for constructing the delay propagation multipliers.

Figures 3-1 and 3-2 also illustrate the proportional allocation used to reduce multiple lines of propagated delay in a single aircraft-operational day when an aircraft gains time. The aircraft arrives 108 minutes late at ORD but is only 62 minutes behind schedule on departure from ORD. This 46-minute reduction in delay is deducted from the lines of propagated and original delay in proportion to their contribution to the preceding 108-minute arrival delay.

4 Airport Delay Propagation Multipliers

The objective of this analysis is to compute a delay propagation multiplier that could be used in the context of a CBA for an investment at an airport. The multiplier has to relate reductions in delay at the airport to reductions in propagated delay across the NAS.

Delay Reductions at the Investment Airport

Based on the delay mapping described in Section 3, all ASQP delay at an airport can be separated into original delay at that airport and delay that propagated into that airport from an upstream source. Given an investment at an airport that is expected to reduce delay at that airport, which delays are reduced: original delays, propagated delays, or both? It is assumed that the reduction is in *original* delay based on the expectation that there is some correspondence between delays that first appear at an airport and the delays that will most likely be reduced by an investment at that airport. In contrast, delays that propagate into an airport are less likely to be reduced by investment at that airport. After all, even an airport with infinite capacity could have arrival and departure delays if those delays propagated from an upstream airport. While the real world is more complex, it seems reasonable to assume that original delays at an airport more closely reflect the delays that would be reduced by investment at that airport.

Identifying Original Delays at an Airport

Focusing on original delays, it is necessary to define what "at an airport" means in the context of the data. If we had perfect information on the cause of each original delay in the system, we could select only the original delays that were caused by a constraint at, say, ORD. This would include original gate departure delays at other airports due to a ground delay program (GDP) or other constraint at ORD but not those gate departure delays due to non-ORD constraints. Original arrival delays into ORD caused by congestion at ORD would be included, but not arrival delays into ORD with non-ORD causes. Original gate departure delays at ORD would seem to be an easy call for inclusion, but those caused by GDPs or other constraints at destination airports would have to be excluded. Finally, arrival delays at the destination airport that were caused by ORD-related constraints encountered after gate pushback (e.g., taxi-out delays or delays clearing ORD airspace) would be counted, but not destination arrival delays that are independent of ORD.

Of course, this level of detail is not available, so the definition of "at an airport" used here seeks to capture the original delays that are *more likely* to be affected by an investment at that airport. Original delay at an airport is defined in this analysis as the sum of three components: original arrival delay into the airport, original departure delay from the airport, and original arrival delay at the destination airports. The original arrival delays into the airport and at the destination airports are included since they could be related to constraints at the investment airport. Airborne queuing and taxi-in delays could be the source of original arrival delays at the airport. Taxi-out and local airspace delays could be the source of original arrival delays at a destination airport. Note again that we are only counting *original* delays on these three components. For example, the original arrival delays into ORD will be less than the observed arrival delays as recorded in ASQP. We are only interested in the fraction of observed ORD arrival delays that does not have an upstream source.

Any definition of "at an airport" will exclude some original delays that should have been included. This is not a problem as long as the excluded original delays propagate in a manner similar to those that are included. The same logic applies to original delays included in the definition that would not have been included given perfect information. If those original delays propagate similarly to the original delays that are correctly included, then the multiplier will not significantly change.

Determining the Propagated Delays Associated with the Original Delays for Cost-Benefit Analysis

Given a set of original delays that occur "at an airport," the associated propagated delays across the NAS linked to that set of original delays can now be determined by looking at the mapping in the second way described at the end of Section 3.

For use in a CBA, some propagated delays should be excluded to avoid the double counting of flight delay, which is the basis for benefit estimates. Consider an original, 30 minute arrival delay that then propagates across the rest of an aircraft-operational day as a 30 minute departure delay, followed by a 30 minute arrival day, followed by a 30 minute departure delay, and so forth. If both propagated arrival and departure delays are counted, then propagated delay per flight would be 60 minutes. If an improvement at the airport then reduces that original 30-minute departure delay and the associated propagated delays to 22 minutes each, then the reduction in propagated delay per flight would be 16 minutes (8 minutes on both arrival and departure). To avoid this double counting and to provide the best basis for valuations using airline direct operating cost and passenger value of time, the multipliers in this paper are based on propagated *arrival* delay only.

