Weather Forecast Accuracy: Study of Impact on Airport Capacity and Estimation of Avoidable Costs

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Abstract - **It is well known that inclement weather is the single biggest factor causing air traffic delays in the U.S. What is less well understood is what share in this overall adverse impact belongs to weather forecast accuracy. While several en-route convective forecast analyses have been conducted, the role of terminal/surface weather forecast accuracy has not been sufficiently well quantified. The objective of this research is therefore to estimate avoidable delays and costs that can be attributed to terminal weather forecast accuracy. We initially focus on arrival delays and cancellations. The well-established Weather-Impacted Traffic Index (WITI) metric based on actual weather is used as a delay proxy alongside its counterpart, WITI-FA ("Forecast Accuracy") metric based on forecast weather. A nomenclature of various relationships between actual and model-estimated arrival rates is built and arrival rate deficit (difference between scheduled and actually achieved rates) attributable to terminal weather forecast accuracy is computed for each case. This allows us to estimate the avoidable portion of arrival delays and cancellations due to terminal weather forecast inaccuracy, both overall and by specific weather factor. We show that our model is reasonably realistic and apply it to estimating the benefit pool for improving terminal forecast accuracy for OEP35 airports. Total benefits are shown to be at least $330M per year for arrival delays due to terminal weather forecast inaccuracy alone.**

Keywords – *Weather Forecast Accuracy; Airport Capacity; Avoidable Delay; Benefit Pool*

I. INTRODUCTION

A. *Weather Impact on Airport Capacity*

It is a trivial statement that inclement weather can have a profound impact on airport capacity. The U.S. airports are particularly vulnerable to this impact because flight schedules are geared toward Visual Flight Rules (VFR) operation when tighter spacing for arrivals and departures helps to increase airport throughput. The obvious downside is the heightened negative impact on operations when VFR cannot be used. In addition to such ubiquitous weather phenomena as low cloud ceilings and visibility, wind is often a factor in airport capacity degradation. Airports with dependent runways (closely-spaced parallel or crossing runways) are especially sensitive to wind, even when it is not particularly strong but comes from a certain direction and forces an airport into a suboptimal runway configuration. In winter, snow- and ice storms sometimes partially or completely shut down airport operations. In summer, the U.S. experiences frequent bouts of severe convective weather that blocks en-route and/or terminal airspace and results in very high delays.

While delays are the leading National Airspace System (NAS) operational response indicator, other factors such as flight cancellations, diversions and excess miles flown contribute to what is known as the cost of irregular operations. Even in terms of direct operating costs for air carriers, losses from irregular operations run into billions of dollars.

When analyzing impact on airport operations, weather and traffic demand (both the overall traffic volume and as compared to available airport capacity) must be considered together. Bad weather that occurs during night hours when traffic volume is low has relatively little impact; conversely, excessive traffic demand may cause high delays even in perfectly good weather. Inclement weather at an airport with ample spare capacity may not be a factor; inclement weather that significantly impacts a mega-airport with little capacity to spare will have repercussions throughout the NAS.

B. *Variance in Operational Responses*

A trend observed in the course of our research shows that operational responses – such as delays – vary greatly even for similar weather and traffic conditions. Since predictability is a key NAS

performance indicator, this undesirable trend must be studied and ways to reduce the variability of operational response must be sought. Part of the issue may be the current state of the NAS demand-to-capacity ratio: if we treat the NAS as a service model, queuing delay variance increases quickly as traffic demand nears, and at times exceeds, capacity. But the set of factors causing operational response variance is complex: the accuracy of terminal and en-route weather forecast products; airspace design and traffic flow management inefficiencies; over-scheduling by airlines at key-market airports resulting in periods of traffic congestion; airport procedures and constraints; conservatism and risk aversion in operational responses; and so on. The variability in the accuracy of weather forecast is also a factor whose impact can be significant and needs to be studied.

C. Estimating Avoidable Delays and Costs Attributable to Weather Forecast Accuracy

Delays can be notionally divided into avoidable and unavoidable. The latter are directly related to the severity of the weather and the applicable airport and airspace procedures and regulations (for example, minimum required spacing on final approach, maximum allowable crosswind, etc). The avoidable portion of delay is comprised of sub-portions corresponding to the factors mentioned in the previous section. Of these, the accuracy of weather forecast is of particular interest to us. An over-forecast may, and often does, lead to excessive cancellations, ground delay programs and traffic reroutes that, in retrospect, wouldn't have been necessary. An under-forecast may cause last-minute traffic flow management actions as the players scramble to mitigate the unforeseen weather impact. This, too, can lead to unplanned delays and reroutes, and can additionally cause significant ripple effects through the NAS. An added negative effect of dealing with inaccurate weather forecasts is that traffic managers and airline planners err widely on the side of caution. Previous day's strategies may end up being applied to current day's traffic and weather situation, thereby adding to system inefficiencies, i.e. increasing avoidable delays and costs. To be able to estimate this important portion of the avoidable delays and costs (due to weather forecast accuracy) we need to quantify the difference between the impact of actual and forecast weather on airport operations.

