ASSESSING DELAY BENEFITS OF THE FINAL APPROACH SPACING TOOL (FAST)*

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ABSTRACT

Air traffic delay grows each year. NASA is developing the Final Approach Spacing Tool (FAST) to help reduce airport arrival delays. FAST is intended to increase throughput and reduce delays. Analysis and field trials have suggested that FAST can help controllers increase arrival throughput on busy runways by several aircraft per hour.

Published simulation studies have predicted that delay reductions from such throughput increases would save several hundred million dollars annually. However, these predictions disagree on delay savings for some airports and omit other airports of interest. Their predicted delay savings for some airports are higher than actual reported delays for those airports. They do not consider hazardous weather disruptions to arrival routes, and they do not address downstream delays caused by schedule disruption.

This paper focuses on simple statistical and analytical measures of delay to resolve these problems. It develops a rule for ranking benefits and compares delay reduction predictions against actual reported delays. It relates delay to ceiling and visibility and thunderstorms. It examines the correlation of delay between airports and estimates the impact of downstream delay on FAST benefits.

INTRODUCTION

The cost of air traffic delay grows each year as traffic and fuel costs increase. As part of the Center-TRACON Automation System (CTAS), NASA is developing the Final Approach Spacing Tool (FAST). FAST will increase throughput and reduce delays by providing advisories for runway balancing, arrival sequencing, and final approach spacing.

Analyses, simulations, and field trials indicate that FAST could help controllers increase arrival throughput on busy runways by several aircraft per hour. Studies by Seagull Technology, Inc. and Logistics Management Institute (LMI) have estimated the potential savings from FAST at 10 major US airports.[1,2,3,4,5,6] Both studies reviewed published field trial results and runway capacity considerations and concluded that FAST has the potential to increase throughput by about 4 arrivals per hour per runway by helping controllers reduce the variance of inter-arrival timing.[7] This more precise arrival timing allows controllers to reduce inter-arrival spacing without increasing the incidence of separation violations.

The studies employed independent demand and capacity estimates and used separate queuing engines to calculate the reduction in queuing delay. Their capacity models, although different in detail, each provided Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) capacity estimates for the principal runway configurations at each airport. The Seagull study used an event-driven queuing model, whereas LMI integrated the Kolmogorov queuing equations to convert capacity improvements into delay savings. They also developed independent cost models to convert delay savings to cost savings.

In spite of these differences, both studies predicted that delay reductions from such throughput increases at 10 major airports would save over $300M annually in direct operating costs. However, their results disagree on predicted delay savings for some airports. They omit some important airports because high simulation setup costs make it too costly to extend the models. They did not validate their predictions with actual delay measurements for the airports studied. Their models focus on delays in IMC and VMC and do not reflect the fact that FAST cannot predict flight trajectories and must cease operating when hazardous weather significantly disrupts arrival routes. Consequently, they also do not account for the fact that FAST will experience unusually large residual queues after the routes have re-opened.

Both studies adopted similar limitations of scope. The dollar savings estimates of both were intentionally

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conservative by focusing only on direct operating cost savings from currently defined FAST functionality. They did not include delay multipliers for downstream savings, passenger delay cost savings, schedule uncertainty cost savings, or savings from possible future FAST improvements. Downstream delay propagation effects, which are large for thunderstorm and IMC days, were omitted for lack of a model applicable to all airports. Passenger delay was excluded from both studies because its dollar value is controversial. The studies omitted dollar benefits for increasing schedule predictability. Although delay reductions will result in less delay uncertainty, there is no model for the magnitude of the savings from reducing the back-up resources needed for dealing with schedule uncertainties. The delay and cost reduction potential of possible future FAST enhancements, such as controller aids for hazardous weather, arrival sequence optimization, or spacing reduction based on wake-vortex measurements were omitted for lack of supportable predictions on their effects on throughput.

OVERVIEW

This study provides guidelines for reconciling disagreements and extending the benefit predictions to additional airports. It provides a rule of thumb for ranking benefits from queuing considerations and for validating the rankings against actual delays. It relates delay to ceiling and visibility data and uses Integrated Terminal Weather System (ITWS) logs to determine the relative importance of hazardous weather delays and runway queuing delays. It examines the correlation of delay between airports and estimates the impact of downstream delay on FAST benefits by using a recently published delay propagation model. It begins with definitions of FAA delay and conventions regarding IMC and VMC. It then examines the statistics of delay in IMC and VMC to calibrate the relationship of between visibility-induced capacity changes and actual airport delay statistics. It also examines the correlation between delays at key airports for both flight delays and schedule delays. It concludes by examining occurrences of hazardous weather in DFW terminal airspace, where strong correlation exists between thunderstorm days and delays.

