Project Report
ATC-291

Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems

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ABSTRACT

Adverse weather accounts for the bulk of the aviation delays at the major New York City airports. In this report, we quantify:

1. Aviation delay reduction with an Integrated Terminal Weather System (ITWS) that incorporates the 30-60 minute predictions of convective storms generated by the Terminal Convective Weather Forecast (TCWF) algorithm,
2. Principal causes of aviation delays with the ITWS in operation, and
3. The extent to which the current delays are "avoidable."

We find that improved decision making by the New York FAA users of ITWS provides an annual delay reduction of over 49,000 hours per year with a monetary value of over $150,000,000 per year.

Convective weather was found to be the leading contributor to delays at Newark International Airport (EWR) between September 1998 and August 2000. It was found that 40% of the arrival delay in this study occurred in association with delay days characterized by convective weather both within and at considerable distances from the New York terminal area. Of the remaining delay, 27% occurred on days characterized by low ceiling/visibility conditions, while 16% occurred on fair weather days with high surface winds.

We also concluded that many of the delays which occur with the current ITWS, over $1,500,000 in one case, could be avoided if the ITWS were extended to provide:

1. Predictions of thunderstorm decay, and
2. Predictions of the onset and ending of capacity limiting events such as low ceilings or high surface winds.

These delay causality results are very important for studies of the effectiveness of changes made to the U.S. aviation system to reduce delays at airports such as Newark as well as for prioritizing FAA research and development expenditures.

ACKNOWLEDGMENTS

Several people have provided valuable insight and contributed significantly to the results in this paper. The authors thank Leo Prusak, head of EWR Tower, for many animated discussions on air traffic control procedures and changing traffic conditions that complicate the quantification of benefits at EWR. He also provided key data on thunderstorm events that helped formulate some of the numerical benefit results.

Jimmy Coshignano and Tom White, traffic managers at the New York TRACON, who were very patient and a tremendous help as we debriefed them on the benefits of ITWS/TCWF to the TRACON. Ronnie Reagan, traffic management officer at the New York TRACON, also provided a candid critique of the operational usage models we developed as well as reviewed in detail the final benefit numbers in this report.

Gary Paul and Jim Sunderland of MCR Inc., provided an in depth critique and advice on much of the methodology employed in this paper. They also kindly provided data from their independent visits to the TRACON to quantify the TCWF delay reduction benefits at New York and we thank them for that. Their discussions with us greatly improved the results provided in this report.

Julio Pereira of the Port Authority of New York and New Jersey also reviewed this paper and helped us obtain accurate data on passenger statistics at the New York airports. We greatly appreciate his help.

We also thank Dale Rhoda of MIT Lincoln Laboratory for a detailed review of this report and continued support of the delay analysis project.

The studies report here are a part of the New York terminal aviation weather research program funded by the Port Authority of New York and New Jersey. In addition to the people mentioned above, we are very appreciative of the support for this innovative program from Tom Bosco of the Port Authority, Carmine Gallo and Mike Sammartino of the FAA Eastern Region, and Glenn Morse and Les Parson of Continental Airlines.

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1. INTRODUCTION

This is an initial report on the ongoing study of:

1. Benefits realized from New York's Integrated Terminal Weather System (ITWS) demonstration system, and
2. Additional delay reduction possibilities if the demonstration system were upgraded to provide improved weather prediction capabilities and/or coverage.

The ITWS demonstration system was introduced in New York in the fall of 1998 through an innovative partnership between the Port Authority of New York and New Jersey, the FAA, and MIT Lincoln Laboratory.[1] A principal objective of this program is to reduce aircraft delays at airports that consistently rank among the highest of all airports in the United States in terms of percentage of flights delayed. In the late summer of 1999, the initial ITWS capability was extended to include 30-60 minute predictions of convective storms generated by the Terminal Convective Weather Forecast (TCWF) algorithm.

Two representative examples of initial operational capability (IOC) ITWS delay reduction are discussed. One key benefit is improved traffic management decision making during convective weather. Traffic managers were able to reduce airport gridlock by releasing several additional departures each hour by properly timing the arrival and impact of lines of convective weather. In the second example, terminal wind information is used to correctly set arrival rates and merge/sequence aircraft during a time of strong vertical wind shear. New York winters are especially vulnerable to vertical wind shear (Cole et al., 2000), so accurate knowledge of terminal winds is critical for traffic managers.

An in-depth study of these two cases using an MIT-developed queuing model shows that nearly $2,000,000 was saved at Newark International Airport (EWR) through the use of ITWS during the convective weather event. It also reveals that use of the terminal wind product led to savings of at least $150,000 on the strong vertical wind shear day.

The overall annual delay reduction at New York using the combination of ITWS and TCWF were quantified using the FAA operational user interview/delay modeling approach that has been used previous for the FAA studies of ITWS and TCWF delay reduction. This analysis showed that the improved decision making by the FAA air traffic personnel at the NY TRACON and towers using ITWS and TCWF is providing delay reduction of over 49,000 hours per year (primary delay reductions of over 27,000 hours; downstream passenger delay reductions of an additional 22,000 hours), with a total monetary value (using standard FAA values for airline direct operating costs and passenger time costs) of over $150,000,000 per year.

To assess the direction of current and future research to alleviate delay in New York, principal weather phenomena leading to delays at EWR are identified and their relative contributions quantified. The Atlantic coastal environment in the Northeast features weather types that were relatively rare at the other ITWS demonstration sites in Memphis, Orlando, and Dallas. At EWR, it is found that convective weather yields the greatest delay on a per-event basis, but that large delays also occur during other weather events (e.g. low ceilings, high surface winds) where the effective airport capacity is reduced.

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[1] The New York ITWS was developed by MIT Lincoln Laboratory under a Cooperative Research and Development Agreement (CRDA) with the Port Authority. The FAA and the Port Authority have a Memorandum of Understanding by which the FAA permits the Port Authority/Lincoln Laboratory to access the FAA weather sensors and provide displays at the FAA facilities.

We also report the preliminary results of investigating how much of the delay that occurs with the IOC ITWS is avoidable. Case study analyses are presented to show that a substantial amount of delay—over $1,500,000 in one case—could be avoided if the ITWS provided storm decay predictions. In the studied case, convection suddenly decayed near New York, leading to a long period where delay could have been avoided had traffic flow management anticipated improving conditions.

Results show that substantial economic saving (approximately $480,000 per event) could also be realized if ITWS had prediction products that aided in the correct timing of the onset and ending of capacity-limiting events such as low ceilings or high surface winds. Future research efforts should also investigate the impact of improved en route weather prediction capabilities given the high percentage of delay at EWR that arises due to convective weather west and south of the New York airspace.

The remainder of the report proceeds as follows. Section 2 will provide background on the New York ITWS and the delay assessment models used to generate the quantitative benefits results. Section 3 presents two cases where the ITWS provided substantial delay reduction benefits in 1999. In section 4, we discuss how the annual delay reduction using ITWS and TCWF were estimated using the FAA operational user interview/delay modeling approach that has been successfully used in previous FAA studies of ITWS delay reduction. Section 5 looks at the principal causes of delays at EWR with ITWS in operation during 1998-2000. Section 6 presents some of our preliminary results on delays that occur with the current ITWS capabilities that might be avoided with more advanced weather prediction capabilities. Finally, Section 7 summarizes our major results and makes recommendations for follow on studies.

2. BACKGROUND

2.1 New York ITWS Demonstration System Features

Under a Cooperative Research and Development Agreement (CRDA) with the Port Authority of New York and New Jersey, Lincoln Laboratory developed and provides experimental operations support for the functional demonstration ITWS as a part of a research program to improve the safety and efficiency of operations at the NYC airports. Emphasis is placed on analyzing and improving the performance of ITWS algorithms in the Northeast coastal environment (Allan et al., 1999), while at the same time addressing issues associated with ITWS usage in a large, congested airspace such as New York.

The New York ITWS ingests data from a variety of radars, including five ASR-9s, two National Weather Service NEXRADs, and one Terminal Doppler Weather Radar (TDWR) (Figure 1).

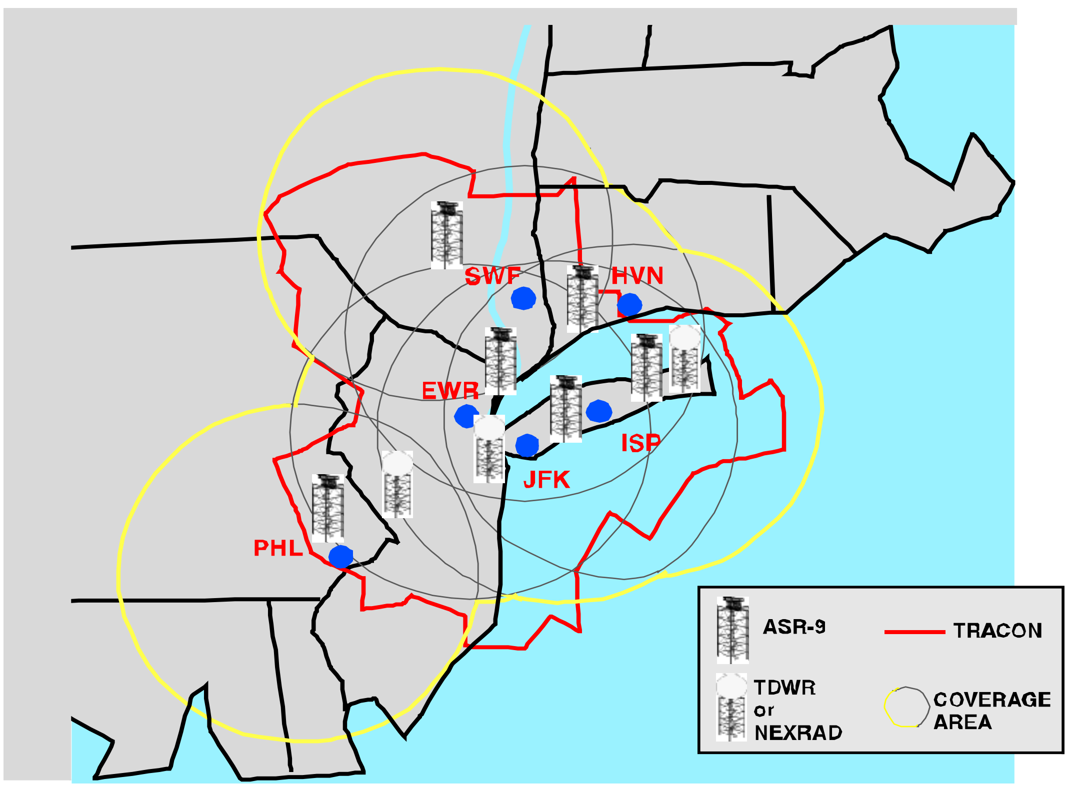

Figure 1. Locations of sensors used in the New York ITWS.

It is also envisioned that a TDWR serving Kennedy International Airport (JFK) and LaGuardia Airport (LGA) will become available in the summer of 2001 and, that the State College, PA NEXRAD will be used to extend coverage to the west of the TRACON. Other sources of data (Table 1) include the Rapid Update Cycle weather forecasting model, aircraft reports (MDCRS), surface METAR observations, LLWAS surface wind observations, and the National Lightning Detection Network (NLDN).

Table 1
ITWS Product Update Rates and Technical Performance

Product	Data Sources	Product Update Interval (min.)	Product Spatial Resolution (nm)	Typical Performance
Microburst detection	TDWR[1]	1	0.1	$P_d > 0.95$, $P_{fa} < 0.05$
Microburst prediction	TDWR, MDCRS, Soundings, ASOS	2.5	---	$P_d \approx 0.3$ $P_{fa} < 0.1$
Gust Front detection	TDWR[1]	5	0.1	$P_d \approx 0.8$, $P_{fa} \approx 0.1$
Gust Front current location	TDWR	1	0.1	----- -----
Gust Front 10- and 20-min. predictions	TDWR	1	0.1	20 min. prediction within ± 1.4 nm 80% of time for wind shifts > 15 knots
Wind Shift	TDWR, LLWAS	5	---	Wind to within ± 8 knots, ± 30° 60% of time for wind shifts > 15 knots[4]
Airport precipitation	TDWR	1	0.5	----- -----
TRACON precipitation	ASR9 mosaic[2]	1	0.5	----- -----
Long Range precipitation (100 and 200 nm)	NEXRAD	6	1, 2	----- -----
Storm Motion	Precip. source	5 – 6	---	Within 10 knots for 90% of storms moving faster than 10 knots
Storm Extrapolated Position (SEP)	Precip. source	1, 6[3]	0.5	Within 1 nm 85% of time for 10 min. SEP and 65% of time for 20 min. SEP
Storm Cell information (hail, severe storm, echo tops, lightning)	NLDN, NEXRAD	5	---	-----
Terminal Winds	TDWR, NEXRAD, MDCRS, RUC	5	1	-----
Tornado Vortex Signature	NEXRAD	6	0.5	
Ribbon display alerts and active runways	TDWR	1	---	-----
Lightning within 20 nm of airport	NLDN	5	0.5	NLDN detects 80-90% of cloud-to-ground lightning[5]

1 At LLWAS expanded network (NE) airports, TDWR derived alerts are integrated with LLWAS NE alerts.
2 ASR reflectivity is quality checked against TDWR and NEXRAD data.
3 Update interval is that of precipitation product.
4 Performance requirement for accuracy of predicted wind shift
5 Cummins, et al., 1998 and Idone, et al., 1998

Performance results from (Klingle-Wilson, 1995) unless otherwise noted.

NLDN = National Lightning Detection Network
RUC = NWS Rapid Update Cycle gridded winds
MDCRS = Meteorological Data Collection and Reporting System

These data are combined into a single integrated, interactive terminal weather graphics display. The rapid 30-second update rate of the ASR-9s, combined with both safety products, terminal winds, and short-term predictions of convective motion create a powerful traffic planning tool for traffic managers using the ITWS. One of the key benefits is shared situational awareness—traffic managers from the National Air Traffic Control System Command Center (ATCSCC) to the Boston Air Route Traffic Control Center (ZBW ARTCC) have access to the same accurate weather information (Figure 2). As well, most of the commercial airlines have either dedicated Situation Displays or Internet access to ITWS (Table 2), and have used the system to great advantage (Maloney, 2000).