D. Research Process

The overall flow of our research process can be summarized as follows:

- Quantify the impact of *actual* (historically recorded) inclement weather, both en-route and terminal, on airport operations;

- Demonstrate how data from weather forecast products can be converted into a format analogous to that of actual weather data, and from that, how the forecast weather impact on airport operations can be quantified;

- Compute the difference ("delta") between actual and forecast weather impact metrics;

- Build a nomenclature of cases of airport weather impact under- and over-forecast. Investigate how flight delays are related to weather forecast accuracy "deltas" for both under- and over-forecast;

- Consider the impact of inaccuracy in the forecast of inclement weather on flight cancellations;

- Develop a method for computing the avoidable portion of delays and cancellations (i.e., costs) attributable to weather forecast inaccuracy;

- From the above, estimate benefit pool, in terms of NAS-wide impact, of improving weather forecast accuracy.

In in this paper we present the results of initial inroads made into tackling this complex task.

II. BACKGROUND

Analysis of avoidable weather delays has been at the center of attention of the JPDO / FAA and their weather-related working groups [1, 2], as well as research conducted by MIT Lincoln Lab [3]. These studies focus on convective weather and its impact on en-route and airport operations. The estimation of potential benefits assumes a perfect forecast and, as a result, a much more precise route planning and ground delay management vis-à-vis projected convective weather. These benefits are estimated to be in the hundreds of millions of dollars annually.

According to the National Center of Atmospheric Research (NCAR), as much as 60 percent of today's delays and cancellations for weather stem from potentially avoidable weather situations [4]; again, this refers mostly to convective weather impacts.

In terms of non-convective terminal weather effects, we found several references to estimated potential benefits of improved weather forecasting. For example, a National Oceanic and Atmospheric Administration (NOAA) report [5] mentions $600M per year as a potential benefit from improved winter weather sensing / forecasting and icing diagnostics at U.S. airports.

A study conducted by NavCanada [6] estimates the benefit of a 100% accurate terminal aerodrome forecast (TAF) at Canadian airports at $12.5M annually as a

conservative number. This would translate into an order-of-magnitude higher potential benefit for the traffic demand levels typical for the U.S. However, this study considered only the impact of inaccurate forecast of Instrument Flight Rules (IFR), i.e., cloud ceiling and visibility, which is primarily associated with the use of alternate airports, carrying extra fuel, and diversion decisions by flight crews.

Surface wind forecast analyses at airports have focused primarily on flight safety and have dealt with phenomena such as low-level wind shear. There are no analyses known to us that have examined the effect of inaccurate wind forecast on airport capacity.

In our research we have focused on the totality of weather impacts on an airport; this includes convective weather impacting arrival and departure routes to/from the airport, as well as terminal weather incorporating precipitation, ceilings and visibility, wind velocity and winter weather. The interplay of these different weather factors is considered and dominant weather impacts, together with the resulting degradation in airport capacity, are determined. We use an airport weather impact model (part of the NAS weather impact model); it is described next.

III. WEATHER IMPACTED TRAFFIC INDEX (WITI) APPLIED TO AN AIRPORT

A. WITI Evolution

A useful method of quantifying air traffic delays, both overall and avoidable, is to employ proxy metrics that would enable "what-if" analyses. One such metric is the Weather Impact Traffic Index, or WITI. This metric was first proposed by the FAA and its initial variants were developed by MITRE [7] and NASA [8]. They focused mostly on en-route convective weather. An enhanced WITI metric was presented in [9]; it reflects both en-route and airport surface weather impacts and includes a drill-down capability for studying individual airports. Further, this metric was extended for use with forecast weather [10] as WITI-FA ("Forecast Accuracy"); thus, the WITI / WITI-FA tandem allows for quantifying the impact of both actual and forecast weather on an air traffic system, be it a single airport or the NAS.

B. Airport WITI metric

The Airport WITI metric is a linear combination of three components [9].

For en-route convective impact calculation ("E-WITI") , we use "flows" – Great Circle tracks between major airports – as "ideal", shortest-path unimpeded flight trajectories; we also use scheduled flight frequencies on these flows scheduled for the day in question. National Convective Weather Detection (NCWD) data is used to populate a hexagonal grid covering the NAS and to calculate how convective weather impacts individual flows between major airports. Intersections of the flows with hexagonal grid cells where convective weather was reported are computed, hour by hour. Each flow's hourly flight frequency is then multiplied by the number of convective reports in all hexagonal cells the flow crosses to get the en-route WITI. Even though aircraft are affected by weather both at the airport and en route, and while en-route delays are a frequent occurrence, the delays "originate" and "eventuate" at airports. According to this principle, en-route weather impact is assigned to major airports in proportion to the distance of a particular area of convective weather from the airport.

To compute the <u>linear portion of the terminal weather impact ("T-WITI")</u>, the WITI Toolset reads the surface weather observations for major airports. Each hourly weather observation is related to the stored hierarchy of weather factors, from most severe to less severe, so that if, for instance, a thunderstorm was reported and also some rain, then rain is not a factor for the given hour. For each of these weather factors, the WITI software stores airport-specific capacity degradation percentages: user-definable parameters whose default values are obtained from FAA capacity benchmarks and from historical data. The Terminal WITI is calculated by taking the capacity degradation percentage for each airport, every hour, and multiplying it by the number of scheduled hourly operations at this airport.