CODAS DELAY DATA

This paper makes extensive use of data from the FAA's Consolidated Operations and Delay Analysis System (CODAS).[8] CODAS reports two main types of delay: airborne and arrival. Both types of delay are given as averages in units of minutes per arrival. In deriving these averages, CODAS counts early arrivals as zero delay rather than negative delay.

CODAS airborne delay is measured relative to the flight duration predicted at the time of departure. It is the actual flight duration minus the predicted flight duration. Airborne delay does not include departure delays and is relatively independent of interactions between airports. The direct operating cost of airborne delay can be readily calculated. Although some airborne delay can be caused by en route weather and traffic flow problems, normally one of its largest components is the terminal queuing delay that runway capacity improvements from FAST are intended to reduce.

CODAS arrival delay is measured relative to scheduled arrival time. It is the actual arrival time minus the most recent OAG scheduled arrival time. If the flight duration predicted on take-off is the same as the scheduled flight duration, the CODAS arrival delay is the sum of the departure delay and the CODAS airborne delay. Arrival delay averages are always several times larger than airborne delay averages. Because departure delay includes pushback delay, ground hold delay, and taxi-out delay, arrival delay is more difficult to cost objectively than is airborne delay.

The CODAS delay database also includes the meteorological conditions at each airport. CODAS defines Visual Meteorological Conditions as the combination of ceiling and visibility for which visual approaches are allowed. To support visual approaches the ceiling must be 500 ft above the minimum vectoring altitude, which is determined by airport elevation, terrain clearance, and other local factors. Thus CODAS VMC corresponds to "high Visual Flight Rules (VFR)". At Boston (BOS), visual approaches are permitted when the ceiling exceeds 2500ft and the visibility exceeds 5mi. At Dallas Fort Worth Airport (DFW), visual approaches are permitted only for ceilings above 3500ft and visibility greater than 5mi. Lower ceiling and visibility conditions are considered IMC. That is, CODAS IMC corresponds to "low VFR" and below. CODAS weather data come in either 15-minute or hourly summaries. Any hour with one or more 15-minute intervals of IMC is considered to be an IMC hour. In our analysis, any day with one or more IMC hours between 6AM and midnight is considered to be an IMC day.

MODEL RESULTS AND CODAS DATA

Figure 1 compares the 1997 CODAS average annual airborne delay at 10 airports with the LMI model estimates for annual delay that would have been saved in 1997 by FAST and TMA at those airports. Although the general trends of the model data and delay data are similar, the delay savings estimates for the airports are large relative to the corresponding CODAS airborne delays. The estimated delay savings are only slightly less than the CODAS airborne delays for seven of the airports. The estimated savings for DFW and Chicago (ORD) both slightly exceed the CODAS delays. The estimated saving for Los Angeles (LAX) is more than 3 times its CODAS delay.

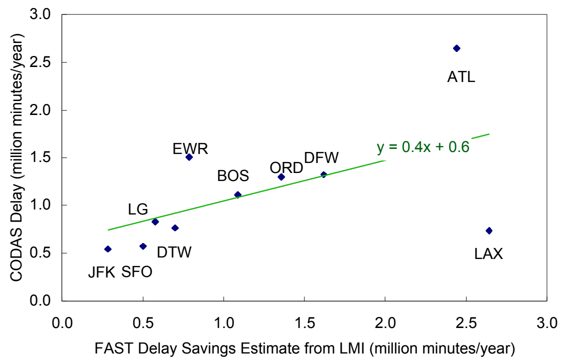

Figure 1. CODAS airborne delay in 1997 vs. LMI estimate of delay savings from FAST.

The results of the Seagull study displayed similar behavior. The delay savings estimated by Seagull for 5 of the airports exceeded their airborne delays, with LAX, LaGuardia (LGA) and ORD savings estimates exceeding CODAS delays by large factors.