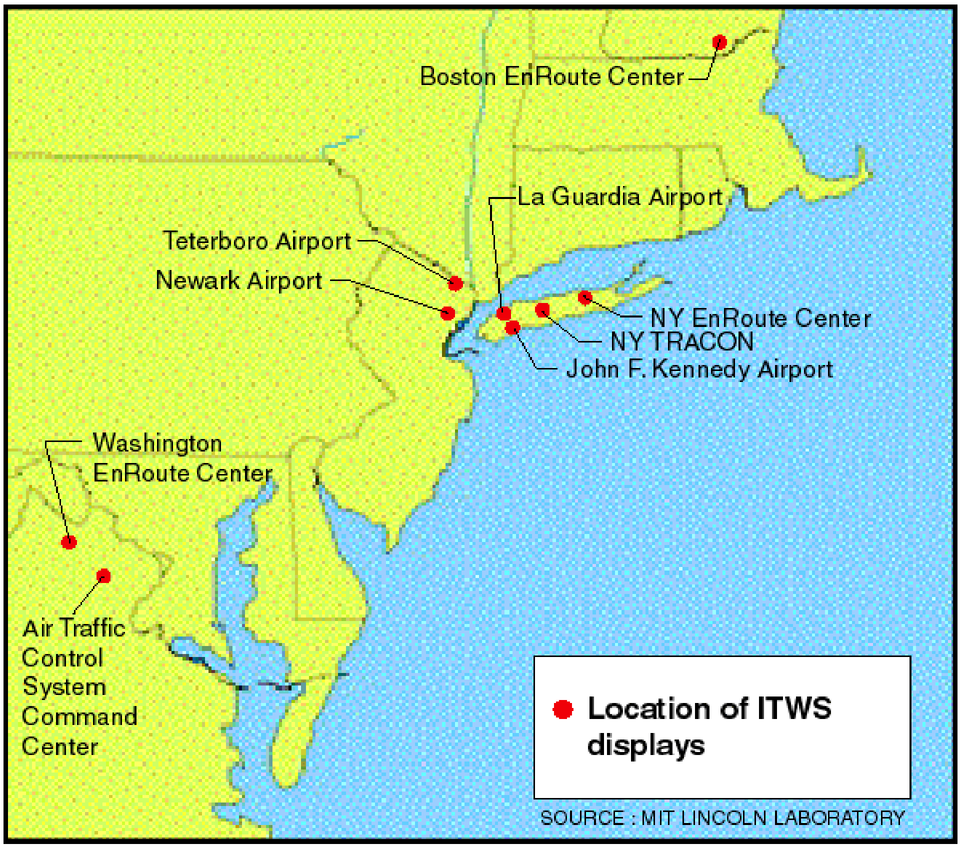

Figure 2. Locations of the operational FAA users.

Table 2
List of Airlines with Access to New York ITWS Information

Airlines with both Situation Display and Internet access	Airlines with Internet access to ITWS/TCWF
Continental	American
Delta	Federal Express
Northwest	Southwest
United	United Parcel Service
	US Airways

Figure 3 is a representative image from the New York ITWS Situation Display, as a strong squall line had just reached EWR. There are three images of the weather shown in three windows. The largest window and lower right window show a precipitation mosaic of five ASR-9 radars that updates every 30 seconds. Light blue lines indicate the leading edge of VIP level 3 (i.e., 41 dBZ) echoes, and traffic managers can use the dashed light blue lines to tell where they will be in 10 and 20 minutes. Since the ASR-9 mosaic updates every 30 seconds, reroutes of aircraft around level 3 or greater weather can be planned with great accuracy.

The red circle in the center of the lower right window shows that a 40-kt microburst is occurring just east of runway 29. This can be used to alert pilots of imminent danger in that location.

Just ahead of the storms over EWR is a purple line. This is a detection of a strong gust front, with winds gusting to nearly 50 kts. The dashed purple lines are the 10 and 20-minute forecast positions of this gust front. They show that the winds will be shifting at JFK and LGA in approximately 20 minutes. The purple vector indicates that 10 minutes after frontal passage, winds are expected to be from the west at 15 kts. This information can be used to plan necessary (or avoid unnecessary) runway reconfigurations at those airports, as the 10 minute lag time allows managers to deduce whether a wind shift will persist or not.

At the top right of Figure 3 there are three yellow panels. These indicate that there is cloud-to-ground lightning within 20 nm of EWR, LGA, and JFK. Just to the left of these panels is a white panel that says "WSA 20." This indicates that a wind shear has just occurred over an EWR Area Noted for Attention (ARENA), and that the report should be relayed to pilots for the next 20 minutes, as required by FAA regulations. The number will automatically decrement over the required 20 minute notification period.

The upper right window shows a 200 nm view of the weather surrounding EWR. This is based on the NEXRAD radar in Fort Dix, NJ, and updates every 5-6 minutes (after every volume scan) during convective events. Traffic planners can use this window to obtain the "big" picture, and anticipate if weather farther to the west or south will impact them later in the day.

Although it is not shown, traffic managers can also click on any of the storm cells in these images, and find out the cell top height in a storm cell information box. This same box will tell them if there is lightning, hail, or severe storm circulation in the cell. Using this information, a traffic manager may determine that a plane is unable to fly over that storm, and may want to give it a wide berth if it contains hail or severe storm circulation.

Another important planning tool is the recently introduced Terminal Convective Weather Forecast Product (TCWF) which commenced operational usage at the NY ITWS site in August 1999.[2] Current weather is tracked (Figure 4) using a sophisticated separation-of-scales technique which tracks the line motion of storms, as opposed to individual cells which may grow and decay on very short time scales (Wolfson, et al., 1999). TCWF produces forecasts of medium and high probability areas of VIP level 3 or greater weather out to 60 minutes. The performance of TCWF is scored in real-time, and made available to users to give an indication of the reliability of the product forecasts at 30 minutes and 60 minutes in the future.

[2] The TCWF is a candidate enhancement to the initial capability ITWS.

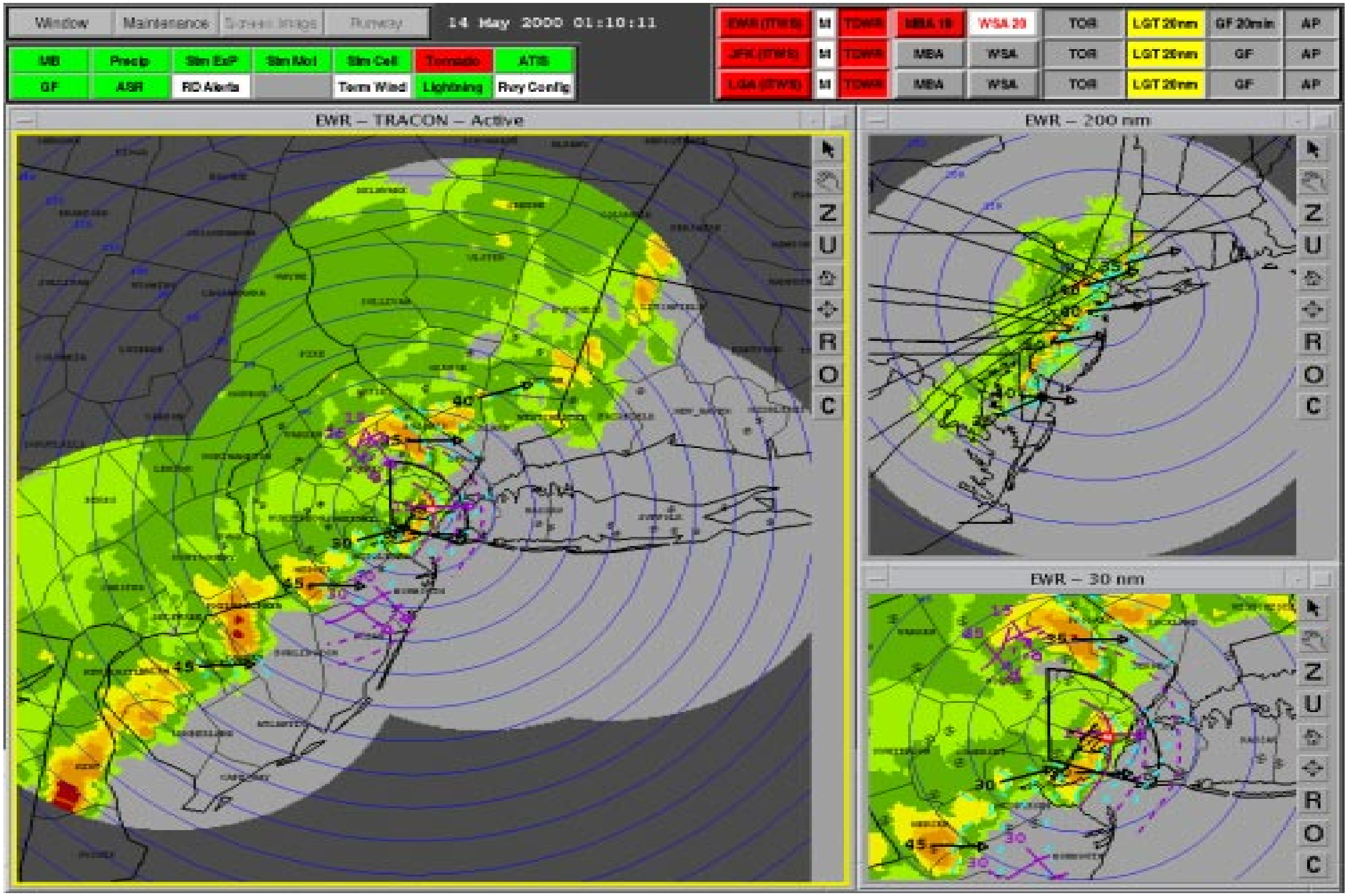

Figure 3. New York ITWS Situation Display. ASR-9 mosaic shown in left and lower right windows; 200 nm NEXRAD image shown in upper right window; precipitation shown as standard 6-level VIP. Black vectors indicate storm motion; light blue (purple) lines indicate the leading edge of level 3 returns (gust fronts); dashed lines indicate the forecast position of the feature 10 and 20 minutes into the future; purple vectors indicate the forecast wind direction 10 minutes after frontal passage. A microburst is noted by the solid red circle in the lower right image.

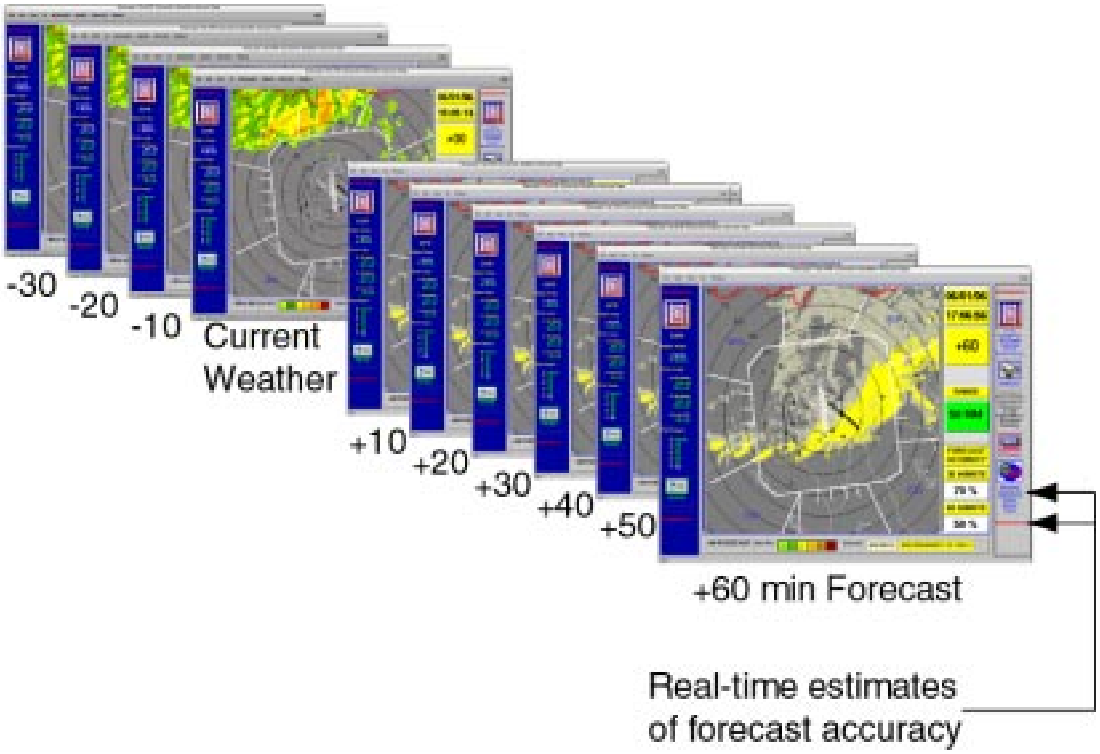

Figure 4. Prototype display concept for Terminal Convective Weather Forecast. The shaded yellow (solid yellow) areas in the +10 to +60 minute forecast windows indicate moderate (high) probability of VIP level 3 or greater weather. The continuous forecast loops from the past 30 minutes to the forecast time (30 or 60 min in the future). Forecast accuracy is continually updated and displayed in real time.

The New York demonstration ITWS is scheduled to be replaced by the production initial operational capability (IOC) ITWS in 2002. Since the TCWF has demonstrated significant benefit it will be included in this deployment.

2.2 Approach to Assessing Delay Reduction

The objective of this study was to determine:

- The delay reduction benefits that have been achieved with the current combination of ITWS and TCWF at New York
- The extent to which the delay that occurs with the current ITWS/TCWF could be reduced with an enhanced terminal weather information system

There are two basic approaches to determining the achieved delay reduction benefits. "Direct" measurement can be used, in which one compares the delays in a "baseline" time period when ITWS/TCWF were not in use to a subsequent time period in which ITWS/TCWF were in use. Alternatively, an FAA operational user interview/delay modeling approach can be used, in which user interviews and/or direct observations of decisions made are used to determine the parameters of models that are then used to estimate the delay reduction benefits. The basic assumption is that the weather product is useful only to the extent that it changes user decisions. Thus, one can analyze the various decisions that the users have stated were improved as a result of having access to the weather decision support system under study.