For the third, <u>non-linear WITI component ("Q-WITI")</u> reflecting Airport Queuing Delay, the airport's capacity in a given hour is compared to scheduled demand, separately for departures and arrivals. To determine capacity, all known runway configurations for the airport, sorted from highest to lowest capacity, are checked. If, in a given hour, wind velocity exceeds operational limits for cross- and tailwind for a given runway surface condition (dry/wet), this particular configuration cannot be used and the next one down the list is checked. Several weather phenomena may affect the airport concurrently; the one with most severe impact is identified. The WITI software then finds the best possible runway configuration under the circumstances. The capacity benchmark stored for the succession of runway configurations at an airport during the day is compared to scheduled traffic demand, hour by hour, and queuing delays are computed as demand-versus-capacity balance fluctuates. In addition to terminal weather, cases when an airport is partly blocked by contiguous areas (or lines) of convective

weather are also considered: this is added as another potential factor reducing airport capacity.

IV. WITI-FA ("FORECAST ACCURACY")

A. WITI-FA for En-Route Weather

The method for quantifying the impact of convective forecast has been presented in [10]; a brief summary follows.

We utilize the Collaborative Convective Forecast Product (CCFP) which is widely used in operations. CCFP, a set of 2-, 4- and 6-hour forecasts, consists of a number of polygons; each is characterized by forecast coverage (sparse, medium, solid) and forecast confidence (low, high). Our goal is to compare the forecast weather impact on traffic to actual impact; for that, we need to convert the forecast convective weather product (CCFP) data to quasi-actual (NCWD) format. The CCFP-to-Quasi-NCWD conversion algorithm can be summarized as follows. We collect hourly NCWD data in hexagonal grid cells covering the NAS. We first compute the maximum possible number of NCWD convective reports, $M,$ in a single hexagonal cell in 1-hr period. Then, depending on the coverage and confidence level of a CCFP area that covers this hexagonal cell, we multiply M by the two percentages representing the coverage/confidence levels (e.g., 25% for sparse coverage, 50% for high confidence, etc). This yields the quasi-NCWD score for the hexagonal cell derived from CCFP. The NCWD and quasi-NCWD scores for each hexagonal cell are used for En-Route WITI (E-WITI) computation: the E-WITI based on actual weather and the E-WITI-FA based on forecast weather. Further specifics of quasi-NCWD and convective WITI-FA computation, such as the use of 1-hour intervals and the interpretation of CCFP coverage and confidence intervals, are discussed in [10].

B. WITI-FA for Surface Weather

Just as the E-WITI-FA metric was constructed for the en-route convective weather forecast, the T-WITI-FA metric can be created to quantify the forecast terminal

weather impact on air traffic (in this case, operations at each airport). For actual weather, we use METAR data; for the forecast weather, a natural choice is the Terminal Area Forecast (TAF). Each METAR or TAF dataset creates a forecast "stream" of weather events. In this process, probabilistic forecast information from TAF is converted to quasi-deterministic format identical to METAR format. Each actual hourly weather observation (or forecast) may lead to airport capacity degradation if inclement weather was observed (forecast, respectively). The T-WITI-FA metric is then computed, analogously to T-WITI, as the <u>forecast</u> percent capacity degradation multiplied by the number of scheduled hourly operations at the airport. The process is described in detail in [10].

Once airport capacity estimates from TAFs are obtained, they can be used for computing the third WITI-FA component, Q-WITI-FA. This is analogous to Q-WITI and it estimates queuing delays for airport departures and arrivals based on forecast surface weather.

C. WITI-FA vs. WITI "Delta"

The three WITI components and their WITI-FA counterparts form the complete WITI and WITI-FA metrics. The difference, or "delta", between these metrics can indicate under-forecast (WITI-FA < WITI) or over-forecast (WITI-FA > WITI). The example of the relationship between weather / traffic demand impact (WITI), forecast accuracy (in this case, the sum of *absolute values* of WITI-FA-minus-WITI "deltas" for OEP35 airports) and airport delay as measured in the FAA Aviation System Performance Metrics (ASPM) database, is shown in Figure 1.
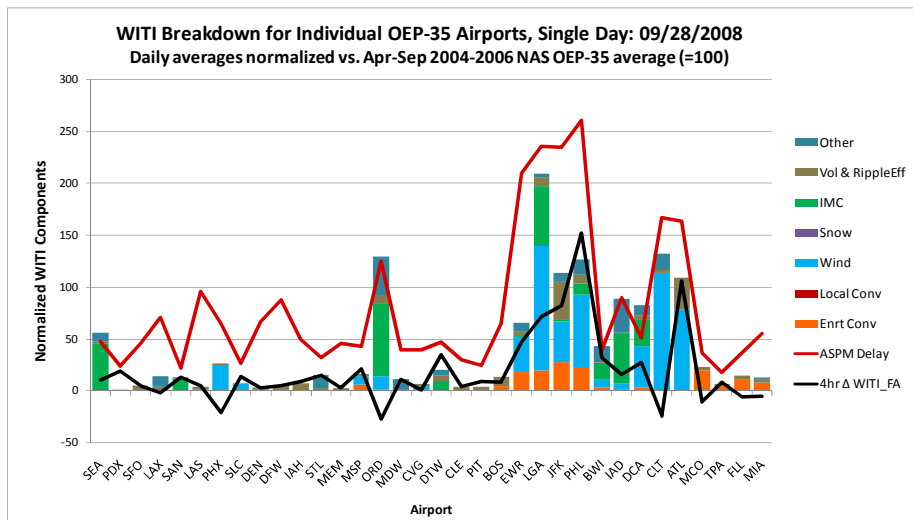

