FLIGHT CONNECTIONS AND THEIR IMPACTS ON DELAY PROPAGATION

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Abstract

The authors present a simple analytic model that explicitly separates the controllable factors that influence delays and propagation of delays in the National Airspace System (NAS) from those factors that are random variables in a given scenario. In this paper, the controllable type of factor will be called "fixed" and the random type of factor will be called "variable." Simple relationships exist among the fixed and variable factors that characterize NAS delay propagation. We show how the model can be applied to better understand delay propagation from specific NAS airports, especially the effects of flight schedule parameters on measured delay. Recorded data from actual NAS operations are used to derive estimates on key model parameters and to show how delay characteristics vary among different airports.

Introduction

Delay is defined in many different ways, depending upon the context. Scheduled departure and arrival delay is how late a flight departs or arrives compared to an airline's schedule. Flights can incur delays while airborne or on the ground, for example as aircraft taxi between the runway and gate. Delay propagates throughout the NAS because of the interdependencies between different scheduled flights. For example, a late arrival of one flight may cause a late departure of the next flight on the itinerary of the aircraft.

Delay metrics of various types are often used as measures of NAS performance in both real operations and in NAS-wide simulation models [1,2]. In this paper, we emphasize metrics showing the effects of delay propagation from one or more airports with congestion or capacity problems to other NAS airports. In order to clarify delay propagation relationships, we present a model of delay propagation in the NAS, which can be applied to actual operations as well as NAS-wide simulation models.

In a previous study, simulated data was used to demonstrate how delay propagates from airport to airport in the NAS [3]. It was shown that under certain conditions, propagated delay can contribute significantly to overall system delay. As delayed aircraft proceed to subsequent airports on their scheduled itineraries, the propagated delay is not experienced as greatly because the effects are dampened out through the additional time airlines place in their schedule to allow for uncertainty in the weather and other factors, such as unplanned maintenance.

Beatty [4] developed the concept of a delay multiplier to estimate the true system impact of a delayed flight. A delay multiplier is applied to the initial delay of an aircraft to estimate the amount of cumulative delays to all flights connected to the initial flight by crew or by airframe. Large delays early in the day are most disruptive. The delay multiplier grows nonlinearly with the size of the initial delay. Therefore, reducing a large initial delay by any amount has a significant effect on total delay for an airline.

Another analysis of airport delay at key airports was reported by Welch and Ahmed at ATM 2003 [5]. In [5], the term "spectrum" refers to the time-windowed distribution of at-gate arrival delay versus throughput. The paper demonstrates that each airport has a unique spectrum, which is a kind of delay "signature" for that airport. In this approach, statistics are aggregated over a period of months under all weather conditions and the resulting spectra have reasonably smooth distributions. However, the results reported in [5] do not distinguish between operations in IMC (instrument meteorological conditions) and VMC (visual meteorological conditions), and the impacts of airline schedule adjustments to account for delays are not always apparent.

In our analysis, we emphasize clear distinctions between clipped and unclipped delays [6], IMC versus VMC operations, fixed vs. variable delays, and incremental differences between delays on consecutive flight legs for a single aircraft. We use a delay propagation model to uncover relationships to airline schedule parameters that may not be apparent with queuing models alone.

Throughout this paper we discuss several quantities which we define here. "Turnaround time" is the time between an aircraft's arrival and subsequent departure from the same airport. "Slack" is defined as the extra time scheduled beyond the minimum feasible turnaround time. "Flight time allowance" is defined as the extra time added to a flight's scheduled arrival time to allow for some expected variability in actual flight time. "Clipped delay" is defined as positive if a flight is late and zero if a flight is early relative to the schedule. "Great circle flight time" is the theoretical time it takes a given type of aircraft to fly from point to point.

