NAS-wide Simulation and Passenger Itinerary Performance:

Implications for NextGen Benefits Analysis

Lance Sherry
Center for Air Transportation Systems Research (CASTR)
George Mason University (GMU), Fairfax, Va., USA
lsherry@gmu.edu

***Abstract*— NAS-wide simulations are one of the methods used to estimate annual system-wide benefits for Air Traffic Control modernization concepts-of-operations and technologies (e.g. NextGen/SESAR). These tools simulate the operation of up to 60,000 flights per day in various combinations of demand (i.e. flights) and capacity (i.e. airport and airspace capacity). The main input to the simulation is a schedule of flights (not a schedule of passenger itineraries). As a result, estimates of passenger delays assume all passengers are on direct itineraries only, and the impact of cancelled flights, missed connection, and airline network effects are not considered.**

This paper describes the results of an aggregate model of the operation of a hub-and-spoke network that takes into account passenger itineraries (i.e. direct and connecting) and all forms of itinerary disruptions (i.e. delayed flights, cancelled flights and missed connections). This model shows that the reduction in lost economic productivity generated from NAS-wide simulations is under-reported, as passenger trip delays due to delayed flights only account for approximately 40% of the total passenger trip delays. Furthermore, the model identifies the significant roles played by factors other than flight performance, such as airline itinerary structure, airline fleet mix (i.e. aircraft size), load factors and airline hub banking structure, on total passenger trip delay. For example, a 7-10% increase in load-factor can nullify the reduction in total passenger trip delay gained by a 5% improvement in on-time performance achieved by NextGen. The implications of these results on NextGen benefits assessments through NAS-wide simulation are discussed.

Keywords-NAS-wide simulation; passenger itineraries; passenger trip delays;NextGen benefits

I. INTRODUCTION

NAS-wide simulations are one of the methods used to estimate annual system-wide benefits of new concepts-of-operations and technologies proposed for the National Airspace System (NAS). These simulations fly up to 60,000 flights per day in various combinations of demand (i.e. schedule of flights) and capacity (i.e. airport and airspace capacity). Examples of NAS-wide Simulations include: NASPAC (Millner, 1993), LMINet ([Long et al., 1999), ACES (Sweet et. al.2002), and PNP (Ramamoorthy et al.,2006).

These simulations yield estimates of the benefits derived from the modernization initiatives in the form of reduced airlines costs, such as reduced distance traveled that yields savings in travel time, fuel burn, and crew costs. The benefits also accrue to the Air Navigation Service Provider (ANSP) in the form of reduced ATC workload and staffing, and to the society at large in the form of increased safety margins and reductions in emissions and noise.

Benefits to the economy are accrued by estimating the reduction in the loss of economic productivity. Lost productivity is derived by multiplying passenger trip delays to an estimate of the passenger value of time (DOT, 2003). For example, in a recent study of the cost to the economy of flight delays in 2007, passenger trip delays were estimated to result in a $16B loss to the U.S. economy.

Traditional NAS-wide simulation analyses capture flight delays due to imbalances between localized flight demand and airspace or airport capacity. The result is passenger delays due to delayed flights only. That is, all passengers are treated as flying on direct itineraries (no connecting itineraries), and the impact of cancelled flights and missed connections is not considered. Further the structure of passenger itineraries and the ability of the network to respond to disruptions in passenger itineraries are not captured.

This paper describes the results of analysis of an aggregate model of the operations of a hub-and-spoke network to estimate the total passenger trip delay based on passenger itineraries. The model explicitly takes into account airline hub-and-spoke banking strategies and frequency of service, itinerary structures (i.e. percentage of itineraries that direct vs. connecting), aircraft size and load factors, as well as on-time flight performance.

The results of the analysis of this model are summarized below:

- Flight delays account for approximately 45% of the total passenger trip delays. The remaining passenger trip delays are a result of cancelled flights and missed connections.
- The way airlines design their network has a significant impact on total passenger trip delay. The ratio between direct and connecting itineraries, the time between banks at the hubs and the frequency of service, and the selection of aircraft size and target load factor for revenue

management, have significant impact on total passenger trip delay.