Figure 1. Normalized WITI components, Delay and WITI-FA-minus-WITI "Delta" (negative = under-forecast, positive = over-forecast) for OEP-35 airports, September 28, 2008

September 28, 2008 was a day with significant terminal weather impact in the eastern part of the

U.S, mostly caused by wind, but also some low ceilings. WITI and Delay metrics are normalized to their 2004-2006 OEP-35 averages (the "100" value on the scale shown). For each airport, every hour, seven factors contributing to weather / traffic demand impact are determined; they are shown in Figure 1. The multicolor bars in Figure 1 add up to the airport's average daily WITI. There obviously is a correlation between delays and the accuracy of weather forecast. However, the impact of this accuracy can be masked by the overall impact of inclement weather. We need to separate the two. The methodology for this is discussed next. We will initially focus on arrival rates because in the U.S., they are subject to slot management and because they are more sensitive to tactical (2-6 hour) weather forecast.

V. AVOIDABLE DELAYS AND COSTS

A. Model-Based Forecast and Actual Airport Arrival Rates

On days with significant weather impact and known discrepancies between actual and forecast weather, it is useful to compare airport arrival rates as follows. Four different hourly arrival rates generated by the WITI toolset are compared:

- Scheduled arrival rates from ASPM database

- Actual arrival rates, also from ASPM

- WITI model-generated arrival rates based on METARs (i.e., actual weather data)

- WITI model-generated rates based on TAFs (i.e., forecast weather data).

Two examples illustrate the utility of this method.

The first example shows the four arrival rates for Philadelphia (PHL) airport on September 28, 2008 (Figure 2). This is the same day as shown in Figure 1, with WITI-FA "delta" for PHL being higher than for other airports. PHL was partially impacted by wind. The 4-hour look-ahead TAF indicated significant weather impact in the morning but the actual impact was milder. The TAF then predicted the impact in the early afternoon hours mostly correctly, and airlines
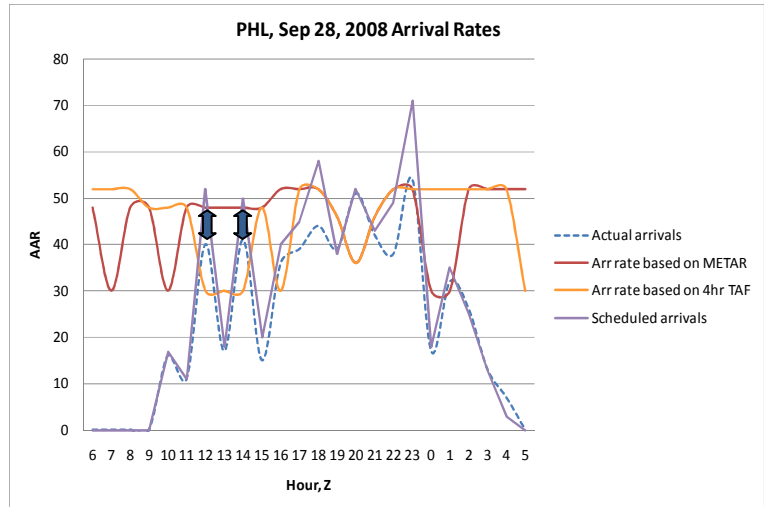

Figure 2. Scheduled, actual and WITI model-computed arrival rates at PHL airport, Sep 28, 2008 (significant impact forecast mostly due to wind). Blue arrows indicate avoidable delays.
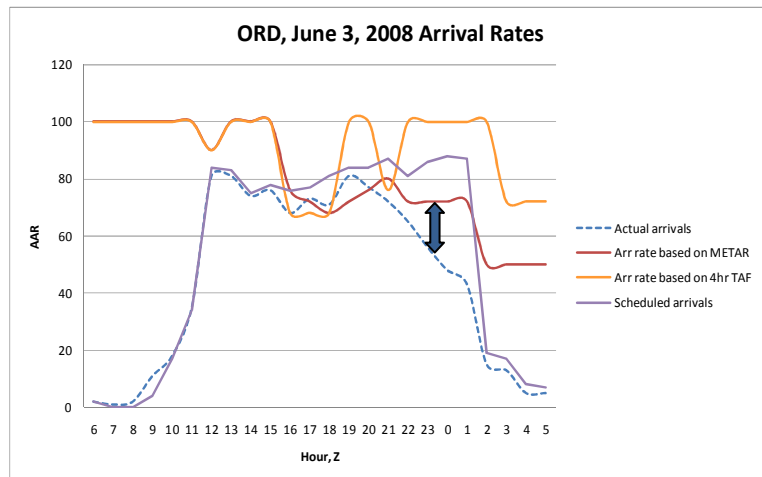

Figure 3. Actual, scheduled and WITI model-based arrival rates at ORD airport, June 3, 2008 (weather: low ceilings)

cancelled some flights in anticipation of this impact (dashed blue line, actual arrivals, is lower than solid blue line, scheduled arrivals).

Analysis of the relationship between the four arrival rates can provide an indication of avoidable delay. In case of an over-forecast as in Fig. 2, the difference between the smaller of scheduled and METAR-indicated rates and the larger of actual and TAF-indicated rates would be the "avoidable arrival rate deficit" related to the avoidable portion of delay. This is denoted by two blue arrows in Fig. 2.

In fact, rather than talking about just delays, we should use the term "avoidable costs" which would include the cost of delays, cancellations, diversions and, in case of convective weather impact, cost of excess miles flown [11].