Mathematical Model of Propagation

Departure and arrival delays for connected flights are related by the following equations:

$$D_d = \text{Max}\{0, D_a + \Delta T_t - S_t\} \quad \text{and}$$
$$D_a = \text{Max}\{0, D'_d + \Delta T_f - P_f\}$$

where

D_a is the clipped arrival delay (relative to schedule)
D_d is the clipped departure delay (relative to schedule)
D'_d is the departure delay at the previous airport in the itinerary of the aircraft
ΔT_t is the variable airport turnaround time between flights
ΔT_f is the variable flight time
S_t is the fixed slack for airport turnaround time.
Note: $S_t = s_t - m_t$ where
s_t is the scheduled airport turnaround time
m_t is the minimum airport turnaround time
(m_t is determined by such factors as airport runway geometry and airline operational procedures)
P_f is the fixed flight time allowance added to the flight time. Note: $P_f = s_f - m_f$ where
s_f is the scheduled flight time between airports
m_f is the minimum flight time between airports
(m_f is determined by great circle flight time).

Hence, we have the following equations for clipped delay propagation:

$$D_a = \text{Max}\{0, D'_a + \Delta T'_t + \Delta T_f - S'_t - P_f\} \quad \text{and}$$
$$D_d = \text{Max}\{0, D'_d + \Delta T_t + \Delta T_f - S_t - P_f\}$$

Typically, airlines would schedule $S_t + P_f$ sufficiently large that $S_t + P_f \geq \Delta T_t + \Delta T_f$ and $D'_a + \Delta T'_t + \Delta T_f - S'_t - P_f \leq D'_a$.

Hence, unless there are problems along the flight route, we might expect that it is very likely that $D_a \leq D'_a$, namely, a flight has less at-gate arrival delay than on the previous leg of its itinerary. Moreover, if $D'_a + \Delta T'_t + \Delta T_f - S'_t - P_f \leq 0$, a flight will arrive earlier than its scheduled at-gate arrival time. For negative delays, $D'_a + \Delta T'_t + \Delta T_f - S'_t - P_f$ is less than zero;
this quantity is referred to as "unclipped flight arrival delay," namely,

$$U_a = D'_a + \Delta T'_t + \Delta T_f - S'_t - P_f \,.$$

Note that for departures, most departure delays are clipped.

The term ΔT_t aggregates all the variable delays that affect airport turnaround time (taxi and gate delays, runway queuing, delays due to weather conditions and mechanical problems, as well as other unexpected events) and ΔT_f aggregates delays that affect flights while between airports (including delays due to weather conditions, congestion, miles-in-trail restrictions, and runway queuing).

The terms S_t and P_f aggregate all the fixed or controllable delays. Average clipped arrival and departure flight delays can be expressed as:

$$\overline{D_a} = \text{Max}\{0, \overline{D'_a} + \overline{\Delta T'_t} + \overline{\Delta T_f} - \overline{S'_t} - \overline{P_f}\} \text{ and}$$
$$\overline{D_d} = \text{Max}\{0, \overline{D'_d} + \overline{\Delta T_t} + \overline{\Delta T_f} - \overline{S_t} - \overline{P_f}\}$$

with

$$\overline{x} == \int_0^\infty xf(x)dx = \int_0^\infty (1-F(x))dx \approx \sum_{k=1}^{n} x_k n_k / \sum_{k=1}^{n} n_k$$

where $F(x) = \int_0^x f\{t)dt$ as the cumulative clipped density function. The average $\overline{V} = \overline{\Delta T_t} + \overline{\Delta T_f}$ represents the variable delays in terms of increased flight and turn times between connected flights; while $\overline{F} = \overline{S_t} + \overline{P_f}$ represents the average slack time between connected flights plus the average flight time allowance. Ideally, one might expect $\overline{V}$ to be approximately the same as $\overline{F}$, perhaps with a margin for error. However, in practice, this is not necessarily the case, and we can look to measure the values of these averages in actual operations. We may also rewrite the equations for clipped delays D_a and D_d in terms of an index representing the order of flights in a connected itinerary for a single aircraft:

$$(D_a)_{k+1} = \text{Max}\ \{0, (D_a)_k + V'_k - F'_k\} \text{ and}$$
$$(D_d)_{k+1} = \text{Max}\ \{0, (D_d)_k + V_k - F_k\}.$$