These results have implications for benefits analysis from NAS-wide simulations:

- The absence of passenger itineraries in traditional NAS-wide simulation analysis results in under-reporting the full impact of delays on economic productivity.
- Careful book-keeping will need to be done when validating the return-on-investment for NextGen. Airline mergers and acquisitions that change the structure of the itinerary network, airlines fleet mix decisions, airline hub-and-spoke designs and frequency of service decisions, and airline revenue management decisions with regard to target load factors all impact total passenger trip delays. For example, an increase in load factors between 7-10% can nullify the gains in reducing total passenger trip delay achieved through NextGen modernization.

This paper is organized as follows: Section 2 describes the properties of passenger itineraries. Section describes the model of NAS-wide itinerary performance. Section 4 describes the results of analysis with examples from a 100 spoke hub-and-spoke network. Section 5 describes the implications of these finding on NextGen benefits analysis.

II. PROPERTIES OF PASSENGER ITINERARIES

An airline transportation system operates flights in a space-time network. The flights are choreographed to enable passenger transfer as well as aircraft and crew placement for subsequent flights. A system composed of the airlines, airports, Air Traffic Control (ATC), and their supply chains provide a mass-transit transportation service. By leveraging economies-of-scale in multiple dimensions, this system provides affordable, rapid, safe transportation to passengers and cargo to distant and/or remote destinations. In terms of speed and cost for transportation of relatively small and lightweight items, this mode of transportation has a complete monopoly for transportation over long distances.

Airlines maximize profit by scheduling *passenger itineraries* in time and space to meet passenger demand for travel. To minimize costs and maximize the utilization of assets, airlines schedule flights in a space-time network whereby itineraries are satisfied by one or more flights and the aircraft and crew are positioned to transport the next batch of passengers on the next leg of their itineraries. The most efficient network that maximizes economies-of-scale is a hub-and-spoke network.

There are two classes of itineraries: direct itineraries and connecting itineraries. Passengers on direct itineraries are transported on a single flight from their origin to their destination. Passengers on connecting itineraries are transported by two (or more) flights whose arrival and departure are synchronized to facilitate connections by passengers.

By virtue of the existence of itineraries, passenger on-time performance is determined by the performance of the itineraries. In some cases, itinerary on-time performance is directly linked to flight on-time performance. For example, for passengers on a direct itinerary, a delayed flight will result in delays for the passengers with direct itineraries on that flight. In other cases, itinerary performance is decoupled from flight on-time performance and is determined by the availability of seats for rebooking. Passengers on itineraries that are cancelled (due to a cancelled flight), or for passengers that miss connections, the delay experienced by the passenger is a function of the ability to get rebooked on an alternate itinerary that is determined by load factors and frequency of service.

A. Relationship between Flights and Itineraries

Individual flights can be disrupted by delays or cancellations. The status of individual flights can be categorized as: on-time, delayed (by more than 15 minutes), or cancelled.

Passenger itineraries can be disrupted by delays, cancellations, or missed connections. The status of direct passenger itineraries can be categorized as: on-time or cancelled. The status of connecting passenger itineraries can be categorized as: on-time or cancelled, or missed connection.

The likelihood and magnitude of a disruption of each type of itinerary is summarized in Table 1. For passengers on direct itineraries, the likelihood of a disruption in the form of a delayed itinerary is a function of the likelihood of a delayed flight. The magnitude of the delay for this itinerary is also determined by the magnitude of the delay of the flight.

TABLE I. ITINERARY DISRUPTIONS: LIKELIHOOD AND MAGNITUDE

Itinerary Type	Probability of Itinerary Disruption	Magnitude of Itinerary Disruption
Direct	Probability of delayed flight	Magnitude of flight delays
	Probability of cancelled flight	Rebooking based on load factor and frequency of service
Connecting	Probability of delayed flight for Hub-to-Destination	Magnitude of flight delays
	Probability of cancelled flight for Origin-to-Hub *AND* Hub-to-Destination	Rebooking based on load factor and frequency of service
	Probability of delayed flight for Origin-to-Hub such that the passengers are unable to make the connection from Hub to Destination	Rebooking based on load factor and frequency of service

For passengers on direct itineraries, the likelihood of a disruption in the form of a cancelled itinerary is a function of the likelihood of a cancelled flight. The magnitude of the delay for this itinerary is determined by the availability of seats on subsequent flights and the frequency of service.