Large queuing delay savings may be caused in part by modeling errors since queuing models, being very sensitive to small errors in demand/capacity assumptions, can easily misestimate delays in peak demand periods. However, annual delay improvements cannot logically exceed the actual annual delay. If the flight duration predicted at the time of each departure were an unbiased estimate of the minimum achievable flight duration, and if the CODAS airborne delay for each airport correctly accounted for all flights into that airport, then the measured delay would always exceed any delay savings that might result from a small incremental improvement in runway capacity.

However, CODAS may systematically underestimate airborne delay. If the aircraft operator at takeoff bases the flight duration prediction on the mean historical flight time for that route, rather than the shortest feasible flight time, CODAS will underestimate airborne delay. Underestimation of arrival delay from intentional schedule padding occurs in the same way.

Non-reporting aircraft can also cause CODAS to incorrectly estimate delay. Most CODAS airborne delay values are estimated from automatic reports obtained from the Airline Service Quality Performance (ASQP) System supported by the 10 largest domestic airlines. However, these reports do not account for all the flights into each airport. ASQP does not contain information on small air carrier, commuter, air taxi, general aviation, cargo, military, or international flights. CODAS estimates the delay for non-reporting aircraft from the Enhanced Traffic Management System (ETMS) and from the airlines' Computerized Reservation System (CRS) schedule database.[9]

Although it underestimates delay, CODAS is nevertheless useful for assessing changes in delay, correlating delay between airports, and studying the effects of weather on delay.

A SIMPLE RANKING RULE

Delay trends are important in validating model predictions with delay statistics and in extending model results to additional airports. Steady-state queuing theory tells us that the benefit of a given capacity increase at an airport is proportional to N^2/R, where N is the total traffic count and R is the number of active runways at the airport. This proportionality holds under the assumption that individual runways are loaded to similar values of mean traffic intensity (ratio of demand to capacity) at all airports. This appears to be a reasonable assumption for most major airports.

Figure 2 shows the FAST savings estimates from the LMI model plotted as a function of N^2/R for the 10 airports studied. The LMI benefit predictions are seen to follow the N^2/R trend reasonably closely, thus lending credence to the savings prediction for LAX, in spite of its inconsistency with CODAS airborne delay.

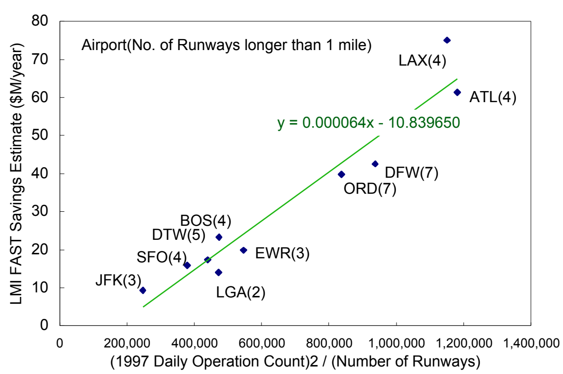

Figure 2. LMI FAST savings estimates vs. (N^2/R).

The trend agreement also allows extension of the LMI results to other airports. We used the rule to provide preliminary benefit estimates for Philadelphia, Charlotte, Denver, Miami, Minneapolis/St. Paul, and St. Louis. The benefits for these six airports ranged from

$11M per year for Denver to $35M per year for Miami. Overall, results indicate that the four largest airports (LAX, ATL, DFW, and ORD) would benefit most from FAST, but if controllers using FAST could indeed have increased runway arrival throughput in 1997 by 4 aircraft per hour at all 16 airports, airline operators would have recovered an estimated $460M in direct operating costs.

IMC DELAY

FAST is intended to help improve airport capacity. Transitions from VMC to IMC cause measurable statistical changes in airport capacity. Therefore, quantifying the relationship between local meteorological conditions and measured delay (i.e., using the transition from IMC to VMC as an analytical surrogate for a capacity increase) can provide baseline comparisons for capacity modeling results.

The FAA's CODAS delay database includes local ceiling, visibility, and wind as well as a meteorological condition indicator that switches from IMC to VMC when visual approaches are allowed at each airport. We used this database to examine the dependence of actual delay data on local meteorological conditions at key airports.

Figure 3 compares CODAS airborne delay on IMC and VMC days at DFW in calendar year 1997. 35% of the days had one or more IMC hours between 6 am and midnight. The top 33 delay days were all IMC days and 38 of the top 40 delay days were IMC days.