Both of these approaches have been attempted for various past analyses. The pros and cons of the two approaches are shown in Table 3. The Laboratory experience has been that the "direct" method is very hard to carry out in practice even though it appears quite straightforward. Rather, all of the previous analyses of ITWS delay reduction benefits and certain other terminal weather decision support systems (e.g., the TDWR and the ASR-9 Weather System Processor) have proceeded by the modeling approach which was used here.

Table 3
Pros and Cons of Delay Reduction Determination Methodologies

	"Direct" Method	FAA Operational User Interview/ Delay Modeling Method
Good features	Easy to explain to recipients of a report	Factors which account for delay reduction are clearly understood Extrapolation to changed circumstances (e.g., operations increases, schedule changes, weather time and duration) is relatively straightforward Only feasible way to assess potential improvement
Problems	Requires very sophisticated knowledge of delay causality to compensate for differences between the "baseline" and "in use" time periods. Factors that must be quantitatively considered are: Weather (severity, time of day, duration) Weather in other locations Traffic changes Airline operations and scheduling Air traffic procedures Traffic flow management changes Not clear which elements of the system account for the delay reduction	May be difficult to validate the approach in some cases Need to make sure that factors considered are independent or that common elements are identified and the impact addressed (e.g., one must make sure one is not counting a factor several times by giving it different names)

First, we determined an initial set of user decisions that were expected to provide significant benefits based on:

- Previous TDWR user interviews by the Volpe Transportation Center for the ITWS benefits assessment in 1994-95 at Memphis, Orlando and Dallas
- Previous discussions with NY ITWS users
- Other ongoing delay reduction analyses (particularly a set of interviews conducted by MCR, Inc. under sponsorship of the FAA to assess the value of TCWF above and beyond ITWS)

Next, New York TRACON ITWS/TCWF users were interviewed to determine the parameters associated with the various improved decision making categories (e.g., number of planes that might have shorter routes, number of additional planes departing per hour, duration of benefit, number of times a benefit typically occurs per day with convective activity, etc). These operational users modified and extended the set of user decisions to be evaluated.

An extremely important result of this process was the realization that the New York terminal area operations during convective weather are very different from the operations at Memphis, Orlando and Dallas. Hence, a number of the delay reduction benefits assessed in this study are new and should be of great interest to researchers of the aviation system.

After the interviews, two basic models were used to translate the results into quantitative estimates of the delay reduction benefits. These are described below.

2.2.1 "Linear" Delay Reduction

The first model corresponds to a transient event (e.g., a group of aircraft must fly a longer route) where there is no reduction in the overall average rate of aircraft movement. Figure 5 illustrates this for the case of a thunderstorm impacting an entry gate into a terminal area. Other examples of this include: altitude changes to avoid clear air turbulence, avoiding missed approaches due to worse visibility conditions than expected, extra taxiing on the airport surface due to a runway change at a lightly loaded airport, and the use of inefficient descent trajectories due to air traffic procedures. A key element of this type of delay is that the benefit for improved performance is typically linear in each of the pertinent variables (e.g., traffic density, likelihood of occurrence, ability to realize the benefit in a given situation with an aviation system feature).

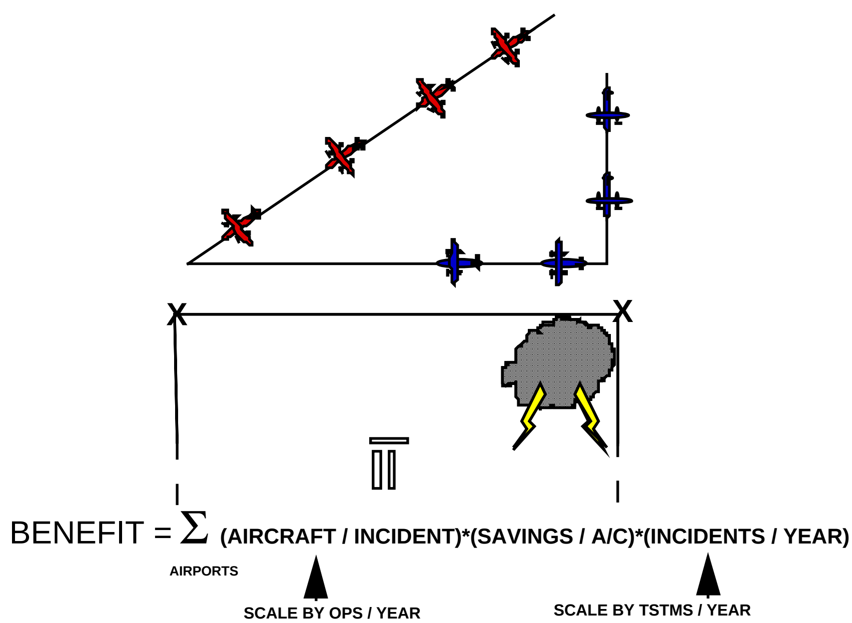

Figure 5. "Fixed" delay model used to analyze cases where a number of planes fly a better route due to the use of the ITWS/TCWF products (from [Evans, 1997]). Advance planning enables aircraft to fly the direct red re-routing, as opposed to the longer blue re-routing.

2.2.2 "Queue" Delay Reduction

Figure 6 shows a simple example of the classic queuing situation where the weather reduces the effective capacity of an airport for some finite time. This simple queuing model can be used to address both air traffic control/airport reductions in effective terminal capacity and traffic flow management actions by interpreting:

1. The effective capacity as the minimum of the air traffic control/airport constraints on the traffic flow and the flow rate imposed by FAA traffic flow management decisions, and
2. The effective duration as the sum of the actual weather event duration and the time period over which an insufficient number of aircraft are available to land due to traffic management holds.

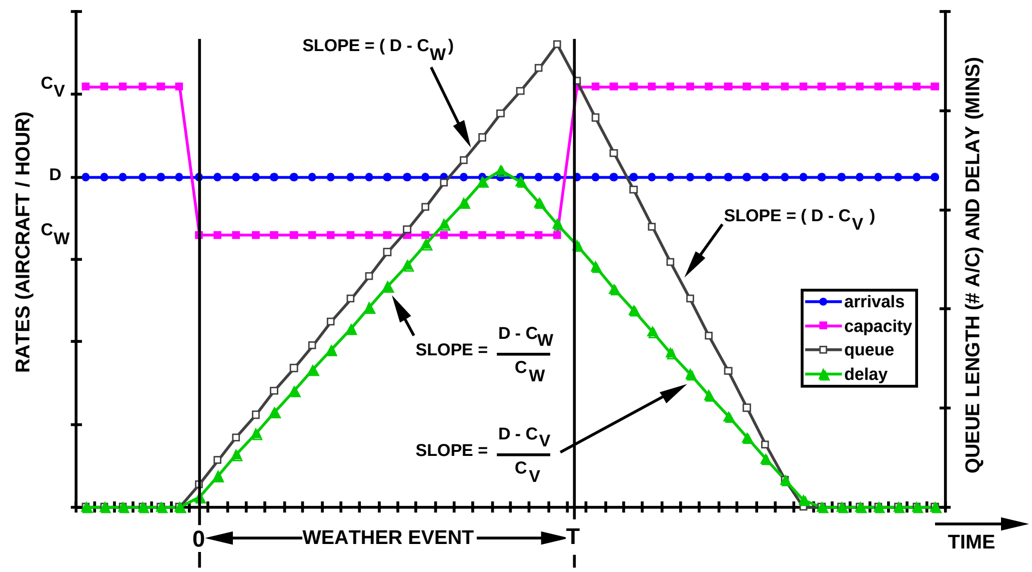

Figure 6. Queuing model for delay when adverse weather reduces the effective capacity of the airport. D = demand, C_W = capacity during adverse weather, C_V = capacity during VMC weather, and T = effective event duration (from [Evans, 1997]).

The effective duration of the weather event from the viewpoint of delay calculation is the actual duration of the weather plus any additional time in which the airport capacity is not fully utilized because the traffic flow managers did not have an adequate flow of planes available when the weather impact ended.

To illustrate, if an actual weather event lasts for two hours and creates a situation in which a number of aircraft desiring to land at the airport are held on the ground at the respective departure airports, the delay event may be viewed as continuing until the ground hold aircraft are released and land at the destination airport. If the minimum flight time for the aircraft being held on the ground is one hour, then the effective duration is at least three hours.[3]

It is straightforward to show that the accumulated delay for all the aircraft involved in the incident shown in Figure 6 is

$$\Sigma(\text{delay to various aircraft}) = 0.5\, T^2\, (D-C_W)\, (C_V-C_W)/(C_V-D)$$

[3] The use of holding patterns near the airport (as in the FAA's Managed Arrival Reservoir technique) will result in a more complicated relationship than illustrated in figure 3, but the general principle still remains that ground holds increase the effective duration of a weather event.

The dependence of delays on the traffic density and traffic flow management procedures here is quite nonlinear. For example, we see that small increases in the effective capacity during a weather event, C_W, can produce larger proportional reductions in the accumulated delay because C_W appears both in differences (e.g., a small increase in C_W will result in a larger fractional change in each of the differences) and in the product of terms.

Since T is squared, reducing the effective duration of a weather event (e.g., by better weather predictions and traffic flow management decision making) can also produce large delay reductions. For example, if a good short-term prediction enables the NY TRACON traffic management coordinator to reduce a 3-hour effective duration weather event to 2.5 hours, the accumulated delay would be reduced 31 percent.

The quantitative queuing results shown in the subsequent sections of this report utilize an enhancement of the very simple queuing model shown in figure 6 in which one allows both the airport capacity and the user demand to vary significantly with time (see [Evans, et. al, 1999] for a description of the model and its validation with measured delay data from Atlanta). The model is implemented by use of a computer spreadsheet, with a multitude of derived fields. Part of the elegance of the model is that it requires only two input fields—demand and capacity as a function of time. Despite the limited input, it was able to model the actual delay fairly well, and was surprisingly accurate in modeling peaks and valleys in the real data (as will be noted in section 6.3.3). For this portion of the study, all air traffic data were taken from the CATER data set; a data set created by manually integrating flight strips for every flight into and out of the New York area airports.

To obtain accurate, realistic results from the model, the capacity and demand profiles used to estimate delays were derived from current flight schedules at the various airports. The demand profile was fairly straightforward. In order to produce a demand that was realistic, we took the demand profile from the five nearest, non-weather, non-delay weekdays (all cases in this study are weekday cases), added any cancellations on those days, and then averaged the five days. This profile, minus cancellations on the study day, was assumed to be the actual demand profile on the day in question.

An accurate determination of capacity was more difficult. The base capacity used for this study was derived from an engineered capacity table for EWR that takes into account runway configuration, ceiling and visibility (hereafter C&V) conditions, and arrival/departure mix. All C&V conditions were taken from METAR reports, runway configurations were taken from CATER, and Arrival/Departure mix was assumed to always be near 50/50 (generally a reasonable assumption, since the other mixes only applied if arrivals or departures were over 75% of the total traffic). Also, actual 60-minute arrival rates, computed continuously and reported in CATER, were culled for comparison.

On several instances, we noted that the actual arrival rate was significantly below our derived capacities. It was necessary for us to consider instances where capacity was reduced for reasons not related to low C&V, such as a nearby thunderstorm or non-weather related issues. As a crude method to account for this, we identified where the actual arrival rate was less than or equal to 70% of expected demand, and where expected demand was greater than 20 arrivals. If this condition was met, then the actual arrival rate was taken as the capacity (if demand was less than 15-20 arrivals, this assumption produced unrealistic capacities). If this condition was not met, then capacity was defined as the maximum of the engineered capacity or the arrival rate. This was done to take into account that, at times, EWR is able to land and depart at rates that exceed engineered capacities.

Given the data on capacities and demand, the expected delay can be computed by the model. In this situation, the delay in minutes can be thought of as the minimum delay expected when demand exceeds capacity. A Ground Delay Program (GDP) is an attempt to incur this delay on the ground, at the originating airport, instead of holding in the air. If the GDP is cancelled too soon, or the airport acceptance rate (AAR) is too high, then holding will still be the result. On the other hand, if the GDP is continued beyond the necessary time (often the case when C&V events end), or the airport acceptance rate AAR is too low, then unnecessary (avoidable) ground delay will result. The model can be used to estimate the avoidable delay by comparing its (assumedly optimal) results with those obtained by lowering the model capacity to the actual arrival rate during the time period after the weather cleared, but before the GDP was cancelled.

2.2.3 Accounting for Flight Delay Propagation Effects

One of the major factors in both delay modeling and determining delay causality from recorded delay statistics is the "delay ripple" effect which arises when an aircraft is delayed on one leg of a flight (e.g., due to adverse weather) such that the next leg (and subsequent legs) flown by that aircraft that day also are delayed. In cases where the subsequent leg(s) are not weather impacted, the delay on the subsequent legs may not be attributed to terminal weather.

DeArmon states that "delay ripple is in general pretty strong" and persists over a number of successive legs [DeArmon, 1992]. Hartman cites a case where the number of passengers delayed (down line impact) due to delay ripple was 27 times greater than the initial number delayed [Hartman, 1993]. A very recent study by a group from American Airlines and MITRE [Beatty, et. al., 1999] shows that the degree of delay propagation depends on the time of day and magnitude of the initial delay encountered.

In our study, we have used the approach used in the ITWS delay reduction study conducted by the FAA, the Volpe Transportation Center, and Lincoln Laboratory in 1994-95. Based on the analysis of delays for flights passing through LaGuardia airport, Dr. Steve Boswell of Lincoln Laboratory developed a model [Boswell and Evans, 1997] in which the amount of delay made up per leg is a random variable. This model suggests that the initial delay savings should be multiplied by 1.8 to arrive at the net delay savings (i.e., that the total downstream delay is approximately 80% of the initial delay). In view of the much larger multiplier factors suggested by Hartman and Beatty, et. al., we feel that the use of the 80% multiplier is a very conservative method of accounting for the delay propagation effect in estimating the benefits of ITWS/TCWF at New York.

2.2.4 Converting Hours of Delay to Monetary Estimates

For this study, we used the official FAA values for the costs of an hour of delay to the airlines and passengers [Hoffer et al., 1998]:

Airline direct operating cost (DOC):	\$3,093 per hour for commercial aircraft
	\$565 per hour for general aviation aircraft

Passenger time cost:	\$26.70 per passenger per hour for commercial flights
	\$31.10 per passenger per hour for general aviation (GA) flights

Traffic was considered for the seven major New York area airports (which produce most of the TRACON traffic): Newark (EWR), Kennedy (JFK), LaGuardia (LGA), Teterboro (TEB), Islip/MacArthur (ISP), Stewart (SWF), and White Plains (HPN). For 1999, actual traffic counts were available for all airports, broken down by commercial versus GA. In addition, the number of commercial passengers was also available. The number of passengers per GA flight was estimated at 2.7 (also provided in the FAA report). Thus, accurate estimates of the dollar benefit were able to be derived for all the area airports. The results for EWR, LGA, and JFK were used directly in benefit computation for those airports.