For passengers on connecting itineraries, the likelihood of a disruption in the form of a delayed itinerary is a function of the likelihood of a delayed flight on the hub-to-destination leg. The magnitude of the delay for this itinerary is also determined by the magnitude of the delay of the flight.

For passengers on connecting itineraries, the likelihood of a disruption in the form of a cancelled itinerary is a function of the likelihood of a cancelled flight on *both* the origin-to-hub *and* the hub-to-destination legs. The magnitude of the delay for this itinerary is determined by the availability of seats on subsequent flights and the frequency of service.

For passengers on connecting itineraries, the likelihood of a disruption in the form of a missed connection itinerary is a function of the likelihood of a delay on the origin-to-hub flight in excess of the connection window. The magnitude of the delay for this itinerary is determined by the availability of seats on subsequent flights and the frequency of service.

B. Itinerary Performance

Three measures are used to assess the impact on NAS itinerary performance:

1) *Total Passenger Delay:* the sum of delays experienced by passengers on disrupted itineraries. Composed of total passenger itinerary delays from direct itineraries (delayed and cancelled) as well as total passenger itinerary delays from connecting itineraries (delayed, cancelled, and missed connections).

2) *Average Delay for Disrupted Itineraries*– average delay for disrupted itineraries only.

3) *Perecent Passengers Disrupted* – the percentage of passengers affected by disrupted itineraries.

III. ANALYTIC MODEL

An aggregate model for the operation of a hub-and-spoke network is outlined in the Figure 1. There are four components: (1) Itinerary Structure, (2) Passenger Allocation to Itineraries, (3) Itinerary Disruption, and Passenger Trip Delays.

The itinerary structure module takes as inputs the number of airports in the hub-and-spoke network, and the percentage of airports served by direct and connecting itineraries. The output of the module is the number of flights and the number of direct and connecting itineraries.

The Passenger Allocation module takes as inputs the number of direct and connecting itineraries and the aircraft size and load factor. The outputs of the module are the number of passengers on each class of itinerary.

The Itinerary Disruption module takes as inputs the probability of a delayed flight. The outputs of the module are the probability and magnitude of disruption for each type of itinerary.