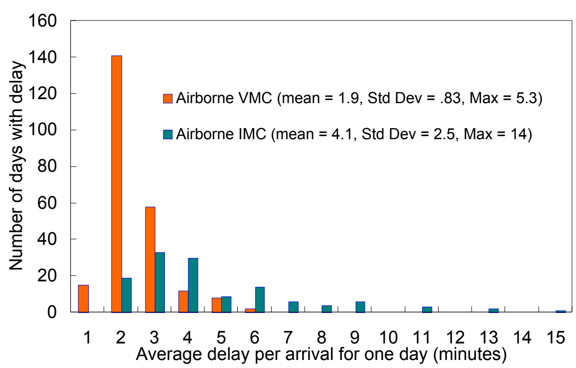

Figure 3. Distribution of CODAS airborne delay on VMC and IMC days - DFW 1997.

On VMC days, the mean was 1.9 minutes of delay per aircraft, the standard deviation was 0.83 minutes per aircraft, and the delay on the worst VMC day averaged 5.3 minutes of delay per aircraft. On IMC days, the means, standard deviations, and peak delays were 2 to 3 times larger than on VMC days. The CODAS arrival delay at DFW in 1997 was 3 to 4 times larger than the airborne delay by all statistical measures, and showed a similar factor of 2-3 increase in IMC.

The tendency for all CODAS arrival and airborne statistics to be 2 times larger in IMC than in VMC appears to be unusual for an airport like DFW. On average, DFW has excess capacity that is not strongly influenced by reduced ceiling and visibility. However, DFW experiences hubbing peaks each day that temporarily exceed even the available VMC runway capacity. During these rushes, a small decrease in either en route or terminal capacity can cause a large increase in delay. In VMC the queues that build up in these brief periods of excess demand are quickly cleared after the demand subsides. It takes longer to clear these queues in IMC. CODAS defines IMC as that combination of ceiling and visibility for which visual approaches are no longer permitted. In 1997 before the new DFW runway became operational, arrival capacity could often be reduced by loss of a diagonal runway, resulting in larger queues during transient arrival rushes and longer residual recovery periods after the rushes subside.

Figure 4 separates the CODAS data into IMC and VMC components for 7 important airports (Atlanta (ATL), DFW, LGA, BOS, Philadelphia (PHL), Newark (EWR), and LAX) with varying operational characteristics. Results similar to DFW were found for all of these airports: on IMC days the means, standard deviations, and peak delays were significantly larger than their values on VMC days.

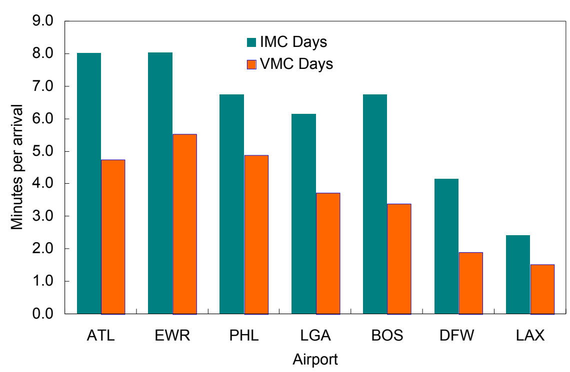

Figure 4. CODAS arrival delay for seven airports on VMC and IMC days – 1997.

The observation that BOS and DFW delays were equally sensitive to IMC is somewhat unexpected. The sensitivity of arrival runway capacity to meteorological conditions differs significantly between these two airports. In some reconfiguration situations, Boston's arrival runway capacity can drop by nearly 50% in

IMC, whereas the biggest IMC arrival runway capacity drop possible at DFW in 1977 was about 33%.

DELAY CORRELATION

The fact that all the airports experience larger delay means and variances on IMC days than on VMC days seems to support the notion of local causality: that is, if we can increase IMC arrival capacity at EWR, we should also reduce delays at EWR. However, CODAS airborne delay is not as local as one might suppose. When we examine the correlation between delays at airport pairs, we find evidence of systematic effects correlating delays over the region for CODAS airborne delays as well as arrival delays. This occurs even on mixed days when one airport experiences some IMC and the other experiences solid VMC. We also see that correlation decreased as the geographical separation between airports increased.