In addition, several benefit categories could not be applied to individual airports (e.g. a certain number of planes per departure fix (from any/all NY airports) receive reduced re-routes, etc.). In these cases, benefits were provided for the TRACON as a whole. In order to arrive at benefit conversions for these flights, a weighted average from the seven airports listed above was utilized for both the airline DOC and passenger cost.

3. BENEFITS—TWO CASE STUDIES

Both the IOC ITWS and TCWF have already provided a substantial economic and safety benefit to EWR, the TRACON, and other aviation users throughout the Northeast corridor. Two days where substantial benefits were attained using the IOC ITWS are detailed in this section as examples cited by the TRACON.

3.1 24 May 1999—An All Day Convection Event

3.1.1 Weather Conditions

Three lines of convective weather created significant problems for the air traffic system in the New York area; lightning was detected within 20nm of EWR for almost ten straight hours. The day started poorly for aviation operations with low ceilings and coastal fog plaguing EWR and LGA. At 0920 LT severe thunderstorms were located in southwest NJ with 43,000 ft echo tops. These weakened only slightly as they reached New York City, at which time they were VIP level 5 intensity with significant lightning; several wind shear events were detected at EWR. A second line of thunderstorms formed along a pre-frontal trough at around 1200 LT (Figure 7), and grew to level 4-6 storms, impacting EWR by 1300 LT. Several wind shear and microburst events were also observed as this second line moved through. Finally, a third round of thunderstorms moved to the northeast tip of Maryland at 1510 LT. One of these cells became severe with hail and level 6 echo intensities. This cell broke off from the main line of storms and moved eastward, rapidly dissipating upon reaching the coast at 1800 LT. The northern part of the line tracked directly toward EWR at 1715 LT. This time there was a well-defined gust front. Upon impact at EWR, winds swung from calm to northwest at 22 kts, gusting to 40 kts. A 25 kt wind shear was also dropped directly on the EWR runways at this time and several microbursts were observed in and around EWR and LGA.

3.1.2 Benefits Cited from Interviews with Traffic Facilities

Traffic managers at the TRACON stated that ITWS was "invaluable", especially since a lightning strike to the building had cut off their access to any other weather information. ITWS was used to plan up to 100 re-routes, while the storm motion and storm extrapolated position products allowed numerous departures between severe weather areas before departure gates were affected or closed. Even though delays were severe on this day (Figure 8), the TRACON still estimated that information from ITWS aided them in releasing five extra planes per airport (EWR, JFK, LGA) per hour during the ten hour duration of severe weather.

The TRACON also considered using the Seaview-Mariner route, in which they route planes to the east to gain altitude and then back to the west to get over the tops of storms. However, on this day they were able to use the storm cell information product to determine that storm tops were in excess of 45,000 ft, and thus too high to fly over. They also noted that the storm motion product showed cell movement at 45 kts toward the northeast. This movement was too fast; by the time the line of storms moved through, it would not have paid to use this route.

In a post-event interview, EWR tower relayed to the authors that the system was used heavily. One key benefit occurred when a level 5 cell moved over the airport, preceded by a strong gust front (with 40 kt winds) and accompanied by wind shear (Figure 9). ITWS detected these events, and activated 20-25 kt loss alerts on all runways at 1750 LT (Figures 10). Out of four airplanes on approach at the time, three aborted their landing attempts based on the ITWS alerts referenced by controllers.

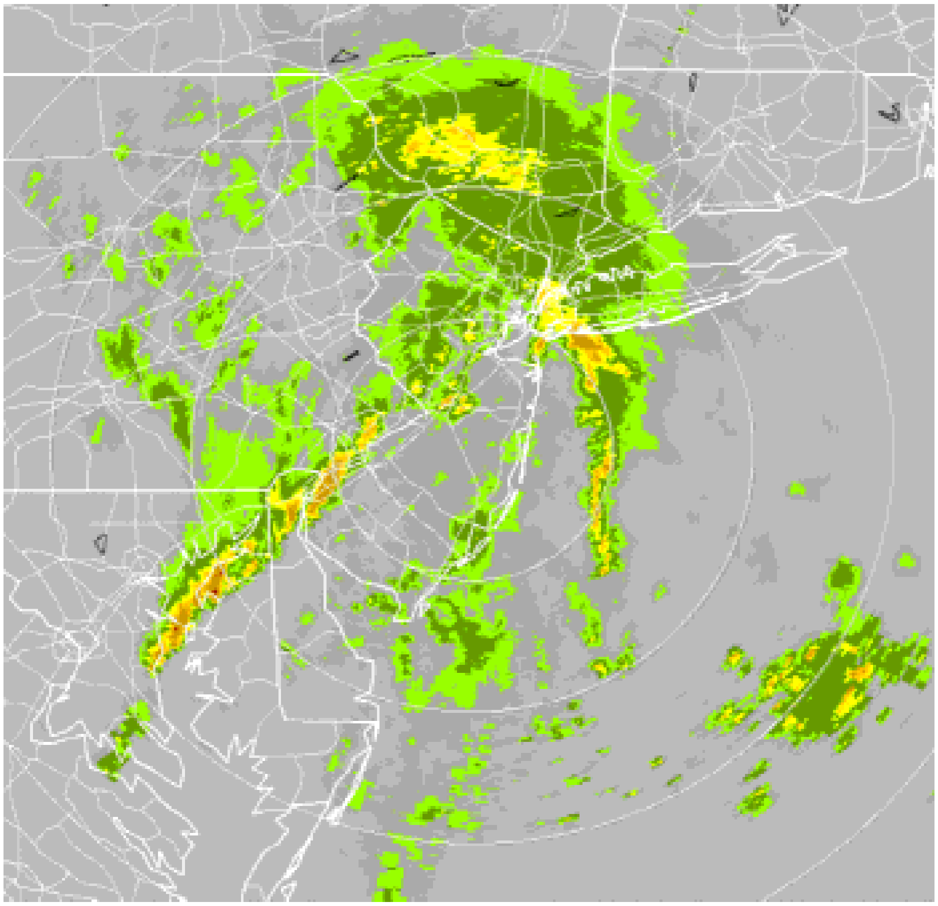

Figure 7. Two lines of thunderstorms up to VIP level 6 intensity as depicted by the Vertically Integrated Liquid water content (VIL). The image is from 1140 LT on 24 May 1999.

3.1.3 Quantified Benefits Using Model—Over $2,000,000 in Savings

The stated TRACON benefit was five extra departures per hour for ten hours for three airports. In order to compute savings from this, we used the queuing model as described earlier, except using departure numbers. The result was a savings of 580 hours of delay at Newark alone (322 hours of primary delay and 258 hours of downstream delay), which translates to an estimated savings of over $2,000,000. Since the TRACON stated they were able to do this at all three airports, likely savings are over $4,000,000 for the entire TRACON (we estimate similar savings at LaGuardia, with limited benefits at Kennedy).

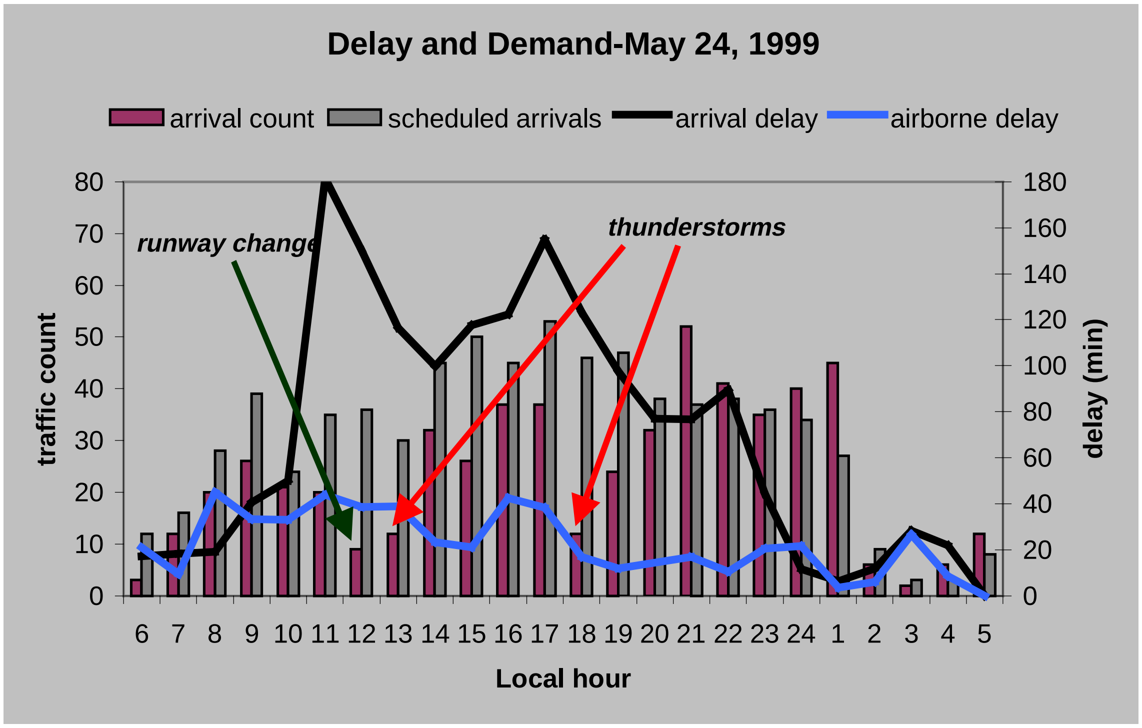

Figure 8. Profile of arrival demand and accompanying delays. Hourly arrival counts are on the primary Y axis, while hourly average airborne delay and hourly average total arrival delay in minutes are on the secondary Y axis. Note the large drop-off in arrival traffic during the periods of thunderstorm passage at EWR and runway changes. All times are local.

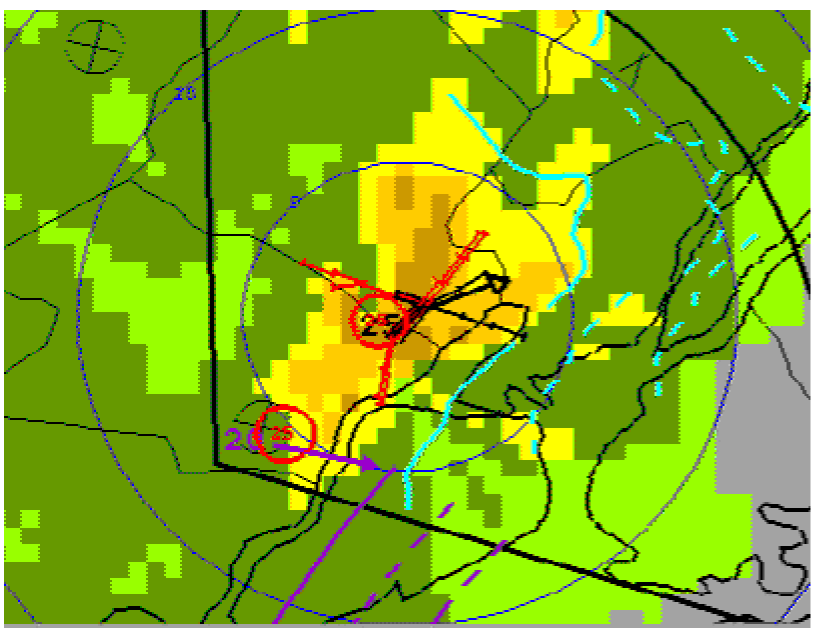

Figure 9. Wind shear impacting EWR runways as a strong level 5 thunderstorm crosses the airport. Red circles denote wind shear detections, with the maximum loss in kts across the shape given inside the circles. Precipitation intensity is a 6-level scale, based on a mosaic of several ASR-9 radars.

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CF 240 17G39
11A   WSA 20K- 1MF
11D
22LA  WSA 15K- RWY
22LD  WSA 25K- RWY
22RA  WSA 15K- RWY
22RD  WSA 25K- RWY
29A
29D   WSA 20K- RWY
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Figure 10. Corresponding ribbon alerts issued to controllers for the wind shear event shown in Figure 9. CF 240 17G39 represents LLWAS centerfield winds of 17 kts from 240 degrees gusting to 39 kts. The second line represents a wind shear alert for a 20 kt loss on one mile final approach to runway 11. The fifth line represents a 25 kt loss on runway 22L at the point of takeoff.

3.2 10 December 1999—Strong Vertical Wind Shear

3.2.1 Weather Conditions

The New York area started out clear during the early morning. A solid line of rain, however, came into view at 1030 LT in Eastern PA, and marched through the region during the late afternoon, passing through EWR at 1630 LT. There was no convective precipitation, and no rapid wind shift. Surface winds became very strong during the night, however, with gusts to 45 kts.

The weather was driven by a rapidly deepening upper-level low moving eastward out of the Ohio River valley. As it intensified, winds became very strong just off the surface, reaching 45-50 kts at 1,800 ft. Ahead of the cold front, there was little downward mixing of the winds, and surface winds remained calm at EWR. The result was a nearly 30 kt per 1,000 ft unidirectional increase of the winds in the lowest levels of the atmosphere (Figure 11). The cold front arrived at 2000 LT, with strong winds forcing runway changes at all of the airports.

3.2.2 Traffic Impacts

The winds caused problems of all types at the airports. EWR reported at least one missed approach, and JFK reported four, between 1600 and 1700 LT. Delays also became extensive at EWR, LGA, and JFK. EWR went into a ground delay program at 1100 LT with a set airport arrival rate (AAR) of 36 aircraft per hour. This number was later revised at 1450 LT to an AAR of 32. Reports of compression problems as planes arrived in the terminal area were extensive. These problems occur when aircraft that are spaced a certain distance apart descend through rapidly changing wind conditions. The result often is a significant decrease in spacing, which results in an overload problem for the TRACON. As a result, restrictions are often passed back to the centers to provide increased spacing in anticipation of terminal area compression.