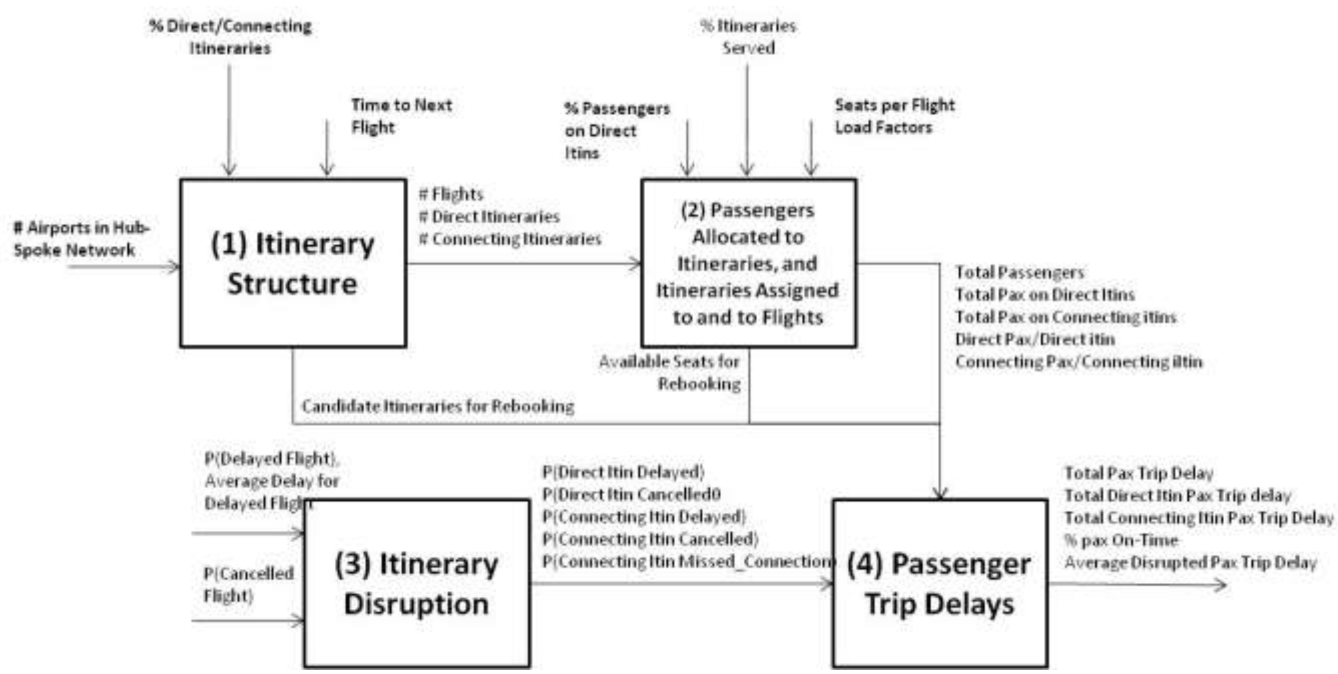

Figure 1. Aggreate model for NAS-wide Itinerary Performance

The Passenger Trip Delay module takes as inputs the number of each type of itinerary, the number of passengers on each itinerary, and the likelihood and magnitude of itinerary disruptions. The outputs of the module are the passenger trip delay statistics: total delay, average delay for disrupted passengers and percent passengers disrupted.

A full description of the model is available in Sherry (2011).

IV. ANALYSIS

The Total Passenger Trip Delay is described by the aggregated equation (1).

Total Passenger Trip Delay = (1)

Pax_{DI} * (P_{DI}Del( ) * D_{DI}Del) +

Pax_{DI} * (P_{DI}Cnx( ) * D_{DI}Cnx) +

Pax_{CI} * (P_{CI}Del( ) * D_{CI}Del) +

Pax_{CI} * (P_{CI}Cnx( ) * D_{CI}Cnx) +

Pax_{CI} * (P_{CI}MC( ) * D_{CI}MC)

Where:

Pax_{DI} – Number of passengers on Direct Itineraries

P_{DI}Del( )– Probability of Direct Itinerary delayed

D_{DI}Del – Average delay for Direct Itinerary delayed

P_{DI}Cnx( ) – Probability of Direct Itinerary cancelled

D_{DI}Cnx – Average delay for Direct Itinerary cancelled

Pax_{CI} – Number of passengers on Direct Itineraries

P_{CI}Del( ) – Probability of Connecting Itinerary delayed

D_{CI}Del – Average delay for Connecting Itinerary delayed

P_{CI}Cnx( ) – Probability of Connecting Itinerary cancelled

D_{CI}Cnx – Average delay for Connecting Itinerary cancelled

P_{CI}MC( ) – Probability of Connecting Itinerary missed connection

D_{CI}MC – Average delay for Connecting Itinerary missed connection

There are five terms in the equation for Total Passenger Trip Delay. The first two terms are for passengers on direct itineraries. The last three terms are for passengers on connecting itineraries.

Each term in the equation is composed of three elements: total number of passengers on an itinerary, the probability of an itinerary disruption, and the magnitude of the delay for each type of itinerary disruption.

A. *Role of Delayed Flights*

Inspection of Equation (1) shows that there are two terms associated with itineraries disrupted by delayed flights and three terms disrupted by cancelled flights and missed connections.

Total Passenger Trip Delay = (2)

// Itineraries disrupted by delayed flights

Pax_{DI} * (P_{DI}Del( ) * D_{DI}Del) +

Pax_{CI} * (P_{CI}Del( ) * D_{CI}Del) +

// Itineraries disrupted by cancelled flights

Pax_{DI} * (P_{DI}Cnx( ) * D_{DI}Cnx) +

Pax_{CI} * (P_{CI}Cnx( ) * D_{CI}Cnx) +

// Itineraries disrupted by missed connections

Pax_{CI} * (P_{CI}MC( ) * D_{CI}MC)

The degree to which these three categories of terms contribute to total passenger trip delay is a function of the relationship between the expected values of delay (i.e. probability of disruption multiplied by the average delay) for category of itinerary disruption. Typical values for likelihood of itinerary disruption and average delays from 2007 are illustrated in Table 2. The result shows that only 38% of the total passenger trip delay is captured when NAS-wide simulations assume only direct itineraries, and do not consider the effects of cancelled flights.