Figure 5 shows the correlation between CODAS arrival delays at EWR and LGA for all days in 1997 for all four combinations of meteorological conditions. The correlation was strong. The correlation between CODAS arrival delays on the days in 1997 in which IMC prevailed at both airports was 0.85. Correlation was equally strong on those few "mixed" days when it was IMC at one airport and VMC at the other. The weakest correlation was for the majority of days when the weather was clear at both airports. Even on these days the correlation was significant and positive at 0.49. Strong correlation between EWR and LGA delays is to be expected. Their traffic is managed by a common TRACON. The airports are close to each other geographically and share common arrival and departure fixes [9]. Because of this physical proximity, weather conditions were also correlated between the two airports: in 1997 there were only 34 days – split 15/19 – in which one airport experienced some IMC and the other experienced solid VMC; there were 121 days when both experienced IMC; and there were 208 days when both experienced solid VMC.

Positive correlation also occurs between CODAS arrival delays at other airport pairs since delays relative to schedule are correlated by the connectivity of the air transport network. What is surprising is that strong positive correlation occurs between CODAS airborne delays at airport pairs, even though those delays are measured relative to planned flight duration rather than scheduled arrival time.

Figure 6 shows the correlation between EWR and PHL for CODAS airborne delays. There was strong correlation even though these were non-schedule-related delays, the distance between the airports is greater, and their air traffic is managed by different facilities.

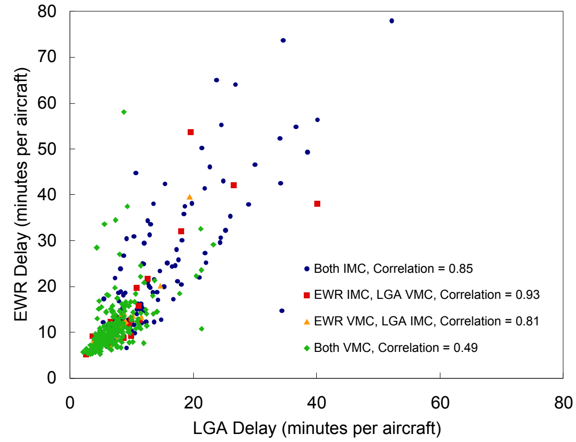

Figure 5. EWR and LGA – daily CODAS arrival delay correlation – 1997 all days.

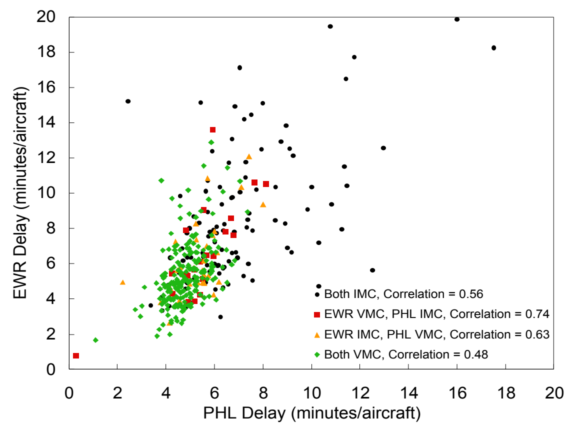

Figure 6. EWR and PHL – daily CODAS airborne delay correlation – 1997 all days.

Figure 7 summarizes the correlation coefficients between selected airports for CODAS airborne and arrival delays for all days in 1997. The correlation generally decreased as the distance between the airport pairs increased.

There was a small positive correlation between delays at PHL and BOS, although most of this correlation was chance on days when it was VMC at both airports and the delay was small. The annual airborne delays were not correlated for widely separated airports. However, the annual arrival delays showed small positive correlation between all of these airport pairs because of downstream schedule impacts on high delay days. For example, the schedule-based arrival delays at DFW and ORD were positively correlated, probably because both airports are major hubs for American Airlines.

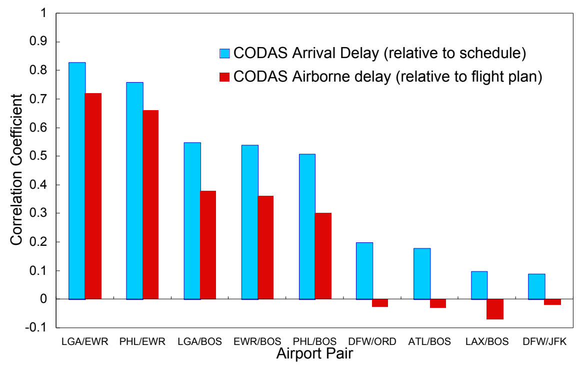

Figure 7. Correlation coefficients for CODAS delay for nine airport pairs - 1997 all days.