Even only counting propagated arrival delay, there is still the possibility of double counting when applying the multiplier to the delay reductions estimated in a local CBA. This problem develops when reductions in departure delay at the investment airport are part of the total estimated delay reduction at that airport. This is frequently the case since estimated delay reductions in CBAs often do not distinguish between reductions in arrival and departure delay. To avoid the double counting of benefits, propagated arrival delay linked to an original departure delay is excluded from the multiplier for the first arrival after the original departure delay. This avoids counting reductions in both departure and arrival delay for the same flight. Propagated arrival delay is included for every arrival after that.

As an illustration, in Figure 4-1, consider the 5-minute original departure delay from BOS. The propagation of that delay for the purposes of a cost-benefit multiplier consists of 2.2 minutes of arrival delay at DFW and 2 minutes of arrival delay at DEN, but not the 5 minutes of arrival delay into ORD at the end of the first segment or the 2.9 and 2.2 minutes of departure delay at ORD and DFW. In other words, with these two adjustments, delay propagation is defined here as propagation from one flight to another, and the multiplier is constructed assuming the local CBA includes reductions in departure delay at the investment airport.

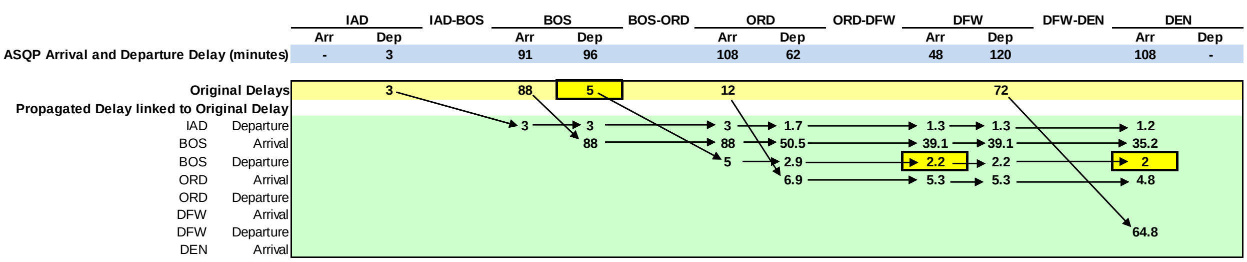

Figure 4-1. Exclusion of Some Propagated Delay for CBA Multipliers

Single Airport Multipliers

As described in Section 3, the mapping of original and propagated delay allows us to determine the original delay component of any arrival or departure delay in ASQP. The mapping also allows us to identify the propagated arrival delays across the NAS that result from any original delay. Combined with our definition of original delay "at an airport," this allows the estimation of a delay propagation multiplier for a single airport. That delay propagation multiplier is defined as

$$Delay\ Propagation\ Multiplier = \frac{O_a + P_a}{O_a}$$

where

O_a = total original delay at airport a,

P_a = total propagated *arrival* delay linked to the original delays at airport a.

Individual airport multipliers based on 2008 ASQP are listed in Table 4-1. The top fifty airports are listed in descending order based on total original delay at the airport. Recall that the delay observed at an airport as recorded in ASQP is a combination of original delay and delay propagated into the airport. The delay values in the table are for original delay only as defined in Section 3, and so will be less than the total delay commonly cited for those airports.