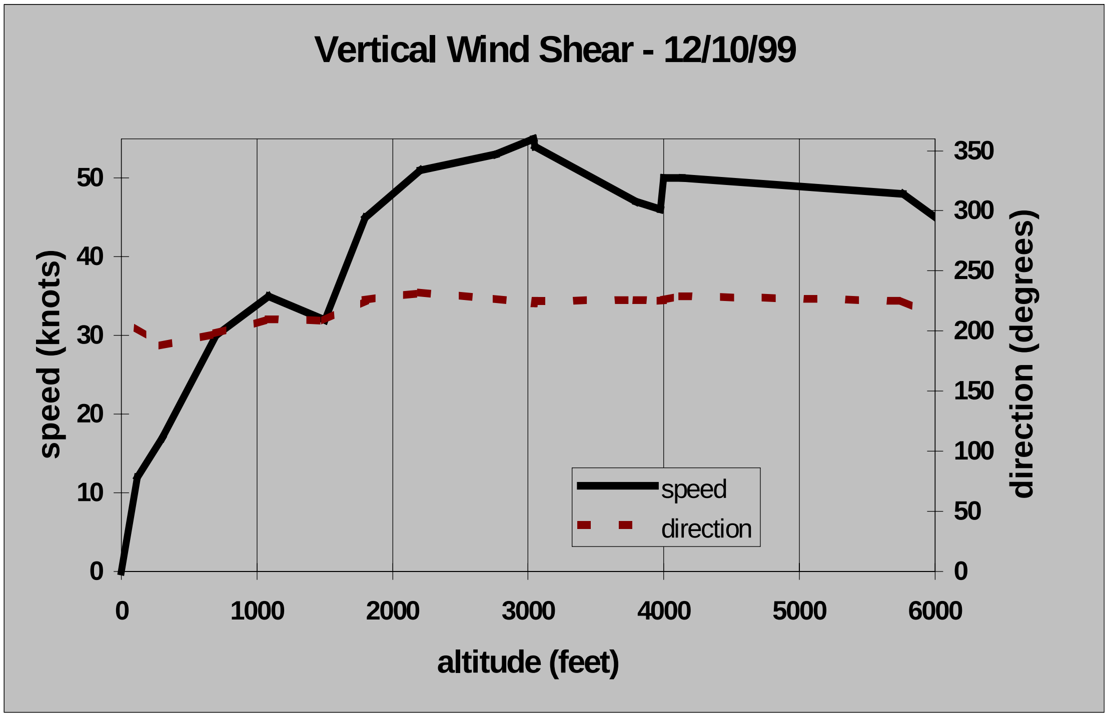

Figure 11. Vertical wind shear over EWR at 1230 LT on 10 December 1999. The dashed line represents wind direction in degrees, while the solid line represents wind speed in knots. Data are taken from aircraft reports (MDCRS).

At the time when missed approaches were reported at JFK, the sky had cleared and surface winds had not yet increased, indicating that vertical wind shear was the primary cause of landing difficulty; TMU logs confirmed this. Until 1500 LT, low ceilings of 1,200-1,500 ft and light rain were also a factor in the reduced capacity at the airports. The AAR rate of 36 during that time was typical of such low ceiling events. However, winds were strengthening by 1600 LT at 2,000 ft, and Figure 12 shows that EWR was not able to land 36 aircraft per hour during this period. The result of not being able to match the AAR to capacity during this time can be seen in the buildup of airborne delay (an indicator of airborne holding). When the program AAR was reduced, airborne delay fell significantly (replaced by ground holding). The second period of airborne delay was much less than the first, and primarily due to EWR being forced into a single runway operation of runway 29 when surface winds strengthened from the northwest (see Figure 13). TMU logs indicated 16 planes held at EWR for longer than 15 minutes on this day, with an average of 29 minutes and maximum of 57 minutes. When they finally decreased the AAR to 32 at 1500 LT, skies were actually clearing, further indicating the impact of vertical wind shear at the airports.

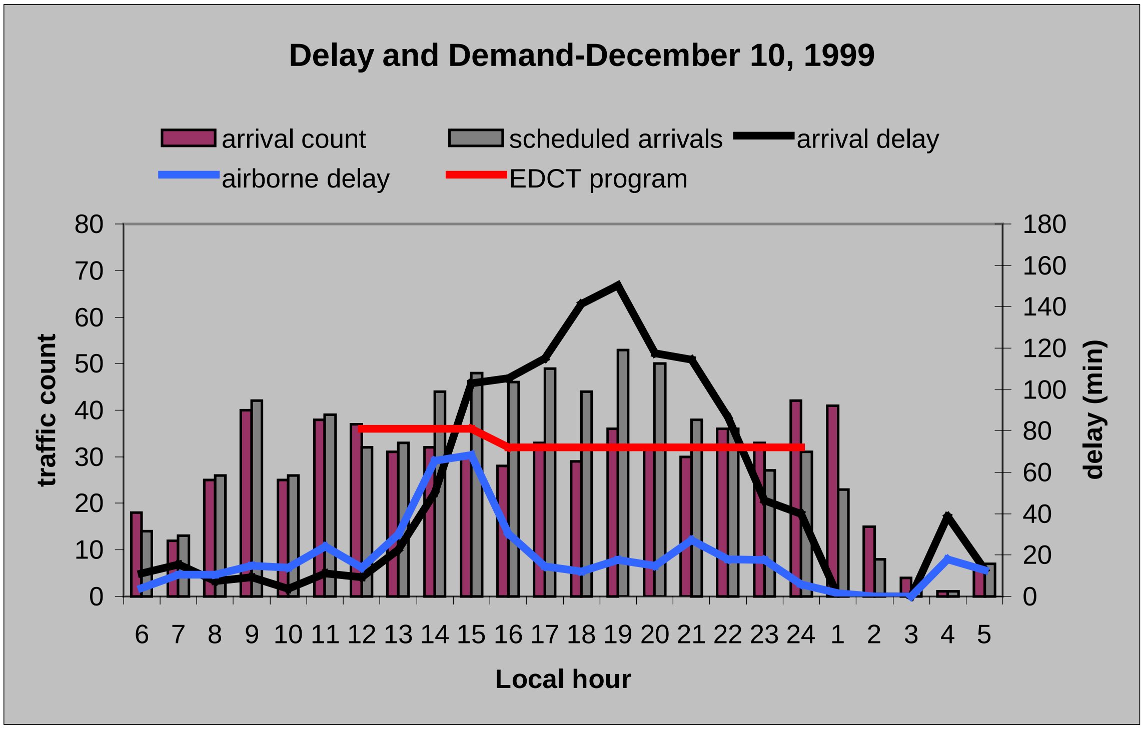

Figure 12. Profile of arrival demand and accompanying delays on 10 December 1999. Hourly arrival counts and the EDCT program arrival rate are on the primary Y axis, while hourly average en route delay and hourly average total arrival delay in minutes are on the secondary Y axis. All times are local.

3.2.3 Benefits Cited from Interviews with Traffic Facilities

Benefits realized from the ITWS Terminal Winds product were significant on this day. Initially, the TRACON had not noticed that Terminal Winds was showing 50 kt winds at 2,000 ft, but when New York ITWS staff alerted them to this fact, they took action almost immediately. The TRACON used it in their decision to reduce the AAR to 32, and told ITWS staff that they estimated it saved them from holding at least 10-15 planes over a few hours. They also said that the center field average (CFA) winds at EWR from the ITWS ribbon display and Situation Display showed when the cold front and associated high surface winds arrived, and that this was used to plan runway changes at LGA and JFK well in advance. They said that this was a big help to them.

Air traffic users also noted the operational benefit of holding planes on the ground as opposed to in the air. The unnecessary workload of holding is greatly decreased, yielding more efficient planning and controlling of the remaining aircraft en route.

3.2.4 Quantified Benefits Using Model

Due to the difficulty quantifying the results of this case via a model, no attempt was made to determine the actual number of hours or dollars saved from this event. Another Terminal Winds case shown later, however, was modeled, and the resultant delay savings were 46 hours, or over $150,000 at Newark. The next section will show that Terminal Winds can routinely save $100,000, and the most severe events can yield a $1,000,000 benefit.

4. ANNUAL DELAY REDUCTION PROVIDED BY ITWS/TCWF AT THE NEW YORK AIRPORTS

It is understood that the results obtained from the specific case studies discussed in the previous section may not be typical of an average delay day during the course of the year. In other words, one cannot merely take the result from one or two case studies, and multiply by the total number of events to arrive at an annual benefits estimate. In this section, we describe the details of the FAA user interview/delay modeling approach that was previously discussed in Section 2.

First, we determined the types of delay reduction benefits that one could expect to achieve through the use of the New York ITWS/TCWF system. This list was compiled from several sources, including past studies at other ITWS sites [see appendix B] and past interviews with New York ITWS/TCWF users. Second, we interviewed New York TRACON ITWS/TCWF users to determine the average benefit from each of the listed categories, as well as the frequency and length of the average event. In addition, TRACON users modified and added several categories to better reflect typical operating procedures in New York, which differ in many respects from TRACON facilities elsewhere. The result was a better understanding by the authors of the true cause of delay in New York, particularly during convective scenarios, and perhaps more importantly, a much better understanding of how the ITWS/TCWF system is used to benefit operations during all types of weather events. After the final numbers were derived, a "sanity check" was performed by re-interviewing TRACON users to be sure the numbers, on the whole, made sense (e.g., no overlapping benefit categories). Another "sanity check" was made for the SWAP departure benefits by comparing the delay per SWAP with and without ITWS/TCWF.

It should be noted that much of the groundwork for this study was laid by MCR, Inc., which had first conducted interviews with the TRACON as a part of their study to assess the benefits of TCWF (over and above ITWS) in the New York airspace system. We also have discussed the quantitative results with MCR (including the "sanity" checks) and it is expected that their results (which will be reported independently) should be similar for the common ATC decisions assessed in the two studies.

One thing that the TRACON interviews revealed was that although individual airport benefits are important, most, if not all benefits have a notable effect on the TRACON as a whole, including all airports within it (from international to municipal). For example, if a departure fix is kept open longer, planes from all airports where flights can get airborne can take advantage of that fix. Thus, for many of the categories, benefits were derived for the TRACON as a whole.

Several benefits clearly had to be quantified using the queuing model that was discussed in Section 2. For example, if more planes per hour can depart a given airport during an event, runway queues are reduced for aircraft departing at a later time, thus extending benefits to aircraft even after the weather impact on operations has ended. For several categories, we were able to quantify these extended benefits by considering the benefits at each airport separately (for EWR, LGA, and JFK), and by using the queuing model described in Section 2.2 of this report. The combination of these benefits (airport-specific and TRACON-wide) comprise a low-end estimate for the annual benefit to the NY aviation community from ITWS/TCWF.

The airport-specific benefits are derived in cases where ITWS/TCWF is directly able to increase capacity at an airport by a given number of aircraft per hour in a given circumstance. Similar to the case studies, an average daily arrival or departure demand is obtained, along with a typical aircraft arrival or departure rate (AAR, ADR) for the scenario. Then, the AAR/ADR is increased by a set amount for a set period of time (due to ITWS/TCWF), and the difference is the benefit. Hourly demand is derived from annual averages of arrivals (or departures), reported in 1999 CODAS data for each airport. Baseline arrival rates/departure rates (capacities) were determined empirically (based on past operations during similar circumstances), while rate increases due to ITWS/TCWF were those obtained in the TRACON interviews. For convective events, empirical departure capacities are the 50th percentile of hourly departure rates during 2000 SWAP events. This was done separately for each of the three airports for the typical eight-hour SWAP period (assumed to be from 1400-2200 LT[4]). The remainder of this section describes the categories and assumptions used in computing these benefits. Abbreviations refer to those in Table 4 (which ends this section).

Terminal Winds has three types of benefits. On high vertical wind shear days (VWS, 13 per year), the AAR is raised by 3 aircraft per hour, per airport, from 1000-1800 LT. On days with high surface winds (HIGH WIND, 20 per year), the AAR is raised by 2 aircraft per hour, per airport, from 1000-1800 LT. On a nearly daily basis (DAILY TW, 150 per year), the AAR is raised by 1 aircraft per hour, per airport, from 1000-1800 LT.

Convective events that result in SWAPs that impact New York operations occur on average about 52 days per year (but were significantly more frequent in 2000, due to new operating procedures and more days with significant weather). Approximately 2/3 of these (35 days) arise from weather that is in or near the New York TRACON airspace (e.g. within 100 nmi of the airports). Of those events, the TRACON is confident that ITWS provides substantial benefits in at least 3/4 of the cases (26 days).

On average, at any given time during a SWAP event, 1-2 arrival and 4 departure gates are closed due to direct weather impacts. If arrival gates are blocked by weather in New York airspace, departure airspace is made available in an attempt to maintain arrival throughput. ITWS/TCWF helps most by alerting the users that problems such as this may develop. In the past, the situation would develop, and all departures would generally be shut off until the arrival flow either stopped, or was reconfigured. Now, utilizing ITWS/TCWF, users can configure arrivals into a single stream earlier (both in time and space), avoiding excessive deviations by both arrival and departures, and more importantly, avoiding the stoppage of departure flows, thereby also avoiding the potential for gridlock. The assumptions made, with the assistance of the TRACON, are that during a SWAP, about 15 planes cross a given fix, on average, per hour, and that the average SWAP is 8 hours in duration.

There are several benefits that fall under the convective heading. First, the TRACON reports that at least 10% more flights depart with ITWS/TCWF than without (SWAP DEPT). This is the single biggest individual benefit at each airport. Also, the TRACON often anticipates the weather dissipating earlier. On average, the AAR can be raised by 4 per hour over a two hour period at the end of the event (WX DISS-RAISE AAR, AARs associated with GDPs are raised two hours earlier than they otherwise would be). This benefit is not computed for JFK, as their capacity is generally already high during these types of events, and more of their flights are unaffected as they come from the east. In this scenario, the departure rate can also be doubled for one hour at each airport (WX DISS-DBL DEPT), as ITWS/TCWF indicates weather dissipating, and personnel recognize (earlier than they otherwise would have) departure routes opening.

Finally, benefits were derived for TRACON-wide categories. These are categories that include no queuing benefits (generally shortening or eliminating reroutes), or that include benefits not easily modeled. In the latter case, the additional queue reduction benefits are simply ignored, which is consistent with the conservative, low-end estimations that are the goal of this study. The assumptions are the same as those described in airport-specific convective benefits.