The second case, ORD on June 3, 2008, reflects a rather complex situation (Figure 3). ORD had very low ceilings through most of the day. Terminal forecast for midday and early afternoon (1600-1800Z) was accurate. Later in the day the forecast called for improved conditions (1900-2000Z). Arrival rates began to increase but the weather did not improve as anticipated. This may have been the reason behind cancelling a significant number of flights (dashed blue line indicating actual arrivals drops steeply compared to solid blue line indicating scheduled arrivals). However, the impact of terminal weather appears to have been milder and an arrival rate of 70-75 could have been achieved. It could be argued that terminal under-forecast may have caused an overreaction and that the difference between actual and METAR-based arrival rates points at an avoidable portion of the impact (in this case, most likely cancellations, not delays), as indicated by an arrow in Figure 3.

B. Nomenclature of "Avoidable Arrival Rate Deficit" Cases

We can identify all meaningful combinations of the different relationships between these four arrival rate variants for both over- and under-forecast cases and develop a method to translate the arrival rate deficit (for over-forecast) or excess (for under-forecast) into avoidable-delay and -cost (cancellation) estimates. There are a total of 24 different possible permutations but only half of them (actual rates being less than scheduled) need to be examined. Of these, cases where METAR-based rates are below all other rates can be discarded because that would indicate that the avoidable (due to weather) portion of delay/cost is zero. Of the remaining cases, six correspond to potential avoidable delays/costs due to over-forecast and three cases deal with under-forecast.

Three examples of arrival rate deficit calculation using a portion of a day in spring 2008 at ORD airport (arrival rates are notional) are shown in Figure 4. Blue arrows indicate total potentially avoidable arrival rate deficit while green arrows indicate potentially avoidable portion of this deficit attributable to weather forecast accuracy. Note that forecast accuracy is considered to be playing a role in arrival rate deficit for both over-forecast and under-forecast cases.

In the first example (an over-forecast, Fig. 4, top), arrival rate deficit calculation (both total deficit and the portion attributable to forecast accuracy) is rather straightforward as indicated by the blue / green arrows.
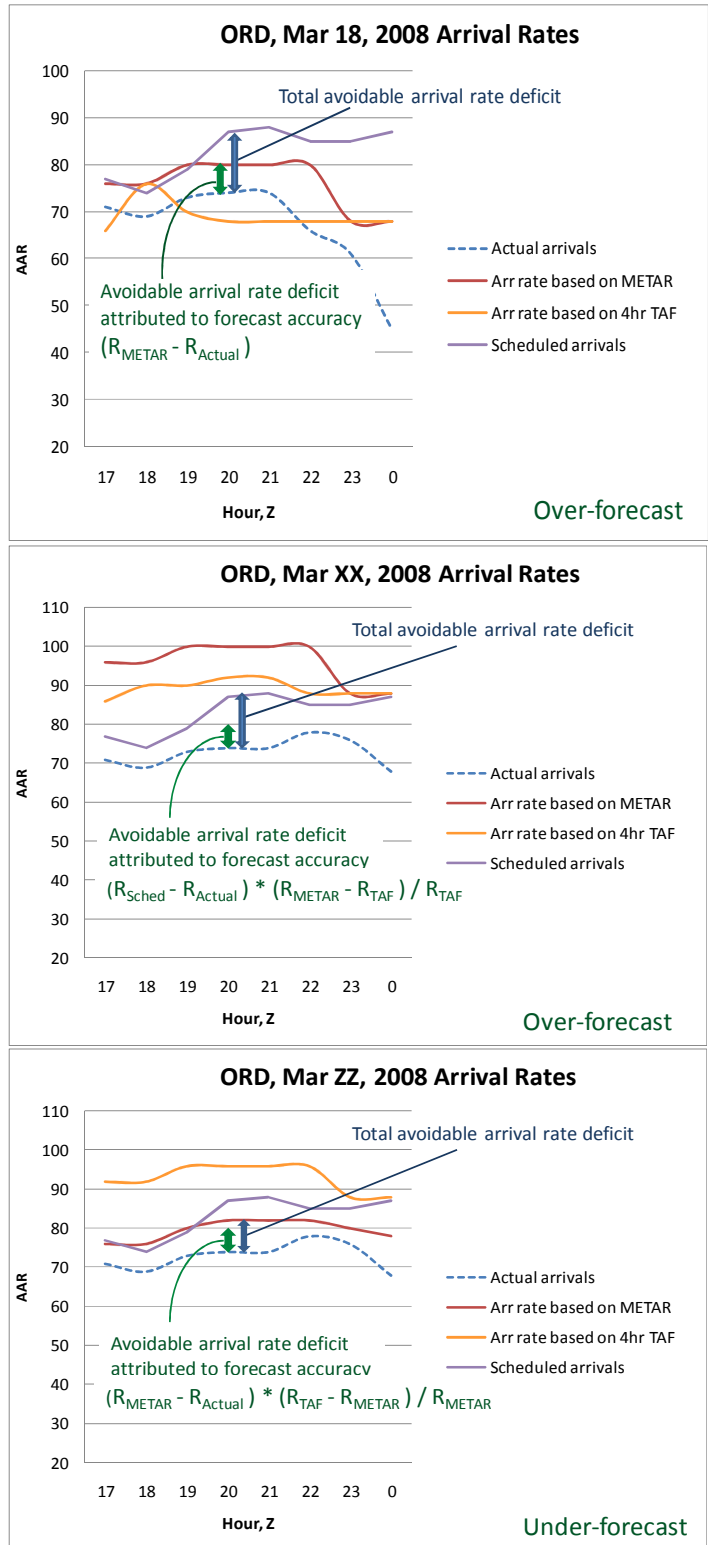