Table 4-1. Delay Propagation Multipliers Based on 2008 ASQP

Airport	Original Delay (minutes)	Propagated Arrival Delay (minutes)	Multiplier
ATL	5,613,616	3,442,862	1.61
ORD	5,586,598	3,598,543	1.64
DFW	3,786,119	2,070,936	1.55
DEN	2,740,415	1,606,444	1.59
EWR	2,572,557	1,312,448	1.51
IAH	2,498,514	1,148,145	1.46
DTW	2,274,800	1,054,822	1.46
JFK	2,192,166	991,642	1.45
LAX	2,176,426	1,078,444	1.50
PHX	1,960,974	995,845	1.51
CLT	1,705,401	766,663	1.45
LGA	1,701,255	878,371	1.52
MSP	1,695,082	631,018	1.37
LAS	1,619,386	900,406	1.56
SFO	1,610,645	891,245	1.55
BOS	1,599,508	827,916	1.52
MCO	1,454,046	928,185	1.64
PHL	1,401,238	737,822	1.53
SEA	1,218,684	584,729	1.48
SLC	1,201,550	655,436	1.55
MIA	1,187,457	523,287	1.44
IAD	1,117,908	654,849	1.59
CVG	1,053,305	488,158	1.46

Table 4-1. Delay Propagation Multipliers Based on 2008 ASQP (Concluded)

Airport	Original Delay (minutes)	Propagated Arrival Delay (minutes)	Multiplier
BWI	990,602	794,769	1.80
MEM	943,040	440,892	1.47
DCA	935,812	431,589	1.46
MDW	880,967	862,570	1.98
FLL	872,508	577,613	1.66
SAN	783,965	502,495	1.64
TPA	781,740	489,494	1.63
CLE	768,740	441,489	1.57
RDU	680,068	420,191	1.62
STL	603,218	449,609	1.75
MKE	542,101	383,578	1.71
MCI	531,014	378,183	1.71
BNA	524,224	375,857	1.72
PDX	486,131	264,937	1.54
PIT	481,133	307,917	1.64
IND	475,850	288,725	1.61
HOU	463,941	507,838	2.09
AUS	419,127	284,364	1.68
DAL	400,496	464,066	2.16
SAT	392,311	261,032	1.67
OAK	382,223	274,746	1.72
MSY	374,284	256,254	1.68
CMH	372,406	250,125	1.67
HNL	365,787	191,918	1.52
SNA	358,921	199,237	1.56
PBI	352,853	216,632	1.61
SMF	344,592	220,712	1.64

The multipliers indicate the amount of propagated delay that is associated with a minute of original delay at that airport. For example, a multiplier of 1.65 means that, on average, one minute of original delay at that airport results in a total of 0.65 minute of propagated arrival delay distributed across arrivals at one or more airports. Note that this includes the possibility that some of that 0.65 minute of propagated delay occurs at the same airport. An original arrival delay at airport A could result in a propagated arrival delay at airport B that continues to propagate back to an arrival at airport A.

Composite Airport Multipliers

A composite multiplier for a combination of airports can also be calculated. For example, there may be a need to construct a composite multiplier for the airports within a metropolitan area. If there are no flights between the airports being combined, then this just requires adding the corresponding original and propagated arrival delays for the airports and applying the equation as for a single airport. A composite multiplier for Newark Liberty International Airport (EWR), John F. Kennedy International Airport (JFK), and La Guardia Airport (LGA) is an example of this situation.[3] In Table 4-2, the total original delay and total propagated arrival delay for each airport are added, and the multiplier calculated, using the equation for a single airport multiplier.

Table 4-2. Composite Multiplier for EWR, JFK and LGA

Airport	Total Original Delay (minutes)	Total Propagated Arrival Delay (minutes)	2008 Multiplier
EWR	2,572,557	1,312,448	1.51
JFK	2,192,166	991,642	1.45
LGA	1,701,255	878,371	1.52
Composite	6,465,978	3,182,461	1.49

A small correction must be made, however, when there are flights between the airports being combined. In that case, the delay minutes for those flights will be double counted and, therefore, should be subtracted from the totals. This occurs because original delay on a flight from the first airport to the second airport will be counted as an original delay at the first airport (on the departure block time) and as an original delay at the second airport (on the arrival block time). The propagated arrival delays associated with those original delays will also be double counted.