Advance planning of departure reroutes due to the 4 closed fixes results in 60 planes (15 planes per fix) per hour saving 10 minutes each over the 8 hour period. Also, the 2 departure fixes normally closed by arrivals deviating are now open, thus 30 planes per hour save 20 minutes each by not having to reroute

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[4] Although there can be considerable variation in time of day and duration of convective events, delays and SWAP programs typically take place in the afternoon and evening due to two factors: a peak in traffic demand and favorable conditions for convection due to a maximum in daytime heating.

(EFFICIENT DEPT RTS). Advance planning of arrival reroutes due to the average 1.5 closed fixes also results in 22-23 planes per hour saving 10 minutes each over the 8 hour period (EFFICIENT ARR RTS). Anticipation of runway shifts using the gust front/wind shift product saves 8 planes per airport 15 minutes each in holding, rerouting, and taxiing (RWY SHIFT). This happens, on average, once during each SWAP event. Utilizing ITWS/TCWF, controllers can land planes right up until the event impacts the airport (instead of shutting down the airport early). This happens at each airport around 15 times per year, and saves 6 planes 45 minutes of holding time (LAND B4 EVENT). Occasionally, ITWS will show that a slow-moving storm is only impacting a small portion of the airport. In these circumstances, part of the airport can sometime continue operating. It is estimated that this occurs 6 times per year, per airport, and saves 30 planes 45 minutes of holding each (PARTIAL ARPT OPEN). Finally, the recognition of dissipating weather not only results in more arrivals and departures (quantified earlier), but also eliminates unnecessary rerouting for those aircraft. As a result, 22-23 arrivals and 30 departures (TRACON-wide) save 20-45 minutes each at the end of events by not being rerouted around weather that will not exist when the plane would arrive there (NO ARR RRT & NO DEP RRT).

Using the above data, the hours of primary delay saved were computed. Conversion to dollar benefits are done using the estimates and methods described in Section 2. The results (Table 4), show an estimated total annual savings of over $150,000,000.

Table 4
Annual Delay Reduction Benefits of ITWS/TCWF at New York

AIRPORT	BENEFIT TYPE	DELAY SAVED (h) Primary	Down	Total	SAVINGS Operations	Passenger(p)	Passenger (d)	Total
EWR	**VWS**	2,083	1,667	3,750	$6,226,640	$4,047,381	$3,237,904	$13,511,925
EWR	**HIGH WIND**	420	336	756	$1,255,341	$815,985	$652,788	$2,724,113
EWR	**DAILY TW**	493	394	887	$1,472,037	$956,839	$765,471	$3,194,347
EWR	**SWAP DEPT**	3,162	2,530	5,692	$9,452,318	$6,144,105	$4,915,284	$20,511,706
EWR	**WX DISS-RAISE AAR**	618	494	1,112	$1,845,650	$1,199,692	$959,753	$4,005,095
EWR	**WX DISS-DBL DEPT**	743	594	1,337	$2,219,961	$1,442,997	$1,154,398	$4,817,356
LGA	**VWS**	3,775	3,020	6,795	$11,191,664	$6,584,270	$5,267,416	$23,043,350
LGA	**HIGH WIND**	1,496	1,197	2,692	$4,433,937	$2,608,570	$2,086,856	$9,129,363
LGA	**DAILY TW**	970	776	1,746	$2,875,586	$1,691,763	$1,353,410	$5,920,759
LGA	**SWAP DEPT**	2,421	1,937	4,358	$7,177,207	$4,222,488	$3,377,991	$14,777,686
LGA	**WX DISS-RAISE AAR**	973	778	1,751	$2,883,986	$1,696,704	$1,357,363	$5,938,053
LGA	**WX DISS-DBL DEPT**	848	678	1,526	$2,514,014	$1,479,042	$1,183,234	$5,176,290
JFK	**VWS**	437	349	786	$1,306,060	$1,042,250	$833,800	$3,182,110
JFK	**HIGH WIND**	89	71	160	$266,248	$212,469	$169,975	$648,691
JFK	**DAILY TW**	78	62	140	$231,845	$185,015	$148,012	$564,872
JFK	**SWAP DEPT**	2,342	1,873	4,215	$7,005,406	$5,590,391	$4,472,313	$17,068,110
JFK	**WX DISS-DBL DEPT**	375	300	675	$1,122,628	$895,870	$716,696	$2,735,193
TRACON	**EFFICIENT DEPT RTS**	4,160	3,328	7,488	$9,816,583	$5,813,500	$4,650,800	$20,280,883
TRACON	**RWY SHIFT**	156	125	281	$368,122	$218,006	$174,405	$760,533
TRACON	**LAND B4 EVT**	96	77	172	$225,652	$133,634	$106,907	$466,192
TRACON	**EFFICIENT ARR RTS**	780	624	1,404	$1,840,609	$1,090,031	$872,025	$3,802,666
TRACON	**NO ARR RRT**	439	351	790	$1,035,343	$613,143	$490,514	$2,138,999
TRACON	**NO DEP RRT**	260	208	468	$613,536	$363,344	$290,675	$1,267,555
TRACON	**PARTIAL ARPT OPEN**	405	324	729	$955,701	$565,978	$452,782	$1,974,461
TOTALS	VWS	6,295	5,036	11,331	$18,724,363	$11,673,901	$9,339,120	$39,737,384
TOTALS	HIGH WIND	2,005	1,604	3,608	$5,955,525	$3,637,023	$2,909,618	$12,502,167
TOTALS	DAILY TW	1,540	1,232	2,772	$4,579,468	$2,833,616	$2,266,893	$9,679,977
TOTALS	SWAP DEPT	7,925	6,340	14,265	$23,634,930	$15,956,984	$12,765,587	$52,357,501
TOTALS	WX DISS-RAISE AAR	1,966	1,572	3,538	$4,729,636	$2,896,396	$2,317,117	$9,943,148
TOTALS	WX DISS-DBL DEPT	5,751	4,601	10,351	$5,856,602	$3,817,909	$3,054,327	$12,728,839
TOTALS	EWR	7,518	6,015	13,553	$22,471,945	$14,606,998	$11,685,598	$48,764,541
TOTALS	LGA	10,483	8,386	18,869	$31,076,394	$18,282,837	$14,626,270	$63,985,501
TOTALS	JFK	3,320	2,656	5,976	$9,932,186	$7,925,994	$6,340,795	$24,198,975
TOTALS	TRACON	6,295	5,036	11,332	$14,855,546	$8,797,635	$7,038,108	$30,691,289
GRAND TOTALS		27,617	22,093	49,710	$78,336,071	$49,613,464	$39,690,771	$167,640,306

*Text in chart in **this color** represent categories where **queuing model** was used, while text in **this color** represent categories where **linear delay model** was used.

**Passenger(p) = Passenger primary delay savings; Passenger(d) = Passenger downstream delay savings

5. PRINCIPAL CAUSES OF WEATHER-RELATED DELAYS AT EWR WITH ITWS IN OPERATION

5.1 Background and Methodology

The Office of Inspector General (OIG) was recently asked to examine sources and causes of flight delays and cancellations. The OIG audit reported "while the Bureau of Transportation Statistics (BTS), the Federal Aviation Administration (FAA), and air carrier systems provide information on the quantity of delays, information on the causes of delays was found to be incomplete and inconsistent." They went on to say that identifying good long-term solutions to reduced delay would be problematic without an accurate source of information on the causes of delay. Part of the problem lies in the fact that the airlines and FAA have different definitions of what delay is and what its causes are.

Our study has sought to make a major advance in attributing causes to weather-related delays at EWR during the two year period covering September 1998 through August 2000[5]. To the authors best knowledge, this is the first time that a concerted effort has been made to estimate delays at an airport related to convective weather well away from that airport's location, and to determine the delays are due to high winds in otherwise fair weather.

Other studies have examined weather contributions to delay at individual airports. Robinson (1989) examined delays at Atlanta's Hartsfield International Airport and found that the maximum delay per operation came from heavy fog, with thunderstorms ranking second and reduced visibility third. Weber, et al. (1991) examined delays at Chicago's O'Hare International Airport and found that the greatest delay per operation came from thunderstorms, with heavy fog ranking second and reduced visibility third. Although there were differences in the methods of these two studies, it is evident that different airports are subject to different weather phenomena and thus have different needs for weather information tools. A sharply contrasting example is San Francisco International Airport, which has a high percentage of days with limited visibility due to marine stratus, while having very few days with thunderstorms (Clark et al. 1997).

Several studies currently underway characterize delays at airports as arising from insufficient capacity during Instrument Meteorological Conditions (IMC), when compared to Visual Meteorological Conditions (VMC). Assuming that paradigm leads one to attempt to model delays as a function of IMC v. VMC conditions respectively <u>at the airport</u>.

Our results for EWR show that the simple IMC v. VMC airport capacity model will not explain the actual delays because:

1. Convective delays can be associated with IMC, VMC, or mixtures of IMC and VMC at the airport. In fact, many of the convective delays arise from storms that are not near the airports with delay problems (see Appendix A).

2. High winds can cause delays during both IMC and VMC conditions. Moreover, high winds during VMC conditions after a front has passed are clearly an important cause of delays at EWR.

Using the Consolidated Operations and Delay Analysis System (CODAS), all days with two consecutive hours of average arrival delay exceeding 15 minutes were identified. For the purposes of this study, a day

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[5] The unusual choice of a time period is due to the availability of data collected at an ITWS field site located in Garden City, New York. This data was critical for accurate statistics on thunderstorms impacting NY TRACON (N90) operations.

was defined as the period starting and ending at 0500 LT. In addition, any hour with fewer than 10 arrivals was not considered (due to the effect one or two flights could have on the average). These "delay days" were then broken into two main groups—one group included delays directly attributable to weather in New York airspace, the other group included delays attributable to causes unrelated to weather in New York airspace. The first group had three subcategories: thunderstorms, low ceilings and/or visibility, and high surface winds. The second group also had three subcategories: delay due to weather elsewhere in the country, delay unrelated to weather, and delay where cause was unknown. Weather data were taken from two sources: METAR surface data at EWR and New York ITWS daily operations reports. All categories were unique (i.e. delay days were put into one, and only one category). The priority list for days that had multiple causes is as follows: thunderstorms, low ceilings and/or visibility, high surface winds, weather elsewhere, unrelated to weather, and unknown. A complete list of the delay days for September 1998 to August 1999, as well as their associated categories, appears in Appendix A.

It is important to realize that in this discussion we are not attempting to convey the idea that weather is the only cause of delay on days with adverse weather. Decisions made by traffic managers and airline schedulers in response to the weather play a significant role in the system. The goal in determining the relationship of weather to delay in New York is to focus research on ways to reduce delay that could have been avoided despite the adverse weather.

5.2 Categories of Delay Days

5.2.1 Thunderstorms

If a METAR report contained the mention of a thunderstorm, that day was listed as a thunderstorm day. However, we augmented METAR identified thunderstorm days by reviewing the ITWS daily operation reports, which generally report any thunderstorms occurring within the New York TRACON and sometimes just beyond its borders. This was a critical source of information, since thunderstorms 100 nmi or more from EWR can significantly disrupt operations, even though a METAR would not mention the storm unless it tracked directly over the airport.[6] In fact, on thunderstorm-induced delay days, 70 percent of the hours during the delay period at EWR were VMC. Furthermore, more than half of the thunderstorm days, including some with very high total delay, had VMC at EWR during the entire delay period (see Appendix A).

5.2.2 Low Ceiling and Visibility (C & V)

The C&V category implicitly includes all significant precipitation events at the airport, as they always result in low ceilings and visibility. Also, contrary to some studies (Clark and Wilson, 1997; Robinson, 1989), we do not consider low ceilings and low visibility as two separate categories. Low visibility and low ceilings both have similar effects on arriving aircraft—they directly limit airport arrival capacity due to horizontal or vertical visibility. C&V days were defined as those that had either ceilings less than 3500 ft or visibility less than five miles. We further required that the two hours of average arrival delay greater than or equal to 15 minutes coincided with the low ceiling and visibility conditions defined above.

5.2.3 High Surface Winds

High wind day identification was more subjective. Ground delay programs are frequently implemented at New York airports when strong, gusty northwest winds make it difficult to control aircraft spacing, and limit capacity by forcing the airport into sub-optimal runway configurations. The primary parallel

[6] The problem in using METAR data to assess convective weather impacts on terminal operations is also discussed by (Bieringer, et al., 1999). They concluded that the use of thunderstorm day climatology for an airport to estimate the frequency of terminal operations impact by convective delays undercounts the frequency of convective impacts by about 80%.

runways at EWR—runways 4 and 22—allow for maximum winds (including gusts) of 20-28 kts for wind directions between 260-340 deg (Figure 13). As a first guess at finding days where high winds caused delays at EWR, we identified all the remaining delay days where the only limiting weather type during the delay period was sustained winds of at least 15 kts during any two of those delay hours. To further remove doubt that winds were a factor in delays on these days, we cross-checked all available EWR and N90 facility logs to make sure that winds were referenced as a problem. If winds were not referenced as a problem, we did not include that day in the wind category. These were called wind days, with the primary assumption being that the high sustained winds of 15 kts or more were gusting to at least 20 kts and making it difficult to sequence aircraft properly. Difficulties with compression on final approach during very windy days can also lead to delays. As stated earlier, compression problems result when descending aircraft encounter rapidly changing winds, and thus become more closely spaced as ground speed decreases. Unless fewer planes are handed off to the TRACON (by increasing aircraft spacing outside the TRACON), there will be an overload of aircraft on final approach, and holding (along with increased workload) will result.