DOWNSTREAM DELAY

Downstream delay caused by schedule connectivity can multiply the cost of large delay events. Late arrivals propagate through airline schedules and result in additional downstream delays. This delay multiplication effect multiplies the dollar benefits from reductions in initial delay. We developed an analytical model that allows us to estimate the magnitude of the downstream arrival delay resulting from direct arrival delay at DFW in 1997. The model is based on a published analysis by Beatty et al of empirical downstream schedule delay trees resulting from 500 delayed flights into DFW.[10] That analysis showed that the number of minutes of downstream delay resulting from each initial delayed flight is roughly proportional to the number of minutes that the initial flight was delayed. The relationship of the delay multiplier to the time and duration of the initial delay was modeled in the form DM=1+S*DD, where DM is the delay multiplier, DD is the number of minutes the initial flight was delayed, and the dimensionless delay-time factor S is an empirically derived function, which is greatest when the initial delay occurs at 6 AM. We found from that S decreases approximately linearly as the time of the initial delay increases from 6 AM to 10 PM, as shown in Figure 8.

This delay-time factor can be used to estimate delay multipliers for CODAS daily average arrival delay (which is equivalent to the mean value of DD). At DFW in 1997 these daily averages ranged from about 2 minutes per flight to about 58 minutes per flight and accumulated 3.72 million minutes of initial delay for flights into DFW over the year. We estimated the value of DM for each day resulting from the reported mean of the initial delay DD for that day. The linearity of the factor S and the nearly symmetric time distribution of arrivals at DFW between 6 AM and 10 PM allow us to estimate the downstream delay for each day from the mean value of S (which corresponds to an initial delay occurring at about 1:30 PM). This approximation tells us that, on average, the downstream delay was about 20% of the initial arrival delay at DFW for all days in 1997. This result is shown in Figure 9, which also includes the delay multiplication factors for calm days and storm days.

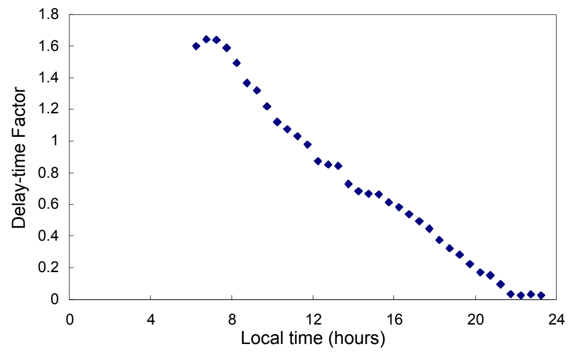

Figure 8. Delay-time factor S as a function of the time of the initial delay.

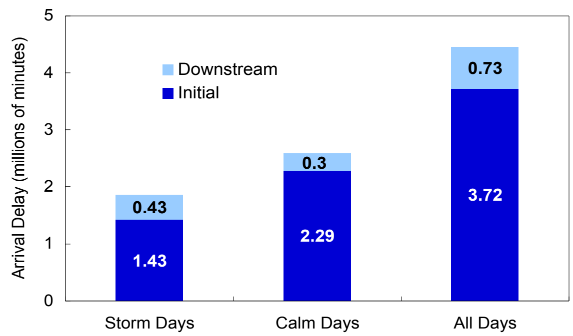

Figure 9. Arrival delay multiplier for days with and without storms at DFW in 1997.

The total cumulative CODAS arrival delay relative to schedule for flights into DFW in 1977 was 1.43 million minutes on thunderstorm days and 2.29 million minutes on days without storms. The result of the downstream delay calculation for days with and without storms is shown as initial plus downstream delay in this stacked column chart. Because storm days had larger initial delay they also had larger downstream delay. Thus, the effective multiplier was about 1.3 for storm days compared to 1.13 for calm days.

HAZARDOUS WEATHER

FAST is currently unable to predict flight trajectories when storms disrupt arrival routes. Thus, thunderstorms reduce the amount of time that FAST can be used. However, such route disruptions are infrequent and the benefit of extra runway capacity increases disproportionately when the storm has passed and controllers must clear out residual storm queues.