Similarly, we have indexed equations for unclipped delays U_a and U_d:

$$(U_a)_{k+1} = (D_a)_k + V'_k - F'_k \text{ and}$$
$$(U_d)_{k+1} = (D_d)_k + V_k - F_k$$

where the variable delay for the *k*th flight is $V_k = (\Delta T_t)_k + (\Delta T_f)_k$, the fixed delay is $F_k = (S_t)_k + (P_f)_k$, and *k* is the index of connected flights (or "hop" number for the itinerary of an aircraft during a single day).

Note that capacity-related delays at the airport or en route to the airport are implicitly embedded in the variable components ΔT_t and ΔT_f of the variable delay V_k. The magnitude of an individual component does not by itself determine the delay signature for an airport; it is the sum of all the contributing components that characterizes an airport's delay signature.

Positive unclipped flight arrival/departure delays may propagate to other airports on the aircraft itinerary, while negative unclipped flight arrival/departure delays (early flights) may contribute to a reduction in delay at other airports. Hence, delay propagation depends on schedule and operating characteristics. To take slack as an example, it is possible to schedule connected flight arrivals and departures for the same aircraft in such a short time interval that any slight increase in the variable components of delay will necessarily propagate to the neighboring airports. It is also possible that flight arrivals and departures may be scheduled so far apart such that little delay propagation occurs.

From the perspective of optimizing delay performance and resource utilization, an airline's goal can be characterized as setting the fixed components, F_k, with enough margin to absorb the anticipated variable components, V_k, but without so much margin that precious aircraft resources are wasted. The differences between $(D_a)_k$ and $(D_a)_{k+1}$, $(U_a)_k$ and $(U_a)_{k+1}$, are measurements of how closely the fixed components, F_k, match the variable components, V_k.

The authors have examined several NAS airports to determine the magnitude of $V_k - F_k$ and its relation to the propagation of both clipped and unclipped flight arrival delays. Arrival at-gate delay propagated noticeably with marginal $V_k - F_k$, while airports with ample (negative) $V_k - F_k$ experienced much smaller arrival at-gate delays for subsequent flights on the itinerary of the same aircraft.

Model Applications

From Airline Service Quality Performance (ASQP) data, statistics regarding $(D_a)_k$, $(D_a)_{k+1}$, $(U_a)_k$ and $(U_a)_{k+1}$ for selected airports can be constructed to characterize the airports in terms of at-gate delay and propagation of delay to subsequent airports on aircraft itineraries.

To summarize the results discussed in the remainder of this paper, La Guardia Airport (LGA) provides ample (negative) $V_k - F_k$ so that the delay sources $(D_a)_k$, $(D_a)_{k+1}$, $(U_a)_k$ and $(U_a)_{k+1}$ are unlikely to propagate even on days with bad weather. Newark International (EWR) and Phoenix Sky Harbor International (PHX) airports have much smaller margins in $V_k - F_k$, so that noticeable arrival delays propagate strongly to neighboring airports, especially on days with bad weather. These propagation effects are shown for LGA, EWR and PHX in Figures 1 through 3. In these figures, “number of hops” refers to the itinerary of individual aircraft after arrival at the airport of interest. Thus, in Figure 1, “1-Hop” is the collection of all flights to the next airport after arrival at LGA. The next airport after LGA varies from aircraft to aircraft; i.e., some aircraft fly from LGA to Chicago and others fly from LGA to Minneapolis and other cities. Arrivals to all these subsequent airports are aggregated to generate the average at-gate arrival delays shown in the figures. Similarly, the average delays shown in Figure 1 for “n-Hop” aggregate at-gate arrival delays for the flights after arrival at LGA, regardless of which airport this happens to be. Each figure plots results for clipped and unclipped delays, for a representative day with predominantly VMC across the NAS (May 8, 2001) and a day with IMC over most NAS resources (September 5, 2001).