The composite delay propagation multiplier for a set of airports is defined as

$$Composite\ Delay\ Propagation\ Multiplier = \frac{\sum_a O_a + \sum_a P_a - \sum_{x,y} O_{x,y} - \sum_{x,y} P_{x,y}}{\sum_a O_a - \sum_{x,y} O_{x,y}}$$

where

$\sum_a O_a$ = total original delay for all airports (*a*) included in the composite multiplier,

$\sum_a P_a$ = total propagated arrival delay linked to the original delays (O_a) at each airport (*a*) in the composite multiplier,

$\sum_{x,y} O_{x,y}$ = Total original arrival delay on all flights between any two airports (*x* and *y*) where both airports are included in the composite multiplier,

$\sum_{x,y} P_{x,y}$ = Total propagated arrival delay linked to the original delays in $O_{x,y}$.

In general, the impact of the adjustment is small. For example, including $O_{x,y}$ and $P_{x,y}$ in a composite multiplier for ORD and San Francisco International Airport (SFO) would only change the composite multiplier from 1.62 to 1.63. When combining two large airports with service between them, the amount of delay on flights between the airports will likely be small relative to total original delay at the two airports and the associated total propagated arrival delay.

A national multiplier is a composite multiplier for all 295 airports in the delay propagation database. The national multiplier is 1.57 for 2008.

3 Actually, in 2008 ASQP there are three flights from JFK to LGA. Assuming they are legitimate flights (not data errors), the change that results from applying the adjustment for those three flights is not detectable until the seventh decimal place of the multiplier.

5 Use and Interpretation of the Multipliers

Given an estimated reduction in original delay at an airport, the multiplier is used to estimate the resulting total reduction in delay across the NAS. The total reduction is the original delay reduction plus the propagated delay reduction.

With an airport investment that is expected to reduce delay and applying the subscript 1 for delays before the airport investment and the subscript 2 for delays after the investment, the reductions in delay due to the investment can be written as

$$Reduction\ in\ original\ delay = O_{a_1} - O_{a_2}$$

$$Reduction\ in\ propagated\ delay = P_{a_1} - P_{a_2}$$

$$Total\ delay\ reduction = O_{a_1} - O_{a_2} + P_{a_1} - P_{a_2} \tag{1}$$

The reduction in original delay is the change captured by the local CBA.

The multiplier is designed to produce the total delay reduction given the reduction in original delay. As presented in Section 4, the multiplier is based on historical data for original and associated propagated delays over a specified time period (e.g., all of 2008) and is defined as

$$Delay\ Propagation\ Multiplier = \frac{O_a + P_a}{O_a}$$

where

O_a = total original delay at airport a,

P_a = total propagated *arrival* delay linked to the original delays at airport a.

The use of the multiplier is based on the assumption that the ratio of associated propagated delay to original delay is constant for the time period under consideration, including before and after the investment. It follows that

$$\frac{P_a}{O_a} = \frac{P_{a_1}}{O_{a_1}} = \frac{P_{a_2}}{O_{a_2}} \tag{2}$$

The multiplier is designed to give the total delay reduction based on the estimated reduction in original delay at an airport.

$$Total\ delay\ reduction = (O_{a_1} - O_{a_2}) * \frac{O_a + P_a}{O_a} \tag{3}$$

Multiplying and rearranging terms gives

$$Total\ delay\ reduction = O_{a_1} - O_{a_2} + (O_{a_1} - O_{a_2})\frac{P_a}{O_a}$$

Substituting terms from (2) shows that the total reduction in delay in (3) is equivalent to that in (1).

$$O_{a_1} - O_{a_2} + O_{a_1}\frac{P_{a_1}}{O_{a_1}} - O_{a_2}\frac{P_{a_2}}{O_{a_2}} = O_{a_1} - O_{a_2} + P_{a_1} - P_{a_2}$$

The assumption is that an economist doing a CBA for an airport investment will have already estimated the reduction in original delay at the airport. The delay propagation multiplier can then be applied to that estimate to give the total reduction in delay across the NAS.

It is important to note that the delay propagation database identifies only the *location* of an original delay, not the *cause* of that original delay. It is possible that an airport has a large amount of original delay, but that airport's infrastructure and weather are not the cause of those original delays. Instead, the actual cause of the delays could be GDPs at a destination airport. In that case, the original delays are real and the propagation is real, but the cause of the original delays is at a different airport from the location of the original delay in the data.