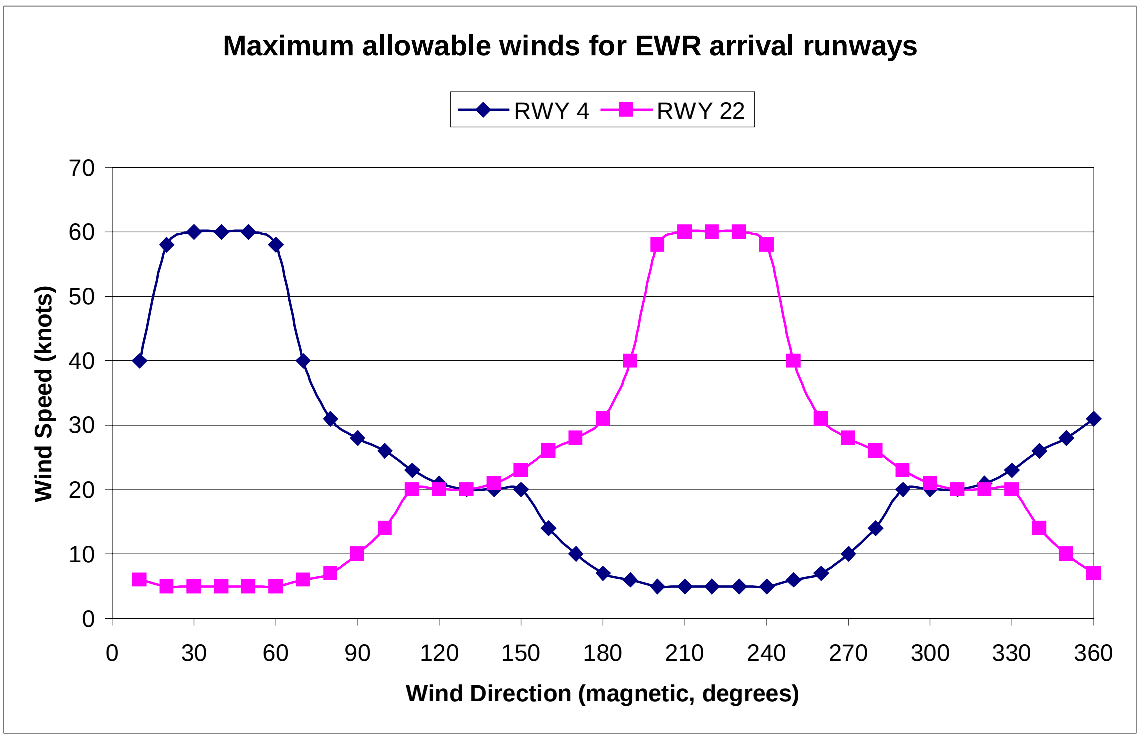

Figure 13. An illustration of reduced capacity created by strong northwest winds at EWR. Winds near or above the shown thresholds significantly reduce capacity, and force use of the low capacity cross runway, 29. The problem occurs both with strong northwest and southeast winds, however the former is by far the dominant problem at EWR. Information obtained from the ATCSCC web site (http://atcscc.faa.gov).

5.2.4 Delay Due to Weather Elsewhere in United States

A very common occurrence during the convective weather season is that the traffic moving to or from New York is delayed by convective weather between the other airport and New York. Thus, we have attempted to identify cases where the arrival delay at EWR in this study arises from weather elsewhere in the country when there was no significant weather in or near (e.g., within 100 nmi) the New York airspace. It has been noted by New York ITWS staff that weather elsewhere generally causes significant impact only when affecting airspace between here and Chicago, Atlanta, and Florida. Thus, only the eastern half of the nation (from the Great Lakes eastward and southward) was considered. During these scenarios, Severe Weather Avoidance Procedures (SWAPs) are often implemented, and departure and arrival delays are usually substantial, especially when widespread thunderstorms close many routes to the south or west of New York. When SWAPs are implemented, preplanned re-routing procedures are implemented to evenly distribute flight plans displaced from closed routes. SWAPs involve extreme coordination, as well as a high workload, for the TRACON and ARTCC facilities involved.

Three important sources of information were used to determine if delay at EWR was due to weather in another location:

1. Facility logs from N90 (TRACON), EWR, and ZNY (New York Center).
2. National radar mosaics archived at the National Climatic Data Center.
3. CODAS delay data from facilities close to severe weather.

If an intense squall line hundreds of miles in length was present between New York and Chicago airspace, and if lengthy delays (several hours of departure delays greater than 15 minutes) were occurring at Chicago O'Hare International Airport (ORD), this was flagged as "weather elsewhere". If there was no squall line, but there were strong storms near Chicago, or any point between New York and Chicago, and if delays were present at ORD, we also attributed these EWR delays to weather elsewhere. If significant weather (such as a snowstorm or thunderstorm) was occurring north of New York in New England, and if long delays were present also at Boston Logan International Airport (BOS), we attributed New York arrival delays to weather elsewhere. A similar method was employed for weather in Washington, DC airspace, using delay information from Washington Dulles International Airport (IAD). If widespread, major convective weather were occurring in the Southeast, it was assumed that any arrival delay at EWR was due either to departure delays in the south because of a major convective outbreak, or the "ripple" effect due to the same weather. Any questionable days were not included in this category if facility logs did not mention restrictions in areas impacted by severe weather.

It is recognized that this is a subjective attempt to determine what amount of arrival delay in New York is due to weather elsewhere. Even on days when there is weather in New York, an undetermined amount of that delay is due both to weather elsewhere, and to the downstream delay effect. Also, although we believe the majority of delays due to weather elsewhere can be attributed to significant precipitation (especially convection), it was impossible to determine if non-precipitating weather elsewhere was inducing delays. For these reasons, we feel it safe to say our assignments of delay incidents to the "weather elsewhere" was quite conservative.

5.2.5 Delay Unrelated to Weather

If there was no weather that fell into any of the above categories during a delay period within the significant demand period (0800 to 2200 LT), then that delay was said to be unrelated to weather.

5.2.6 Delay Cause Unknown

There were several days where it simply could not be determined with any degree of confidence what the source of delay was. Most of these cases were days on which average delays were high for a few hours during the late evening or very early morning hours. These may have represented long-haul flights arriving during off-peak hours that had been delayed for some unknown reason. In many cases the delay could have been due to weather on the west coast or some other far-away destination. It may also have been that the flights were delayed for mechanical reasons. In other cases, weather in the eastern half of the nation was not of a magnitude to definitively say it disrupted air travel in the east. Rather than guess, we simply said that the cause of delay was unknown.

5.3 Weather Impacts for September 1998 through August 2000

The two years included in this study were very different in terms of precipitation. The full year period of September 1998 through August 1999 was 25% drier than the climatological average, while the full year period of September 1999 through August 2000 was 13% wetter than the average. The same result held true for the two summers: the summer of 1999 was almost 30% drier than average, while the summer of 2000 was 25% wetter than climatology[7]. This is very pertinent for the findings in this section, since it suggests that the delay causality results for the two years together represent a reasonable average of what might be expected at EWR in a "climatologically average" year.

Convective weather clearly has the biggest impact on EWR operations (Table 1 and Figure 14), primarily during the spring and summer months (Figure 15). Not only are the impacts more severe per event than any other category, but cancellations and diversions are by far the highest of any category (see Appendix A). Delays associated with convective weather both inside and outside New York TRACON airspace account for almost 40% of all arrival delay at EWR. In fact, convective weather elsewhere is related to 14% of all arrival delay at EWR in a year.

Why is it that thunderstorms disrupt air travel so severely and what can be done about it? A level 3 or greater thunderstorm is generally anywhere from 25,000 to greater than 50,000 – too high for most aircraft to fly over. In the busy airspace in and around New York, this is akin to parking a car on a busy highway in the middle of rush hour. The result is a major traffic jam. A hotly debated topic is what the most effective ways are of dealing with aircraft flows near thunderstorms. One common method of alleviating impacts is to reduce traffic in the skies by intentionally delaying aircraft on the ground using Ground Delay Programs (GDP)[8]. This allows airborne aircraft more leeway in maneuvering around storms. A common misperception is that airports such as EWR can't land as many aircraft on days when there are thunderstorms nearby – as long as the storm is not over the airport, the real problem is getting enough aircraft to the runways. It can be seen in Table 5 and Figure 15 that during weather events, New York often makes use of GDPs to reduce airborne volume and mitigate airborne delays. What is noteworthy is the sharp increase in use of GDPs during 2000, especially on days when weather elsewhere is impacting New York operations.

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[7] Source: National Climatic Data Center

[8] For every flight, CODAS directly reports the amount of delay that is directly attributable to GDPs. When a GDP is in effect, each flight is given a computer-generated Estimated Departure Clearance Time (EDCT), in order to meter the arrival rate at the destination airport. Since a flight is not permitted to leave before this time, that portion of the delay can be easily determined. It is hoped that this forced ground delay significantly reduces airborne holding and diversions.

Table 5

Summary of weather impacts at EWR from September 1998 through August 2000. All statistics are for arrivals and are from the CODAS data set. It is also important to note that GDP data was missing from CODAS from late June to late August of 2000. The GDP results in the table for that year are extrapolated from those months where the data were available. This is not expected to change the results significantly.

Primary Delay Cause	Number of events		Average delay per event (min*1000)		Percent of total annual delay		Percent of delay due to GDP per category	
Thunderstorms	36	48	16.8	17.1	24.6	27.8	28.6	41.9
Low Ceiling/Visibility	53	42	14.7	15.9	31.6	22.6	36.2	52.2
High Winds	25	44	12.3	12.3	12.6	18.3	24.6	46.3
Convective Weather Elsewhere	31	36	9.9	12.6	12.4	15.4	6.1	40.0
Weather Elsewhere (non-conv.)	9	1	8.9	5.1	3.2	0.2	2.6	0
None	33	44	6.9	7.4	8.9	11.0	2.1	4.2
Unknown	24	21	6.9	6.6	6.7	4.7	0	0

shaded columns represent September 1998–August 1999
adjacent columns represent September 1999–August 2000

Similar to thunderstorms in total annual impact and second in average delay per event was ceiling and visibility. This category is also first in delay due to GDP, with almost 45% of C&V arrival delay directly attributable to GDPs. This is likely a function of the persistence of many C&V events, which results in lengthy programs. There are, however, several influencing factors besides the low ceiling and low visibility involved in some of these cases. Many of these cases occurred during East coast storms, which often featured heavy rain, freezing rain, snow, strong winds, and high vertical wind shear, all of which contribute their own unique difficulties to aviation. Significant vertical wind shear was present on about 20% of C&V days (based on a review of ITWS operations logs). On these days, delays were generally 10 percent greater than the overall C&V average, while cancellations averaged 50 percent higher. While the vertical wind shear itself is certainly part of the cause for greater delay, as noted above, the wind shear was often featured as part of a significant east coast storm. It is also important to note winter weather events. There were 11 days (including 2 of the vertical wind shear days) classified as winter weather days. On these days, delays on average were 10 percent greater, but cancellations nearly doubled, due to the relatively long-lead time in the prediction of snowstorms. Increased delays in snow are partially attributable to snowplow and runway treatment operations. Overall, however, we feel that low C&V was the leading, persistent factor contributing to delay on all days in this category.

High wind days ranked third on the list in terms of average delay per event, and constituted over 15% of all delay during the year of the study. This is a category that is often overlooked when considering what weather leads to delays. Traffic managers typically institute a GDP when winds are strong and gusty from the northwest, especially during the winter (Figure 14) when pressure gradients tend to be stronger. On some of these days there is even strong vertical wind shear, which leads to higher average delays and cancellations. It can be difficult to predict and react to surface wind conditions, which can be highly variable and localized in nature. In New York, LGA and EWR both suffer when winds are strong during peak demand periods, because of the limitations of their runway configurations.

More than 15% of all delay was due to weather elsewhere in the country, although the true number may be even higher than this. Future research initiatives to reduce delays at EWR should include improved en route weather prediction products since reducing the EWR delays due to en route weather could result in tremendous delay reduction. We have often observed cases where the New York skies were clear of weather, but empty of airplanes, due to weather blocking routes into and out of the east. Reducing the frequency and duration of such events involves improved weather products and improvements in the coordination and effort between the FAA System Command Center and various en route centers throughout much of the country. In this study, 90% of the delay due to weather elsewhere was convective in nature, while only 10% were attributable to non-convective--but significant--rainfall or snowfall.

There were 77 cases in which weather did not appear to be a factor in delays. Note that both the delay per event, and the overall delay for the year are small. There are also a small number of GDP delays within this category. Some of these were days in which there was considerable haze in New York. In other words, they were days in which capacities were reduced due to visibility, but only minimally so. The surface visibility was above the study threshold of 5 miles, so it was not considered in that category. Other days were instances where there was a major equipment outage. Many of these "no weather" delays, however, represent how close New York airports operate to VFR capacities, and how easily delays can be created, even on clear weather days.

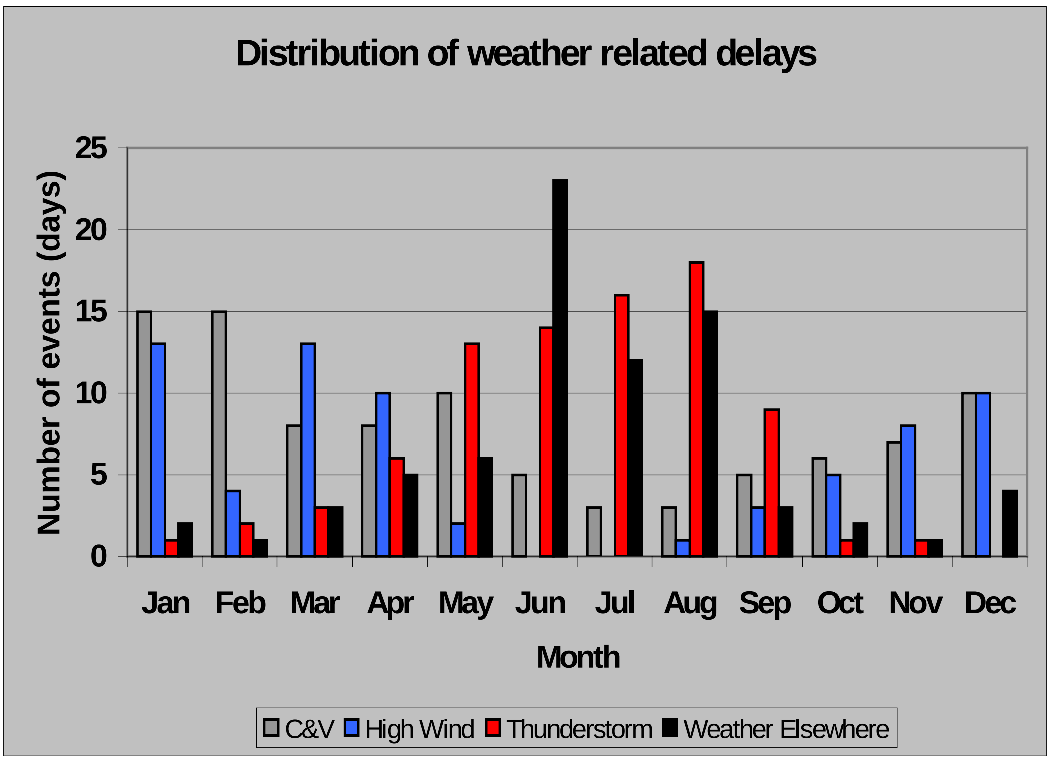

Figure 14. Illustration of the distribution of weather-related delay categories by month. The data include days which met the criteria set forth in the paper for delay days during the one year period of the study (September 1998 through August 2000), and should not be taken to represent any actual climatology, either for the two year period, or any other period of time.