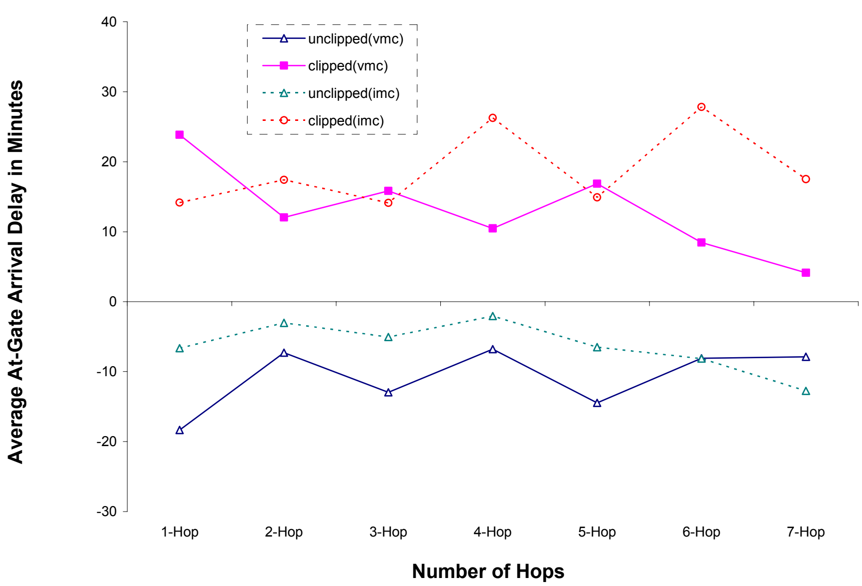

Figure 1. Propagated Delay Profile for Departing Flights from LGA

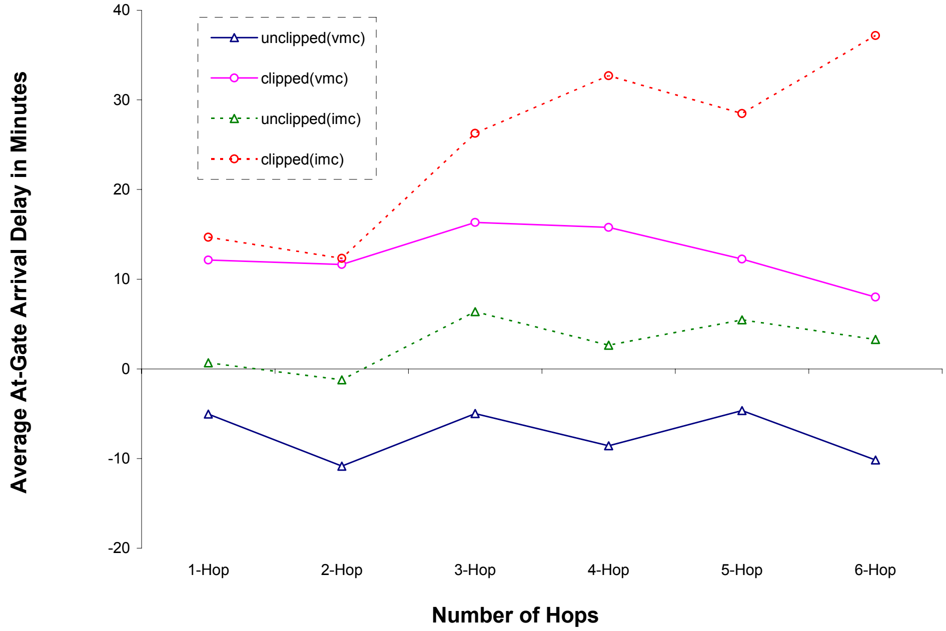

Figure 2. Propagated Delay Profile for Departing Flights from EWR

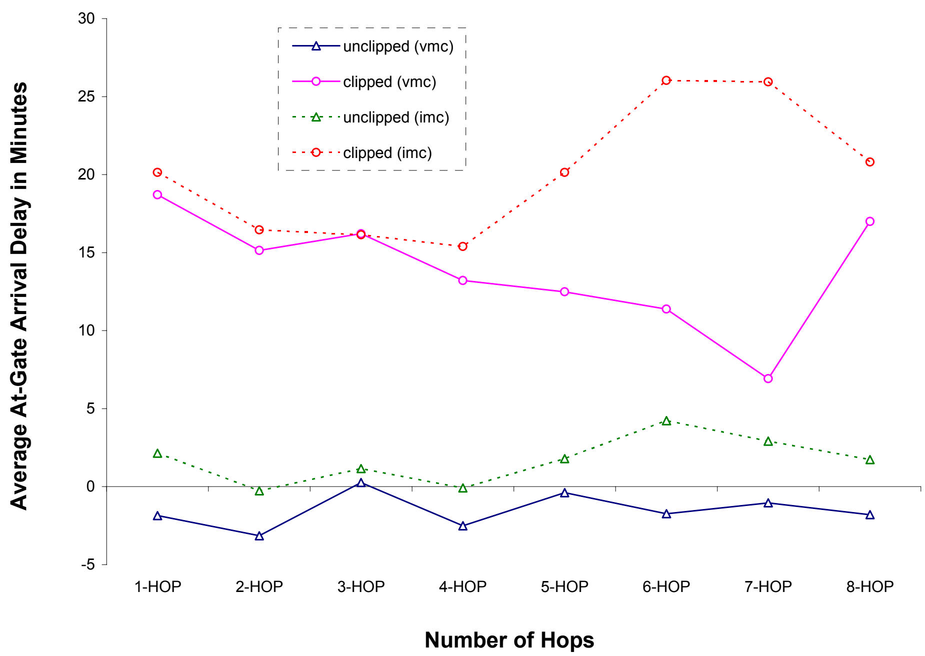

Figure 3. Propagated Delay Profile for Departing Flights from PHX

At LGA, the average $V_k - F_k$ is about -15 minutes. Flights into LGA are scheduled with ample slack, and flights out of LGA have ample flight time allowance. So, on average, the schedule will absorb most variable delays for subsequent flights even during bad weather conditions. Average clipped arrival at-gate delays at LGA during VMC gradually reduced from 15 minutes to 5 minutes, while average unclipped flight arrival at-gate delays during IMC also reduced gradually from -5 minutes to -15 minutes.

For airport EWR, the average $V_k - F_k$ is between -5 and -10 minutes. This is because slack is sufficient, on average, to absorb the variable delays on VMC days without noticeable clipped or unclipped at-gate delay propagation to neighboring airports. However, the slack is not sufficient to absorb weather-related delays on IMC days. Both clipped and unclipped flight at-gate delays do propagate and increase from EWR to other airports, with average unclipped delay increasing from 0 to 5 minutes and average clipped delay increasing from 10 to 35 minutes.

For airport PHX, the average $V_k - F_k$ is less than -5 minutes. This is because flights are scheduled with little slack, such that on IMC days, both unclipped and clipped delays are propagated from airport to airport across several downstream hops. Nevertheless, on VMC days, neither unclipped nor clipped arrived at-gate delays propagated significantly. This suggests that a value of -5 minutes for average $V_k - F_k$ is sufficient for PHX on VMC days.