This is a critical point for the use of these multipliers in a CBA. It is assumed that an economist doing a CBA for an airport investment will establish that some portion of the observed arrival and departure delays at that airport is caused by a constraint at that airport, and that the constraint will be reduced by the proposed investment. The validity of using the multipliers depends on the CBA economist establishing the validity of the causal relationship between delays at the airport and an alterable constraint at the airport. By itself, the multiplier for an airport does not establish that investment at the airport will reduce either original delay at the airport or associated propagated arrival delay.

Care should also be taken with the interpretation of the multipliers. For example, a high multiplier for an airport does not indicate a high total original delay or high average original delay per departure. A low multiplier does not indicate a low total original delay or low average original delay per flight. A review of the underlying data reveals that, if anything, the relationship is the opposite of what might be expected. Among the 50 airports in Table 4-1, an airport with high total original delay or high average original delay per departure tends to have a slightly lower multiplier (see Figures 5-1 and 5-2). The multipliers only indicate the extent to which a minute of original delay at an airport propagates as arrival delay (on a different flight by the same aircraft) at downstream airports.

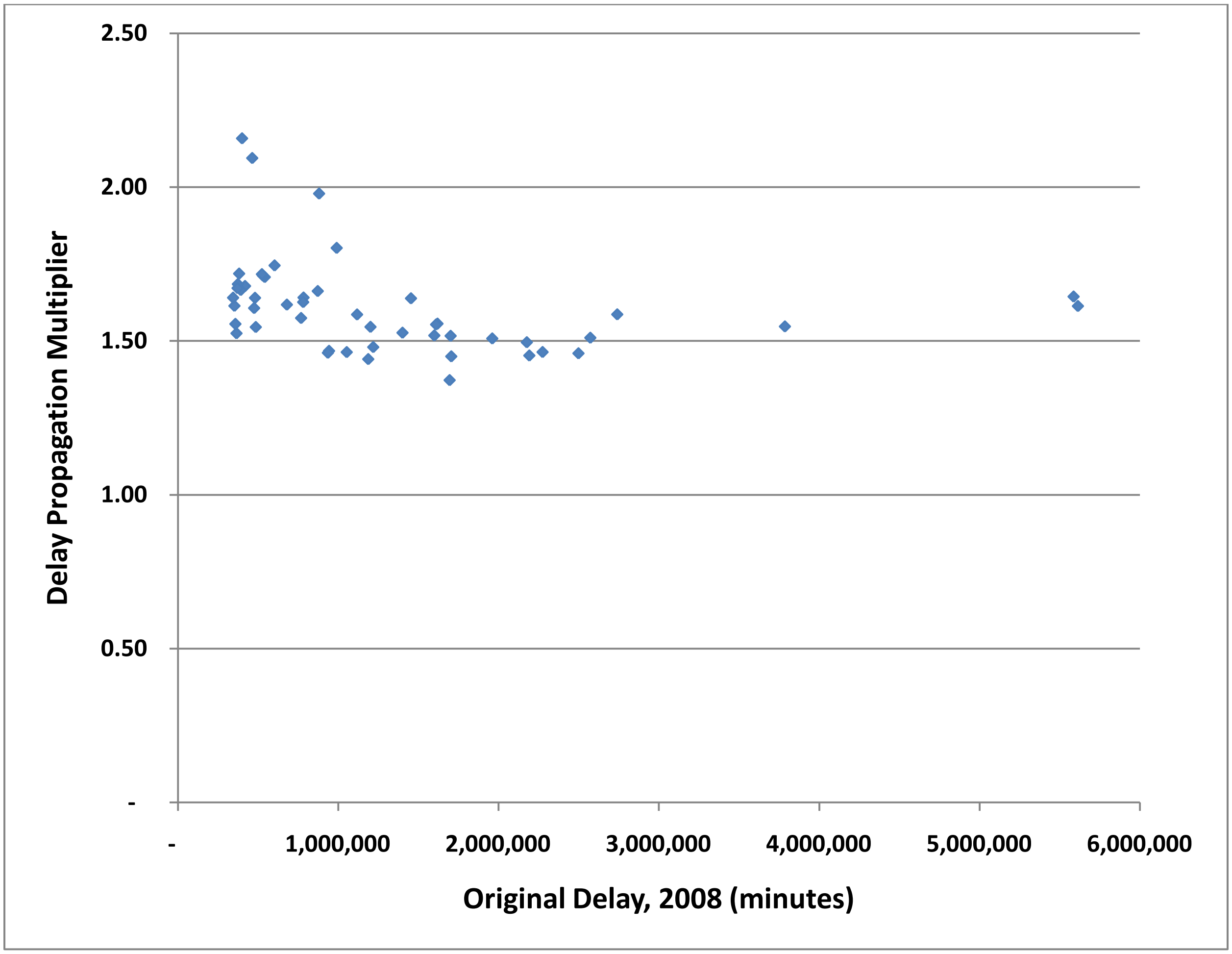

Figure 5-1. Delay Propagation Multiplier and Total Original Delay by Airport

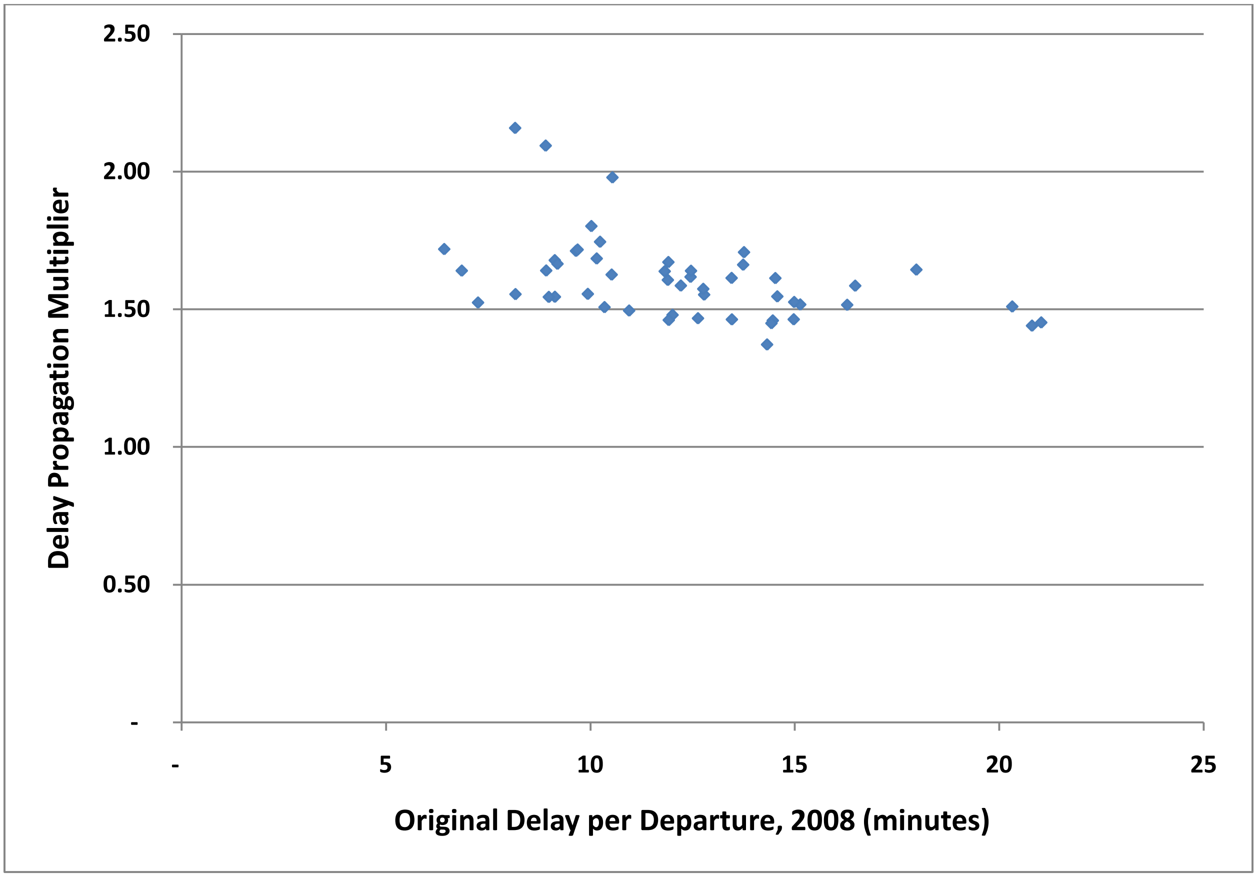

Figure 5-2. Delay Propagation Multiplier and Original Delay per Departure by Airport

Delay propagation is a network phenomenon and is influenced by a wide range of factors across the network. The variation in the multipliers reflects the variation across the airports of these factors. Relevant factors include decisions by the airlines serving the airport (schedules, crew and aircraft positioning, cancellations), the weather and delay patterns at the airports served from the investment airport, and the position of the investment airport within each airline's network (primary hub, secondary hub, or spoke). The delay propagation multipliers reasonably relate the original delay at an airport to the resulting propagated arrival delay, but the multipliers should not be interpreted as a characteristic solely of an airport.