Figure 4. Examples of arrival rate deficit calculation for over-forecast while scheduled arrival rate is higher than model-based (top); over-forecast while scheduled arrival rate is lower than model-based (middle); and for under-forecast (bottom)

Total avoidable arrival rate (R") deficit "D" is:

$$D_{Total} = R_{Scheduled} - R_{Actual}$$

while the portion of that total deficit attributable to terminal weather forecast accuracy ("FA"), is:

$$D_{FA} = R_{METAR} - R_{Actual}$$

Here, we assume that actual arrival rates could not go higher than justified by actual weather (METAR).

In the second example (Fig. 4, middle), scheduled arrival rates are below METAR- and TAF-model based rates. This indicates that in principle, airport capacity should not have depended on weather. But if actual rates are lower than scheduled, we do have a deficit. In case of an over-forecast, as in Fig 4, middle, this may be an over-reaction to the inclement-weather forecast.

Total avoidable arrival rate deficit is, again,

$$D_{Total} = R_{Scheduled} - R_{Actual}$$

while the portion of that total deficit attributable to terminal weather forecast accuracy ("FA") is:

$$D_{FA} = (R_{Scheduled} - R_{Actual}) / (R_{METAR} - R_{TAF}) / R_{TAF}$$

Here, we attribute only a portion of the total arrival rate deficit to forecast accuracy. We use the difference between METAR- and TAF-based rates relative to the entire TAF-based rate ("forecast's relative margin of error") as a multiplier; this is typically in the order of 5% to 10%. In our view, such a model reflects the effect of the weather forecast error on the likely behavior of airport, ATM and airline operators. The wider the relative magnitude of the forecast error, the more likely it is to have an impact on operations.

In case of an under-forecast (Fig. 4, bottom), actual weather was much worse than predicted and the operators' subsequent attitude may have been to reject the forecast: "if it's like this now, it's going to be like this for the rest of the day". Also, in case of snow or low ceilings, this type of under-forecast situation may often lead to early cancellations (not delays) as the leading cause of arrival rate deficit.

Total avoidable arrival rate deficit is now

$$D_{Total} = R_{METAR} - R_{Actual}$$

(rather than $R_{Scheduled} - R_{Actual}$ because actual arrival rates could not go higher than justified by actual weather (METAR)). The portion of that total deficit attributable to terminal weather forecast accuracy ("FA") is:

$$D_{FA} = (R_{METAR} - R_{Actual}) / (R_{TAF} - R_{METAR}) / R_{METAR}$$

In this case, we assume that large forecast errors (in this case, a major under-forecast) relative to the overall magnitude of weather impact would cause more delays and cancellations than a minor under-forecast. We therefore use the difference between METAR- and TAF-based rates relative to the entire METAR-based rate as a multiplier (Fig. 4, bottom).

C. Estimating Avoidable Delays and Cancellations

For each day and every OEP35 airport, the four arrival rates are computed. A simple queuing model is employed based on the arrival rate deficit calculations such as those illustrated in the previous section. Notional arrival queuing delays can then be computed. A current hour's arrival rate deficit (or surplus) is added to (subtracted from) the previous hour's queuing delay; the resulting cumulative queuing delay is set to 0 if it was negative. The underlying assumption is that an arrival rate deficit of 1 during a given hour means one hour arrival delay – clearly a simplification but an acceptable one for a macro-level model such as WITI.

We compute two queuing delays: one is based on the total arrival rate deficit for the airport and the other is based on the arrival rate deficit attributable to weather forecast inaccuracy. The computation uses formulas described in the previous section. We have created a simple model that determines the mix of delays and cancellations; it is based on empirical data suggesting that if delays extend beyond three hours per flight, cancellations are stepped up so as to keep delays at an acceptable maximum level. Therefore, in our model, at a given hour of the day any arrival rate deficit "older" than two hours is split between delays (i.e., contributing to queuing delay accumulation) and cancellations.
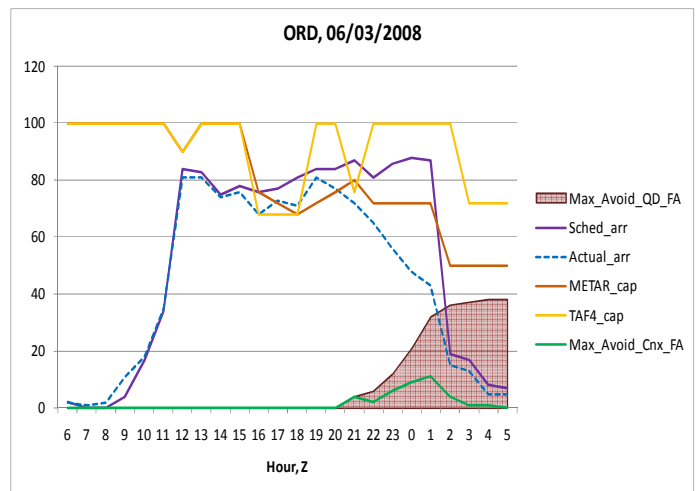