To determine the net effect of thunderstorms on FAST benefits it is necessary to quantify the relationship between hazardous weather and delay. We examined hazardous weather delays at DFW in 1997 and at EWR in 1999.[11] Weekly report logs from the Integrated Terminal Weather System (ITWS) at DFW indicate that there were 94 days with thunderstorms within 50 nautical miles of DFW.[12] The DFW TRACON logs show that on about 50 of these days the storms involved enough disruption to air traffic to cause delays. At EWR there were 36 days with thunderstorms within 100 NM of the airport that caused major delays. These numbers are higher than the number of days in which thunderstorms were officially reported at DFW and EWR. Tower personnel report thunderstorms at an airport when they detect lightning or thunder. On average that occurs 45 days a year at DFW and 26 days a year at EWR.

Figure 10 is a plot of the CODAS airborne delay at DFW on the 50 worst delay days in 1997 sorted by delay magnitude. The 14 worst days all had thunderstorm activity. Thirty-four of the 40 worst airborne delay days were thunderstorm days. Large airborne delays are strongly associated with thunderstorms. Yet, in spite of the fact that days with very high delay often experienced thunderstorms, the total annual delay on storm-free days was about 42% larger.

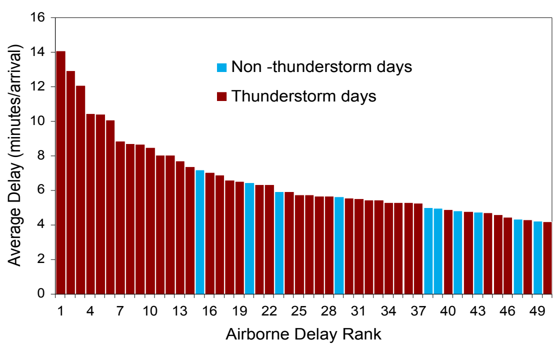

Figure 10. CODAS airborne delay on 50 worst days -DFW 1997.

Figure 11 shows the cumulative 1997 CODAS airborne delay separately for thunderstorm days and all other days at DFW sorted in order of descending airborne delay. We multiplied the average delay on each day by that day's arrival count to obtain the cumulative aircraft delay minutes. The cumulative annual CODAS airborne delay on thunderstorm days was about 415,000 minutes. The cumulative delay on other days was 591,000 minutes. The direct operating cost to airlines at DFW in 1997 can be estimated by multiplying the airborne Delays by the $19/minute estimate obtained from the Seagull and LMI benefit analyses. The results total $11.2M for storm-free days and $7.9M for thunderstorm days.

The large savings for calm days occurred partly because there were more calm days and, to a lesser extent, because there were more arrivals on calm days. The cumulative minutes and dollars for thunderstorm days would be larger if the calculation included nominal delay and dollar equivalents for each cancelled flight. A complete cost accounting for downstream delay increases storm-related costs relative to costs on storm-free days because larger delays cause larger downstream ripple effects. We examine the magnitude of this effect below.

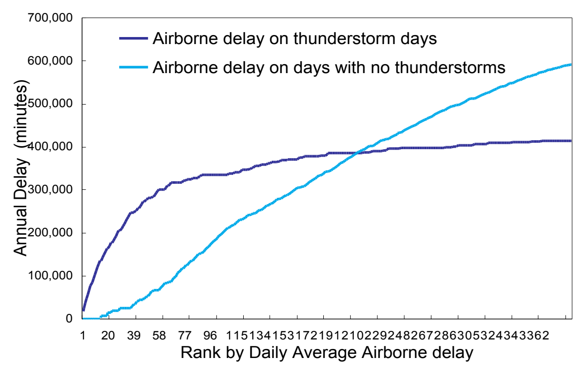

Figure 11. Cumulative CODAS airborne delay on days with and without storms– DFW 1997.

Thunderstorms and IMC are both important contributors to large CODAS airborne delays at DFW. But there are also other sources of delay. Although the predominantly North-South orientation of the DFW runways makes it potentially vulnerable to crosswinds, DFW had only one day in 1997 that was free of IMC and thunderstorm activity but that had CODAS airborne delays greater than the average for an IMC day. On December 9, the delay built up during five hours of 20- to 25-kt crosswinds after 1PM, but a long period of delay in the morning when the winds were below 10 kt also contributed to the high daily delay. Unlike EWR in 1998, where winds alone caused numerous large delay events, DFW in 1997 did not experience significant delay contributions from high winds.