Finally, it is possible to construct custom multipliers for specific investments at an airport. The multipliers in Table 4-1 were computed using the scheduled airline service and delays as captured in ASQP. These multipliers are constructed on the assumption that an airport investment broadly reduces arrival and departure delays at that airport. However, it may be that an airport investment under consideration will have a narrower impact on delay (e.g., only for arrivals or departures, only for a particular set of airlines, only for certain aircraft types, or only for certain months). It is possible to construct a multiplier using the delay propagation database that only considers those types of original delays at an airport. The resulting multiplier will differ only to the extent that the subset of original delay selected propagates differently from the average propagation of all original delay at the airport.

A few additional issues are presented below.

Aircraft-to-Aircraft Propagation of Delay

The propagation of delay from one aircraft to another is not recorded as such under this approach. For example, if an aircraft is held at the gate for connecting passengers on a late flight, the delay is not recorded as having propagated from the late flight to the held flight. Instead, an original departure delay will appear for the held flight and that original delay may then propagate through the remainder of that aircraft-operational day.

The propagation of delay from one aircraft to another is the primary motivation for the use of complex statistical analyses in some recent studies. Even with advanced techniques, these studies still confront the problem that at a large, congested airport there are hundreds of delays that could potentially be related to the arrival or departure of one delayed aircraft. The same could be said for the en route portion of a flight. Even if theoretically tractable, publicly available data does not support the theoretical potential of the models. Because these kinds of interactions are not included, the approach described in this paper produces a conservative baseline estimate of delay propagation multipliers for individual airports.