Figure 5. Avoidable delays and cancellations attributable to weather forecast inaccuracy (shaded area, "QD_FA", hours, and green line, "Cnx_FA", number of cancellations), shown alongside the four hourly arrival rates: scheduled, actual, METAR- and 4-hr TAF based.
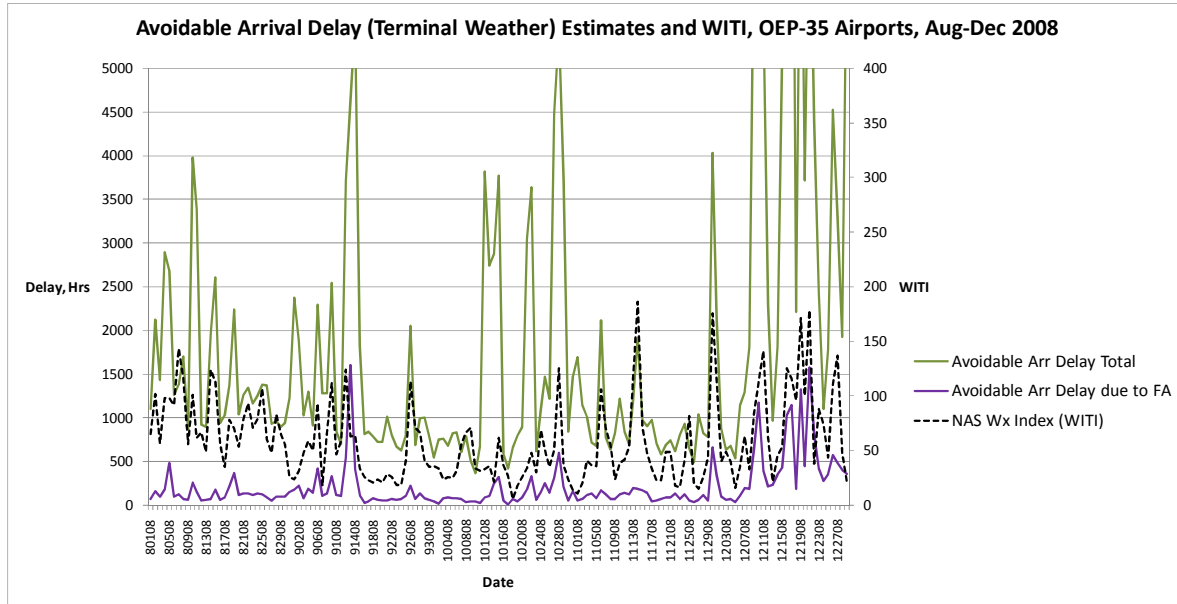
Figure 6. Total and forecast-accuracy related ("FA") maximum avoidable arrival delays, OEP35 arrivals, Apr-Dec 2008 (delay hours / day), as well as the NAS Weather Index (WITI).

An estimate for avoidable cancellations – overall and those attributable to weather forecast inaccuracy – is also computed for each day /airport. It, too, is based on arrival rate deficit but there is no cumulative build-up of cancellations as was the case with queuing delays. As mentioned above, at a given hour of the day a portion of the arrival rate deficit "older" than two hours is counted as cancelled flights.

Figure 5 illustrates the avoidable queuing delays/cancellations computation results for one airport, ORD, on June 3, 2008 (see also Figure 3). Substantial queuing delays accumulate towards the end of the day (a major portion of arrival rate deficit turns into delays); and cancellations peak in the early evening hours and then drop down (a portion of arrival rate deficit turns into cancellations).

Note that the number of cancellations (green line) at, say, 0100Z is significantly lower than the arrival rate deficit; this is because only a portion of that deficit is attributable to weather forecast, as was illustrated in Fig. 4, bottom.

Figure 6 shows a sample of NAS-wide avoidable arrival delay estimates computed for August-December 2008 (NAS is represented by OEP-35 airports). NAS-wide WITI is shown as a dotted line for reference. WITI scale is on the right and delay scale is on the left side of the chart in Fig. 6. The "FA" graph represents the avoidable portion of delays due to forecast accuracy.

D. Benefit Pool of Improved Terminal Weather Forecast Accuracy

The above computations allow us to estimate the benefit pool of improving terminal weather forecast accuracy.

We have assumed a $53/min cost of delay [11] and a $10,000 cost of a cancellation [12]; these numbers reflect only direct operating costs for air carriers.

With these input parameters, Figures 7 and 8 show the resulting totals for avoidable delays due to terminal weather forecast accuracy for all of 2008 as well as their share in the total avoidable delays due to terminal weather.