The global impacts of at-gate delay propagation can be characterized by the distribution functions for the number of connecting flights that contribute to the average delay calculation at a given number of hops, for each airport and for each combination of weather and delay conditions. (For clipped delays, flights with negative delays are excluded.) Figure 4 illustrates these distributions for the three sample airports, for a day of widespread VMC conditions (May 8, 2001) and another day of IMC conditions (September 5, 2001). Note that there are significantly more aircraft with downstream flights at airport PHX than those at EWR or LGA.

Figure 5 illustrates the distribution of departed flights at LGA, EWR, and PHX. Note that the distribution of delayed (clipped) flights depended on weather condition and traffic volume, namely, the size of flights with unclipped delay. On days that have good weather and airports that have ample $V_k - F_k$, most of clipped flight arrival delays are caused by only a few flights that experienced unpredictable events such as mechanical failures. Figure 6 shows the sparseness of clipped flight delays at airport LGA on May 8, 2001.

The fraction of flights with positive arrival delay (i.e., those with nonzero clipped delay) for each of the three airports for both May 8, 2001 (VMC) and September 5, 2001 (IMC) is shown in Figure 7. Note that LGA has the smaller fraction of delayed flights for all weather conditions; EWR demonstrates high sensitivity to poor weather conditions (IMC); and PHX maintains a relatively high fraction of delayed flights regardless of weather conditions.