Isolated Growth in Propagated Delay

Under the approach described in this paper, an increase in total delay for an aircraft at any point in its schedule is always classified as an original delay. Therefore, x minutes of propagated delay at one arrival can, at most, produce x minutes of propagated delay at the next arrival. There is no mechanism for a propagated delay to directly result in additional propagated delay.

Consider an aircraft that arrives late and then has a long turn time that results in a departure of that aircraft even further behind schedule. The portion of the departure delay accounted for by the arrival delay would be classified as propagated delay while the additional delay in turning the aircraft would be classified as original delay at that airport. However, it is possible, from an operational perspective, that the longer than usual turn time was caused by the late arrival of the aircraft, and so could be considered an additional propagated delay. Again, because these delays are not included, the approach described in this paper produces a conservative estimate of delay propagation.

Actual Passenger Delay

This approach only captures the *aircraft* delays that passengers encounter. It does not capture the total delay experienced by passengers in trying to get from their origin to their destination. For example, a passenger may experience an in-flight delay of 1 hour, resulting in a missed connection. That passenger may then have to spend 6 hours at the airport waiting for another flight. That flight may then be delayed 30 minutes en route. The 1.5 hours of delay against schedule that the passenger experiences are captured in the data, but the 6 hours waiting for the next available flight are not. As load factors increase, these types of passenger delays increase relative to the type of airframe-against-schedule delays that are captured in the data [see Bratu and Barnhart, 2005].