Delays can also be caused by inefficient handling of arrival traffic or by contention for air space and runways in peak arrival periods. We found that days with high average delay at DFW have statistically lower daily arrival counts. (This was seen at EWR also, where the average number of cancellations per thunderstorm or IMC event was more than 26 flights.) An airline does not cancel a flight because the demand it will generate might cause delays. Airlines cancel flights because they anticipate—or are already experiencing—costly disruptions from other causes. Although high peak demand usually increases peak delay, high daily demand is negatively correlated with high daily delay at DFW.

We further analyzed the effect of weather on delay at DFW in 1997 by dividing the days into categories with and without thunderstorms and with and without periods of IMC. We found that solid VMC days with thunderstorms had mean delays almost as small as VMC days without thunderstorms, likely because the storms were far from the airport and good visibility at the airport helped clear any queues that occurred from flow disruptions. Consequently it is not necessary to distinguish between the two types of VMC days.

Figure 12 summarizes the CODAS airborne delay for the whole year for the three main weather combinations. As shown in part a), VMC days had the smallest average CODAS airborne delay (1.9 minutes per arrival). Days with IMC and no thunderstorms averaged 2.9 minutes of delay per arrival. Days with thunderstorms plus IMC averaged 6.1 minutes of delay by per arrival, more than double that of storm-free IMC days.

Part b) shows the number of days at DFW in 1997 that experienced each weather category. 237 days were solid VMC. 79 days had one or more hours of IMC, but no thunderstorm activity within 50 NMI of the airport. And 49 days had one or more hours of IMC plus thunderstorms within 50 NMI of the airport.

Part C gives the resulting cumulative annual delay for each of the three weather conditions. Because the many small VMC delays occurred regularly during daily arrival rushes they contributed 46%, of the annual total. The 79 IMC days without thunderstorms contributed 24% of the annual total. The 49 days that had both thunderstorms and periods of IMC contributed the remaining 30%, which was the second largest cumulative annual delay. These 49 days also included 5 of the 6 ground hold days for flights into DFW in 1997. Part d) of the figure shows the distribution of delays with weather when the downstream arrival delay multipiers of Figure 8 are used to multiply airborne delays. The percentage contribution of storm days increases slightly, but VMC days still predominate.

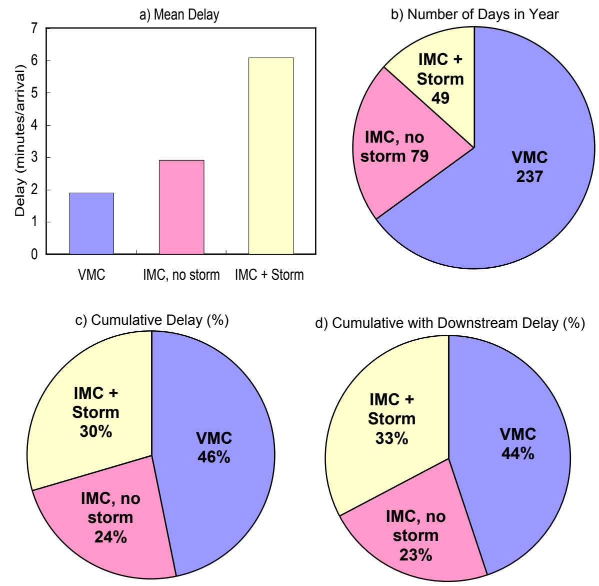

Figure 12. CODAS airborne delay statistics for three weather conditions – DFW 1997.

Conclusions

The overall direct savings estimates of prior simulation studies appear to be both consistent with their underlying capacity predictions and conservative. However, their conclusion that there is potential for a full-time capacity increase of 4 aircraft per hour is critical to their results and should be validated by analysis of operational and radar data for individual airports. FAST benefits will accrue in all weather conditions. However, because en route and terminal airspace congestion causes queuing delay every day during arrival rushes, VMC days will contribute most of the annual delay benefit. Large queuing delays are also caused when thunderstorms and strong winds disrupt routes, and although thunderstorms occur relatively infrequently, they contribute significantly to annual delay. Therefore the ability to clear out storm queues may be an important benefit potential for FAST that was not considered in prior studies. Downstream delay propagation data indicates that accounting for downstream delay can increase FAST benefits by an additional 20%.

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