Max Avoid.QD-FA	
Hours	*81,429*
Cost	$258,944,220
Percent total	12.2%

Figure 7. Results for maximum avoidable queuing delay, all of 2008, OEP35 arrivals

Max Avoid Cnx-FA	
Cancellations	*7,308*
Cost	$73,080,000
Percent total	6.9%

Figure 8. Results for maximum avoidable cancellations, all of 2008, OEP35 arrivals

Avoidable Arrival Queuing Delays Attributable to Terminal Weather Forecast Inaccuracy, OEP-35 Airports, 2008, Percentage by Weather Factor

- Local Thunderstorms
- Wind
- Snow / Winter Precip
- IMC
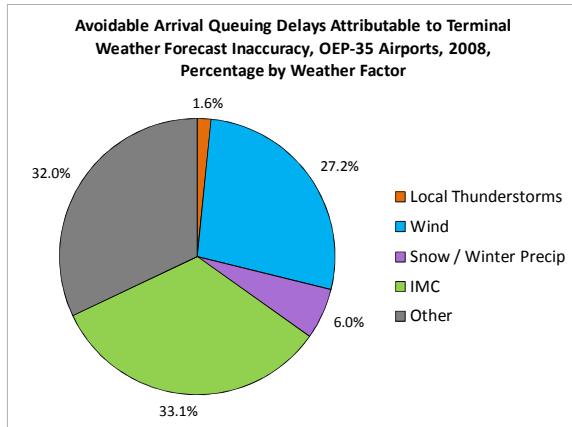- Other

1.6% · 27.2% · 32.0% · 6.0% · 33.1%

Figure 9. Breakdown of avoidable arrival queuing delays attributable to forecast inaccuracy

If we were to develop a similar model for departure rates, departure delays and cancellations, the overall numbers would increase, but not dramatically. An arrival delay, which is basically the difference between scheduled and actual time of arrival, could originate at the departure airport and be registered as a departure delay there; but the total NAS-wide delay for a day, or a year, is not a sum of all arrival and departure delays; it is much less. Also, arrival cancellations in our model are a good approximation for overall flight cancellations.

As a reality check, the number of minutes of our hypothetical total for avoidable arrival delays due to terminal weather in 2008 adds up to about 40,000,000. This can be compared to the actual total number of arrival delay minutes for OEP-35 airports in 2008: approximately 102,000,000 [13], i.e., avoidable portion of arrival delays due to terminal weather is about 40% of total. Our hypothetical total for avoidable arrival cancellations in 2008 adds up to approx. 106,000, compared to 97,000 actual departure cancellations in *fiscal* year 2008 [13] (full calendar year 2008 cancellation data not yet available at the time of completing this paper).

There is currently no historical data available to validate these estimates; but they seem to be within reasonable limits. Potentially-avoidable delay estimates for *convective* weather are higher (up to 60% of total, [1-4]) but terminal weather may be more difficult to predict accurately, including wind direction and gusts, exact cloud ceilings and the amount of snow or ice precipitation at an exact location. Also, even though terminal weather changes continuously, its impact is often <u>discrete</u>: cloud ceilings below airport-specific minimum (boundary between visual and instrument conditions) necessitate different arrival rates than ceilings above that minimum. Tail- or crosswind exceeding a certain threshold may render a particular runway

configuration unusable, which again may drastically change airport arrival rates. An airport cannot react too rapidly to relatively fast changes in winter precipitation or in wind / low-ceilings conditions: there is a great deal of "inertia" in traffic flow readjustments and runway direction changes. This natural inertia explains the overall conservatism of airport ground delay programs. On the other hand, impact of convective weather can in part be mitigated by reroutes, not just ground delays (including "pinpoint" reroutes of individual flights), and the latest generation of short-term convective forecast products brings higher accuracy of the forecast and therefore a potential for greater delay reduction. These considerations may explain why the potentially-avoidable portion of delays due to convective weather may be larger as compared with avoidable delays due to terminal weather.

The percentages of avoidable delays and avoidable cancellations attributable to terminal weather forecast inaccuracy amount to 12.2% and 6.9% of their respective totals. Based on Fig. 7 and 8, the estimated total annual cost of such avoidable delays and cancellations is in the order of $330M for terminal weather forecast and arrivals alone (including the impact of inaccurate convective weather forecast at, or in close proximity of, OEP-35 airports but *excluding* en-route or terminal airspace). This approximate number represents a lower bound of the potential benefit pool for improving surface and terminal weather forecast accuracy. Increasing the number of airports under consideration from OEP-35 to, say, ASPM-75 and adding departure delay costs could bring this number closer to perhaps $400-450M per year. It is worth pointing out that all the above estimates are for direct operating costs of scheduled air carriers only; adding costs to other segments of aviation industry, as well as passenger costs, would further increase the potential benefit pool estimate.

We have also computed the share of each significant terminal weather factor in the overall total. When the WITI software registers an avoidable arrival queuing delay attributable to terminal weather forecast inaccuracy, it records the dominant weather factor (the "greater" of relevant METAR or TAF). The approximate breakdown for 2008 is shown in Figure 9.

Inaccurate forecast of IMC (low ceilings/visibility, heavy rain) is the largest contributor, followed by significant wind (speed or gusts > 15 Kt) and winter precipitation. The "Other" category includes minor weather impacts such as wind below 15 Kt (causing airports to use less-than-optimal runway configurations), light rain or drizzle, etc.

VI. CONCLUSIONS

Using the WITI metric extended to quantify the impact of forecast weather on the NAS, as well as the combination of actual and model-based arrival rates for OEP35 airports under a wide variety of weather conditions, we have been able to estimate the avoidable arrival delays attributable to terminal weather forecast. Our estimates, while based on a high-level airport model in WITI software tool, do pass a reality check. We have demonstrated a method to estimate not only the upper bound of all avoidable delays but also the portion of avoidable arrival delay attributable to terminal weather forecast inaccuracy and break it down by specific weather factor. The computed annual cost of avoidable arrival delays related to terminal weather forecast is in the order of $330M. This number provides a reasonable initial estimate for the benefit pool of improving terminal weather forecast accuracy.

ACKNOWLEDGEMENTS

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