TABLE II. PERCENTAGE OF TOTAL PASSENGER TRIP DELAY FROM ITINERARIES DISRUPTED BY DELAYED FLIGHTS

	Probability of Disrupted Itin	**Average Delay**	**Expected Value of Delays**	**Percentage of Total**
Direct – Delayed	0.3	60	18	
Connecting – Delayed	0.3	60	18	
		Sub-Total	36	38%
Direct – Cancelled	0.02	645	12.9	
Connecting – Cancelled	0.04	645	25.8	
Connecting – Missed Connection	0.03	645	19.35	
		Sub-Total	58.05	62%
		TOTAL	94.05	100%

B. *Role of Itinerary Strcuture*

Airline mergers and the resulting consolidation of hubs, or elimination of direct itineraries to match demand with profitable service, results in changes in itinerary structure. Typically, during weak travel demand, airlines are obliged to consolidate hub operations by eliminating non-hub direct itineraries. Conversely, during periods of growth in travel demand, expansion occurs by adding direct itineraries.

These shifts in itinerary structure directly affect the number of passengers on direct itineraries, Pax_{DI}, and the number of passengers on connecting itineraries, Pax_{CI}. For example, in 2007, an estimated 50% of the passengers travelled on direct itineraries. By 2009, following airline consolidation of the network, 45% of the passengers were on direct itineraries.

Equation (1) can be re-organized to isolate the number of passengers on each type of itinerary.

Total Passenger Trip Delay = (3)

Pax_{DI} * [(P_{DI}Del( ) * D_{DI}Del) + (P_{DI}Cnx( ) * D_{DI}Cnx)] +

Pax_{CI} * [(P_{CI}Del( ) * D_{CI}Del) + (P_{CI}Cnx( ) * D_{CI}Cnx) +

(P_{CI}MC( ) * D_{CI}MC)]

Whereas passengers on direct itineraries can be disrupted by delayed flights and cancelled flight, connecting itineraries can be disrupted by delayed flights, cancelled flights *and* missed connections. By a simple count of terms, the contribution of passengers on connecting itineraries to the total passengers trip delay is greater than the contribution by passengers on direct itineraries. This effect is magnified by the differences in likelihood of disruptions. By definition connecting itineraries have twice the likelihood of a disruption due to cancelled flights.

In this way shifts in network itinerary structure can have a significant impact on total passenger trip delay.

C. *Role of Aircrat Size, Load Factor and Frequency of Service*

Airlines are constantly tinkering with their fleet mix, network structure, frequency of service, and revenue management algorithms and parameters (e.g. no-show rates, over-booking percent). To match travel demand with seat supply, and to use their assets on profitable routes, airlines adjust frequency of service to feeder airports.

Also, to reduce costs of operations, airlines adjust their banking structure at hub airports. In periods of weak travel demand, airlines have migrated to “rolling hubs” (also known as “continuous hubs”). This format of hub operations significantly reduces the number of gate agents and other airline labor and capital equipment required to handle a “bank” by extending the time during which the flights for the arriving bank arrive at the hub, and flights for the departing bank depart the hub.

The impact of these changes results in changes in load factors and frequency of service. These two factors drive the magnitude of the trip delays experienced by rebooked passengers due to cancelled flights (D_{CI}Cnx) and missed connections (D_{CI}MC).

When itineraries are disrupted by cancelled flights or missed connections, passengers must be rebooked on alternate itineraries. There are two factors that determine the trip delay experienced rebooked passengers: (i) the availability of seats on alternate itineraries is determined by the aircraft size and load factor, and (2) the frequency of service (i.e. time between flights).

D_{CI}Cnx = f(load factor, time to next flight) (4)

D_{CI}MC = f(load factor, time to next flight)

Figure 2 shows the effect of increased load factor on rebooking delays. It takes a geometrically higher number of flights to accommodate rebooked passengers as the load factor increases. For example, the cancellation of a 100 passenger flight would take 2 additional flights with load factor of 0.5 to rebook all the passengers. Rebooking the same flight would take 10 flights with load factor of 0.9. Figure 2 also shows how the effect of adjusting the time to next flight (i.e. frequency of service). As the frequency decreases, and time to next flight increases, the delay experienced by rebooked passengers increases.