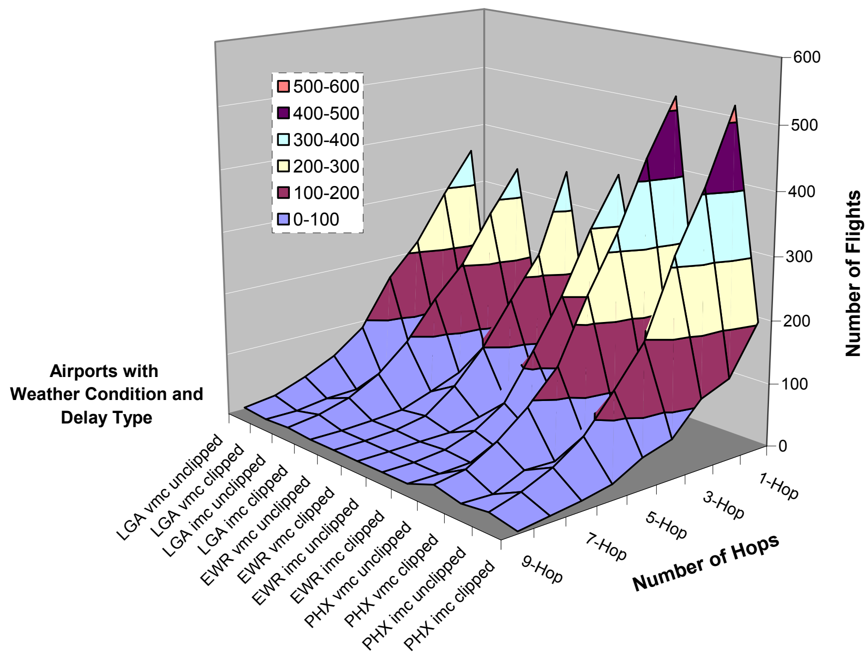

Figure 4. Distributions of Number of Departed Flight Connections

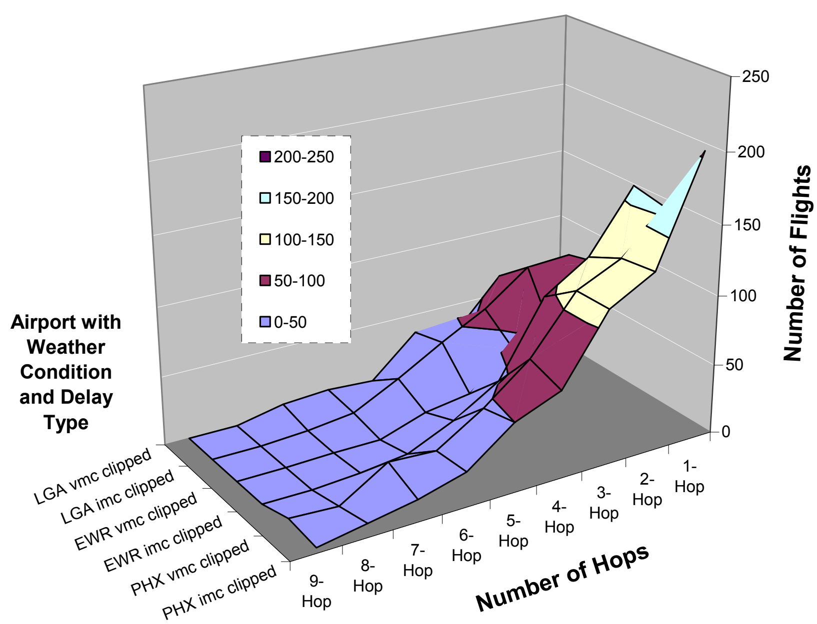

Figure 5. Distribution of Number of Flights with Positive Delay

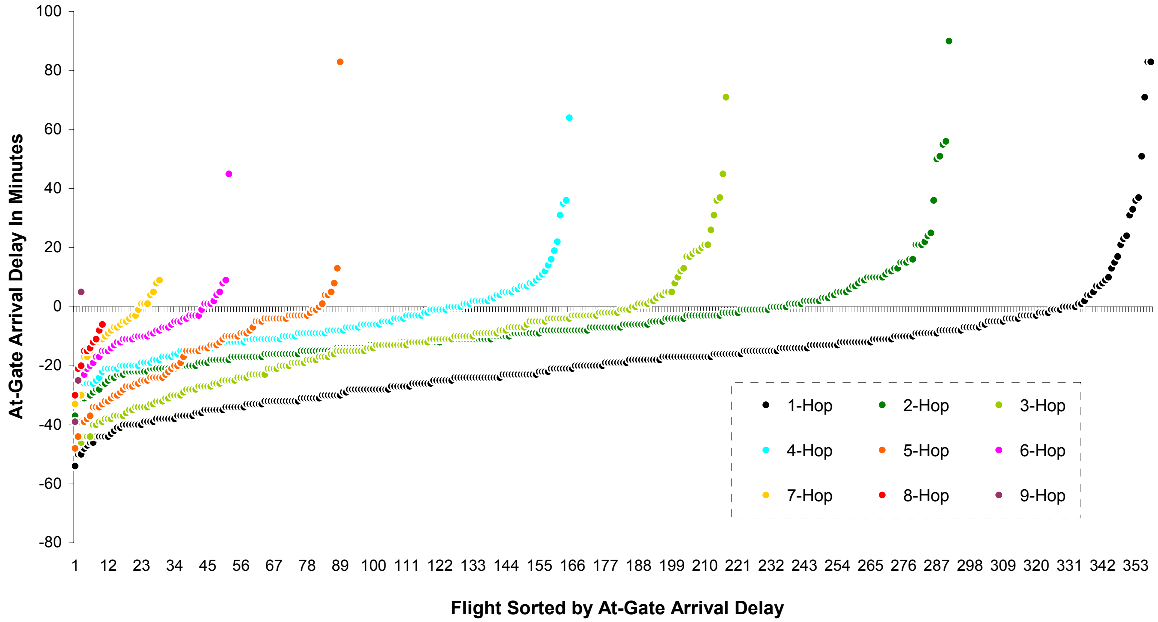

Figure 6. Propagated At-Gate Arrival Delays from LGA on an Almost VMC Day

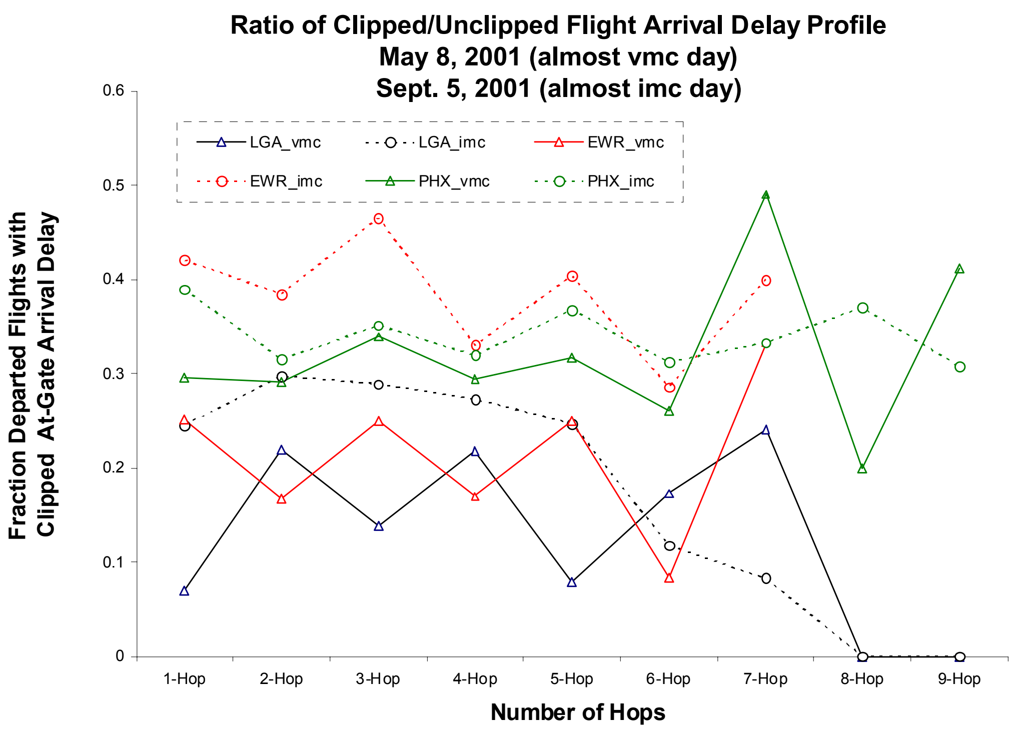

Figure 7. Percentage of Delayed Departures from Sample Airports

By examining the profiles of unclipped and clipped flight delays and their distribution over different operating and weather conditions, one can understand the influence of schedule parameters on at-gate delay, and possible mitigations to reduce the intensity of both clipped and unclipped flight delays.

Conclusions

In this paper, we have completed development of a recursive model of delay propagation which explicitly separates the fixed (controllable) components that influence delay, namely $s_t, m_t, s_f, m_f, P_f,\ S_t$ from the variable (random) components, namely ΔT_t and ΔT_f. The model can be used to estimate slack and flight time allowance needed to compensate for the variable components. We have used real-world NAS data to determine the relative magnitudes of fixed and variable components of delay for three specific airports. Based on historical data, we can determine both the magnitude and impact of certain variable elements throughout the NAS with respect to flight connections and delay propagation. The distributions of both the fixed and variable delays across flights at an airport constitutes a unique kind of airport delay "signature" that distinguished different airports.

This paper goes beyond our previous two papers [7, 6] in that we separate explicitly the fixed (controllable) components from the variable (random) components, and that a simpler and symmetric delay propagation equation is used for both arrivals and departures.

We have used our recursive flight delay propagation model to examine both clipped and unclipped delays for major airlines recorded in ASQP for representative near-VMC and IMC days. The profiles presented from ASQP delay statistics are consistent with what one would expect from the model for clipped (D_k) vs. unclipped (U_k) delays.

Moreover, this recursive delay propagation model allows air traffic analysts to determine and understand the unique delay profile or signature as a consequence of interaction between the fixed and variable delay components at each airport. The model emphasizes the importance of schedule parameters, in addition to queuing effects, on delay performance in the NAS.

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