Airline Responses to Delay

The delay information in ASQP describes the result of a wide range of complex adjustments made by airlines in response to delays and disruptions in the NAS. Examples of airline adjustments include aircraft swaps, flight crew swaps, schedule padding, and cancellations. The approach presented in this paper only examines result of all these adjustments. It is based on delay against schedule rather than delay relative to theoretical, unimpeded flight times. This approach does not consider the pattern of delay propagation that may have occurred if the airlines had executed their original flight plans.

6 Conclusions

The approach summarized here and the resulting delay propagation multipliers offer a consistent and conservative baseline for incorporating delay propagation into CBAs. The approach is straightforward and easily updated. The multipliers reflect differences in delay propagation across airports and can be constructed in a general form or to address particular types of investment and delay reduction at an airport. Although not a perfect measure of delay propagation, the multipliers provide a reasonable way of including the benefit of reduced delay propagation in airport investment decisions.

7 List of References

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Appendix A Glossary

ADOC	Airline Direct Operating Cost
APO	Office of Aviation Policy and Planning
ASQP	Airline Service Quality Performance
BOS	General Edward Lawrence Logan International Airport
CAASD	The MITRE Corporation’s Center for Advanced Aviation System Development
CBA	Cost-Benefit Analysis
DEN	Denver International Airport
DFW	Dallas/Fort Worth International Airport
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FIFO	First-In-First-Out
GDP	Ground Delay Program
IAD	Washington Dulles International Airport
JFK	John F. Kennedy International Airport
LGA	La Guardia Airport
LIFO	Last-In-First-Out
NAS	National Airspace System
ORD	Chicago O'Hare International Airport
PVT	Passenger Value of Time
SFO	San Francisco International Airport
US	United States

Airport Identifiers

ATL	Hartsfield - Jackson Atlanta International Airport
AUS	Austin-Bergstrom International Airport
BNA	Nashville International Airport
BOS	General Edward Lawrence Logan International Airport
BWI	Baltimore/Washington International Thurgood Marshall Airport
CLE	Cleveland-Hopkins International Airport
CLT	Charlotte/Douglas International Airport
CMH	Port Columbus International Airport
CVG	Cincinnati/Northern Kentucky International Airport
DAL	Dallas Love Field Airport
DCA	Ronald Reagan Washington National Airport
DEN	Denver International Airport
DFW	Dallas/Fort Worth International Airport
DTW	Detroit Metropolitan Wayne County Airport
EWR	Newark Liberty International Airport
FLL	Fort Lauderdale/Hollywood International Airport
HNL	Honolulu International Airport
HOU	William P Hobby Airport
IAD	Washington Dulles International Airport
IAH	George Bush Intercontinental/Houston Airport
IND	Indianapolis International Airport
JFK	John F Kennedy International Airport
LAS	Mc Carran International Airport
LAX	Los Angeles International Airport
LGA	La Guardia Airport
MCI	Kansas City International Airport
MCO	Orlando International Airport
MDW	Chicago Midway International Airport
MEM	Memphis International Airport
MIA	Miami International Airport
MKE	General Mitchell International Airport
MSP	Minneapolis-St Paul International/Wold-Chamberlain Airport
MSY	Louis Armstrong New Orleans International Airport
OAK	Metropolitan Oakland International Airport
ORD	Chicago O'Hare International Airport
PBI	Palm Beach International Airport
PDX	Portland International Airport
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
PIT	Pittsburgh International Airport
RDU	Raleigh-Durham International Airport

SAN	San Diego International Airport
SAT	San Antonio International Airport
SEA	Seattle-Tacoma International Airport
SEE	Gillespie Field Airport
SFO	San Francisco International Airport
SLC	Salt Lake City International Airport
SMF	Sacramento International Airport
SNA	John Wayne-Orange County Airport
STL	Lambert-St Louis International Airport
TPA	Tampa International Airport