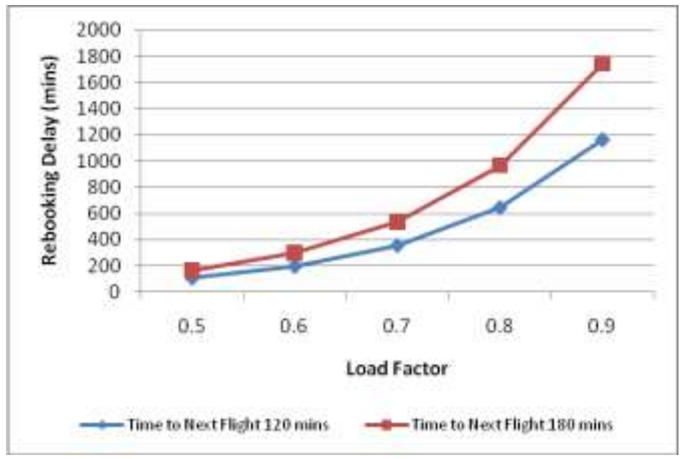

Figure 2. Effect of Load Factor and Time to Next Flight on trip delays experienced by rebooked passengers

D. *Role of on-Time Flight Performance*

The imbalance between flight demand, and local airspace and airport capacity. When the imbalance can be forecasted in time, departing flights are delayed on the ground at their origin until a forecast slot at their destination or in en-route airspace is available. In some cases an airline may choose to tactically cancel a flight rather than accept the assigned delay. This type of system-wide traffic demand-capacity imbalance is coordinated by Traffic Flow Management (TFM) using Collaborative Decision Management (CDM). Imbalances that are not forecast are managed by air traffic controllers within a Center airspace (or within a sector airspace) by miles-in-trail or re-routing.

In both the forecast and non-forecast cases, the degree of imbalance determines the likelihood of a flight experiencing a delay. This is known as the Percentage On-Time Performance. The degree of imbalance also determines the magnitude of a delayed flight.

Flight on-time performance affects total passenger trip delays directly on direct and connecting itineraries. The probability of a passenger experiencing a delayed itinerary is equivalent to the probability of a delayed flight. This applies to direct itineraries and only the outbound (hub to destination) leg of a connecting itineraries.

$P_{DI}Del(\,)$ = probability of delayed flight Origin-Destination (5)
$P_{CI}Del(\,)$ = probability of delayed flight Hub-Destination

The on-time performance has three knock-on effects. First, the average delay experienced by a delayed flight is correlated with on-time performance. Both direct and connecting itineraries that are delayed will experience the average delay for a delayed flight. Figure 3 shows the relationship between the probability of a delayed flight and the magnitude of delays for delayed flights.

$D_{DI}Del$ = average delay for a delayed flight Origin-Destination (6)
$D_{CI}Del$ = average delay for a delayed flight Hub-Destination

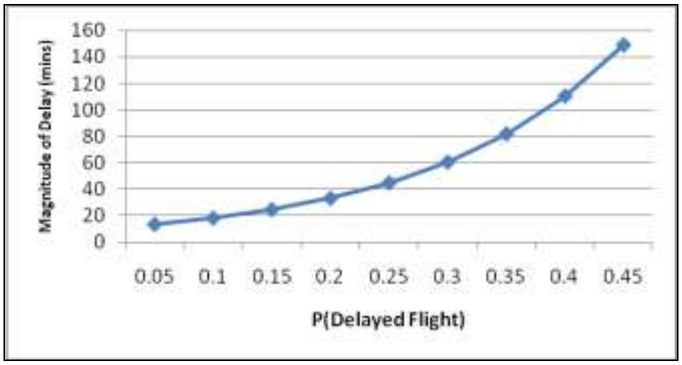

Figure 3. The magnitude of delays for delayed flights increase exponentially as the probability of delayed flights increases

The second knock-on effect of on-time flight performance is flight cancellation rates. Figure 4 shows the relationship between probability of a delayed flight and the probability of a cancelled flight.

$D_{CI}Cnx = f$(probability of a delayed flight) (7)

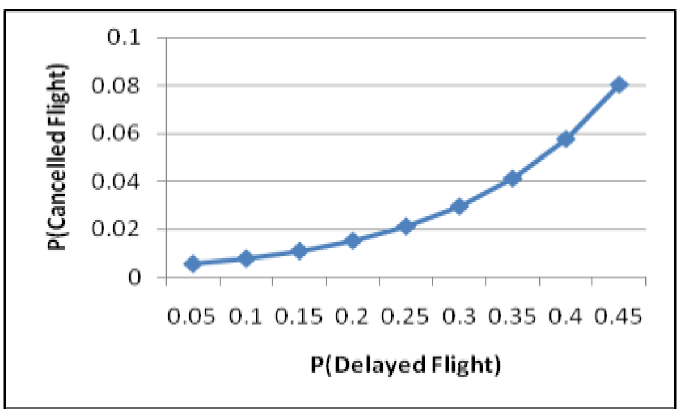

Figure 4. Probability of a cancelled flight incraeses exponentially as the probability of a delayed flight increases

The third knock-on effect of on-time performance is on the probability of a missed connection. This probability is a function of both the likelihood of a delayed flight from origin-to-hub, and connecting time window to the departure of the hub-to-destination flight. (See Ball, Lovell, Mukherjee, Subramanian, 2006)

$P_{CI}MC(\,) = f$(probability of a delayed flight, connecting time window) (8)

E. What is NextGen worth?

As this analysis has shown, under the conditions of an equal split between passengers on direct and connecting itineraries, there are two approaches to reduce total passenger trip delay.

(1) Improve On-time Flight Performance through ATC modernization: This has the ripple effect of reducing the magnitude of flight delays, the probability of cancelled flights and the probability of missed of connections.

(2) Adjust Load Factors (and/or Time to Next Flight): A reduction in load factors creates a reservoir of seats available for rebooking that significantly reduces the effect on total passenger trip delays on direct and connecting itineraries disrupted by cancelations, and connecting itineraries disrupted by missed connections

This raises the following thought experiment:

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How many additional passengers could
be transported on the same network
(i.e. no change in network structure,
number of flights, or aircraft size),
if on-time performance was improved
while maintaining a fixed socially/
economically acceptable total
passenger trip delay.
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For a 100 spoke hub-and-spoke network, with an even split of 16,000 passengers between direct and connecting itineraries, to maintain a target level of passenger trip delays, a 5% change in on-time performance is equivalent to 7-10% change in load factors.

In other words, with a 5% improvement in on-time performance, a society could allow airlines to sell 7-10% more tickets per flight without affecting total passenger trip delay.

V. CONCLUSIONS

A large portion of the benefits of NextGen modernization is accrued by the reduction in passenger trip delays and the associated reduction in lost economic productivity (i.e. passenger value of time).

NAS-wide simulations are frequently used to estimate annual system-wide benefits of new concepts-of-operations and technologies. The simulations evaluate the effect on operations of up to 60,000 flights per day in various combinations of demand (i.e. time-space schedule of flights) and capacity (i.e. airport and airspace capacity).

These simulation yield estimates of the benefits in the form of reduced airlines costs (i.e. reduced fuel burn, crew costs, ..), reduced ATC workload, as well as benefits to the economy in the form of passenger value of time derived from passengers delays from delayed flights. The approach has can be improved by:

A. Complete Estimation of Benefits Accrued by Reducing Passenger Trip Delays on all Itineraries

As shown by this analysis, the estimates of the benefits accrued by the reduction of passenger trip delays are under-estimated for NAS simulations that do not explicitly account for the delay experienced by passengers on cancelled or miss connected itineraries. A complete accounting requires the analysis of passenger itineraries.

B. Book-keeping for Role of Network Structure, Fleet Mix, and Load Factor

Careful book-keeping will need to be done when validating the return-on-investment for NextGen. Airline mergers and acquisitions that change the structure of the itinerary network, airlines fleet mix decisions, airline hub-and-spoke designs and frequency of service decisions, and airline revenue management decisions with regard to target load factors all impact total passenger trip delays. For example, an increase in load factors between 7-10% can increase total passenger trip delay the same amount as a 5% improvement in flight on-time performance from NextGen modernization will decrease total passenger trip delay.

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