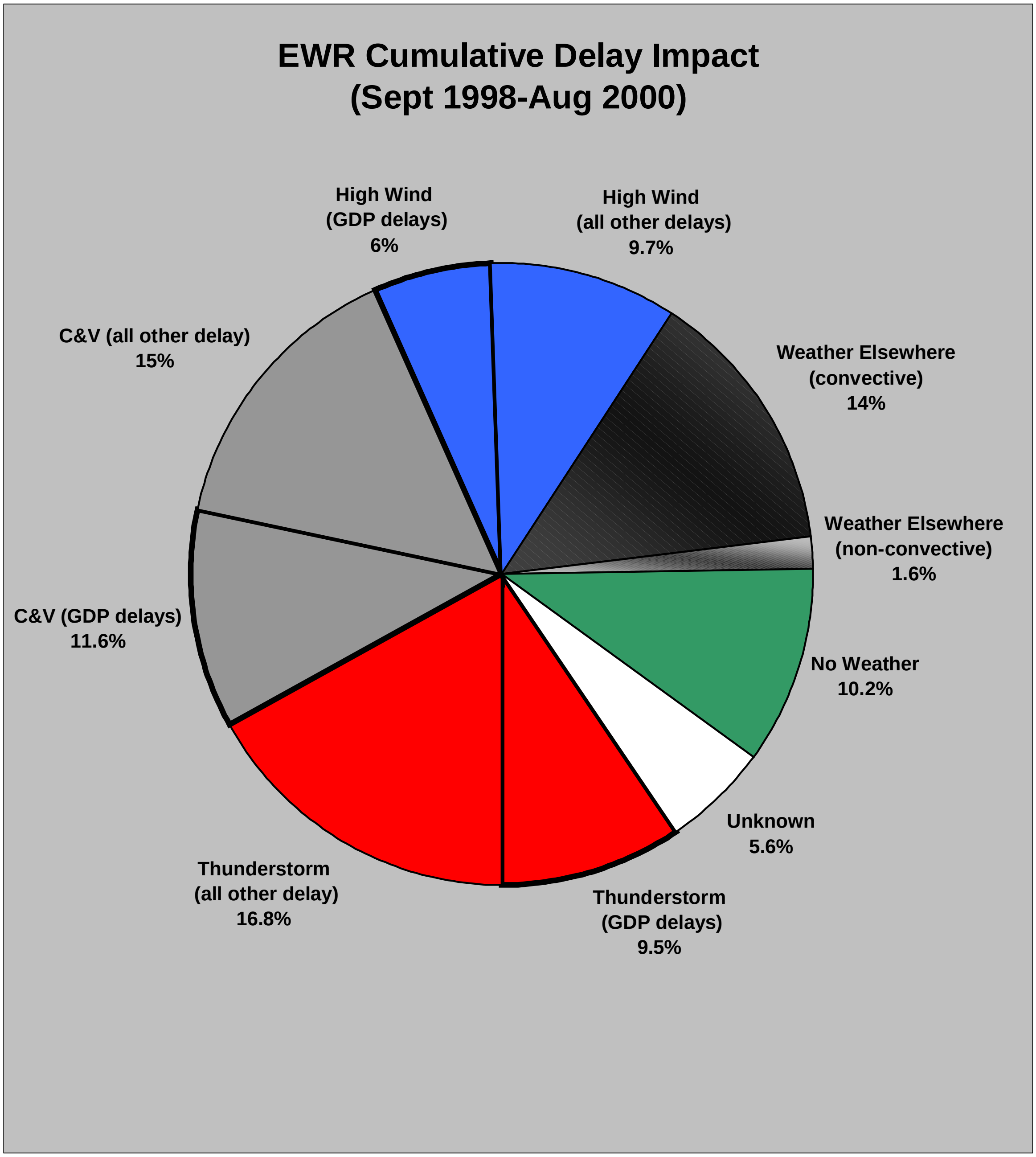

Figure 15. Percentage of total delay contributed by each group defined in study. Weather elsewhere is also separated into convective and non-convective events.

6. "AVOIDABLE" DELAY AT EWR WITH ITWS/TCWF IN OPERATION

6.1 Introduction

A critical issue in investing in air traffic management information systems such as preplanned product improvements for the ITWS and TCWF is what amount of delay that occurs with ITWS/TCWF in operation is actually avoidable, and what can be done to eliminate that avoidable delay. In this section, we discuss what might be done to reduce the various weather causes of delays that were discussed in Section 5

6.2 Delay Reduction Tools

6.2.1 High Winds

Perhaps the most difficult weather induced delay to address is the high wind problem. High winds tend to be a problem in New York most often in winter when large-scale storm systems are the strongest. Little can be done about the delays due to inability to use certain runways during high winds. However, providing automation aids such as the Center-TRACON Automation System (CTAS) and high quality estimates of the 3-dimensional winds, could mitigate controller problems in merging and sequencing aircraft to the usable runways. We have not quantified the extent to which the controllers at the TRACON do not achieve the desired spacing between landing aircraft during high wind events. NASA Ames, however, is conducting studies to determine to what extent CTAS might be able to increase the arrival acceptance rate at airports such as Newark.

Another problem on high wind days is that during the winter on clear-air days, Doppler radars suffer from a lack of clear-air scatterers (dust, haze, and insects) which provide valuable wind information. When the TDWR and NEXRAD Doppler radar data are unusable, the 3-dimensional winds must be estimated from aircraft (MDCRS) reports, model data (e.g., RUC), profilers, and surface sensors (e.g., ASOS). While these sources are important, Doppler radar data provide (1) the finest spatial resolution, (2) widespread coverage in the TRACON airspace, and (3) frequent updates which are helpful in dynamic situations.

As with low ceiling/visibility events, traffic managers usually address capacity-limiting winds by instituting ground delay programs. Short-term (1-3h) predictions of high wind conditions would help reduce delay by aiding in the correct timing and duration of those GDPs.

6.2.2 Thunderstorms

Quantifying avoidable delays during thunderstorm events is very complex, due to the widespread, en route nature of the problem. Since TCWF, and other convective weather research efforts are examining avoidable convective weather delay (Evans and Ducot, 1994; Forman, et al., 1999), we did not estimate avoidable thunderstorm delays in the study phase reported here.

6.2.3 Low Ceiling and Visibility

We will focus the rest of this discussion on what delay is avoidable during low C&V by various approaches.

6.2.3.1 Wake Vortex Advisory Systems

A weather adaptive wake vortex advisory system [Evans, 1995] may be a fruitful way of increasing capacity by permitting decreased spacing on landing or take-off under atmospheric conditions conducive to rapid dissipation of wake vortices. A study of the major West Coast airports [Evans, et al., 1999] showed that such a system could be quite beneficial at a number of these airports. Since the West Coast airports encounter winter storms that are similar to those at New York (low ceilings and visibility with high winds), a study of a weather adaptive wake vortex advisory at New York is warranted. However, this could not be carried out in this phase of the study.

6.2.3.2 Predicting the End of Low Ceiling and Visibility Events

Section 5 showed that low ceiling and visibility account for the largest percentage of weather delays at EWR during the study period. The extremely busy and congested Northeast Corridor surrounding EWR is especially characterized by short-duration flights, and the potential benefit of short-term C&V forecasts is significant as discussed by Evans (1995) and Wilson and Clark (1997). A program is underway to predict the burn-off of low ceilings due to marine stratus clouds at San Francisco International Airport (SFO) (Wilson and Clark, 1997)

Unlike SFO, EWR C&V conditions are largely driven by synoptic scale weather systems. Out of the 53 cases identified in Section 5 of this study, 33 were accompanied by stratiform rain of three hours duration or more. The remaining 20 cases were either rain free or featured scattered showers. Of the 33 rain events, the commencement of IMC conditions coincided with the onset of precipitation in 21 instances. This suggests that the commencement of precipitation may often be used as a proxy for IMC conditions. One possibility for reduction of delay under these circumstances would be to use the one-hour precipitation forecast of TCWF (Wolfson, et al., 1999) in conjunction with rapid-update satellite data to determine the onset/commencement of low C&V conditions.

6.3 12 February 1999—$1,500,000 in Avoidable Delay

6.3.1 Discussion

Opportunities exist for predicting the end of some low ceiling and visibility events using the current ITWS and TCWF storm tracking capabilities. It has been often observed that convection rapidly decays as it moves eastward through the New York TRACON's airspace. One frequent cause of this is the influence of cool ocean water on the marine environment near the coast, which often acts to increase atmospheric stability. If traffic managers know that convection to the west is dying as it moves into their airspace, they can increase arrival rates accordingly. The following example is a classic case where managers were able to use ITWS effectively to great economic benefit. However, opportunities existed for substantial additional economic saving through the accurate knowledge of the onset of low C&V, and the fact that a squall line had dissipated to only level 1 rain.

6.3.2 Weather Event Description

On 12 February 1999, a cold front tracked from west to east during the day. At EWR, the day started out with low ceilings and visibility but improved to VMC when the cold front entered the western edge of the TRACON. At this time the line was comprised of fairly strong VIP level 4 and 5 thunderstorms.

During the morning, with C&V conditions still low and a strong low-level jet of nearly 50 kts, the decision was made to implement an afternoon GDP with a 34 AAR rate starting at 1300 LT at EWR. As it became increasingly apparent that the cold front featured strong convection and turbulence, the decision was made to go into a SWAP at 1600 LT. This was suspended at 2100 LT with the cold front well to the east of JFK. However, as the line entered the TRACON, it unexpectedly began to dissipate, and weakened to only a level 1-2 line when still over an hour away from EWR. When the front passed over New York City, it was thunderstorm free, although the strong attendant wind shift led to 25 kt gains on EWR runways.

With the unexpected VMC prior to frontal passage, and the rapid dissipation of the line, there was a lengthy period between 1530 and 2245 LT where the capacity was not being met because of the SWAP and GDP. However, we assumed that traffic managers were able to match the arrival rate with capacity between 1830 and 1915 LT as the front crossed EWR, as it was recognized that with the strong wind shift, gain alerts, and localized turbulence, the assumed engineered capacities would be too high.

6.3.3 Results of Modeling 12 February 1999

The modeled actual delay (adjusting capacity to the actual arrival rate) is shown in Figure 16, while Figure 17 represents just the unavoidable delay (using derived capacities based on C&V conditions). The adjustment period was from 1545-2245 LT. The start time was chosen as the time the C&V conditions improved, while the area was free of significant precipitation. The end time represents the time that actual arrival rates finally increased to ideal capacity. In addition, the period from 1830-1915 LT was adjusted for both runs, to represent reduced capacity during the turbulent passage of the dissipating squall line. CODAS delay data is provided underlying each chart. Note in Figure 16 how well the model delay corresponds to the actual CODAS delay. This correspondence was typical of many of our modeled cases.

It was found that the total primary avoidable delay in this case was 230.9 hours. Using the same method as described in Section 2.2.4, this yields an estimated loss of $1,497,602 in direct operating costs as well as primary and downstream passenger costs. Air traffic control was able, however, to utilize the Terminal Winds product to their advantage by landing at least 3 extra planes per hour after the frontal passage, when there was a strong upper level jet creating significant vertical wind shear. We estimate that this saved a total of 25.9 hours of primary delay for a total benefit of $167,782.

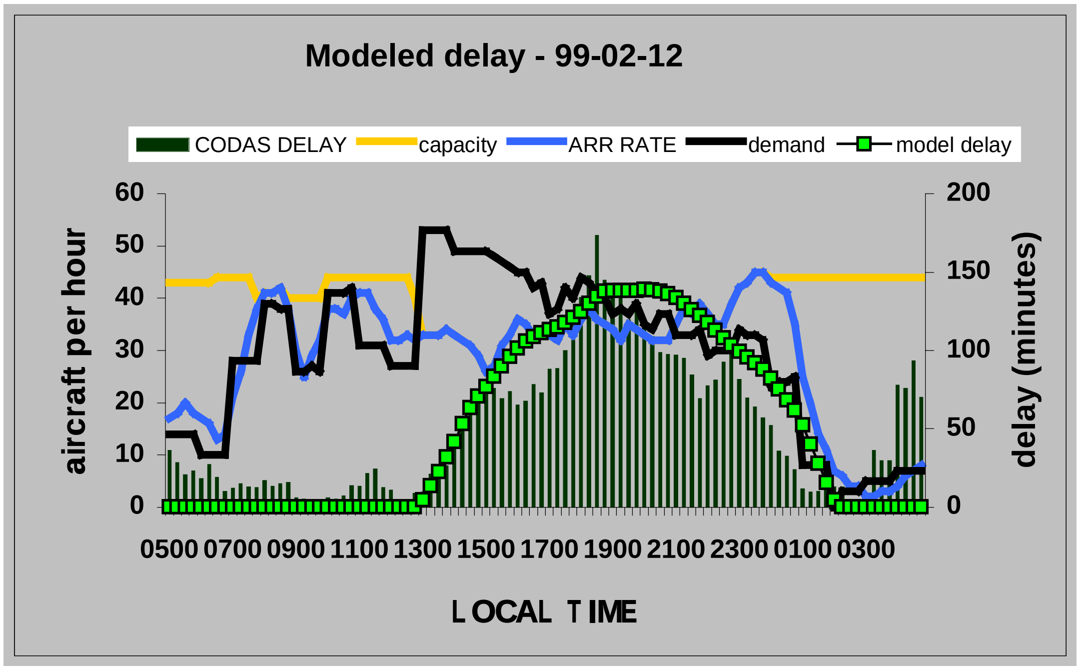

Figure 16. Delay information from the queuing model, assuming capacity equal to the actual arrival rate from 1545-2245 LT. CODAS delay is shown for comparison.

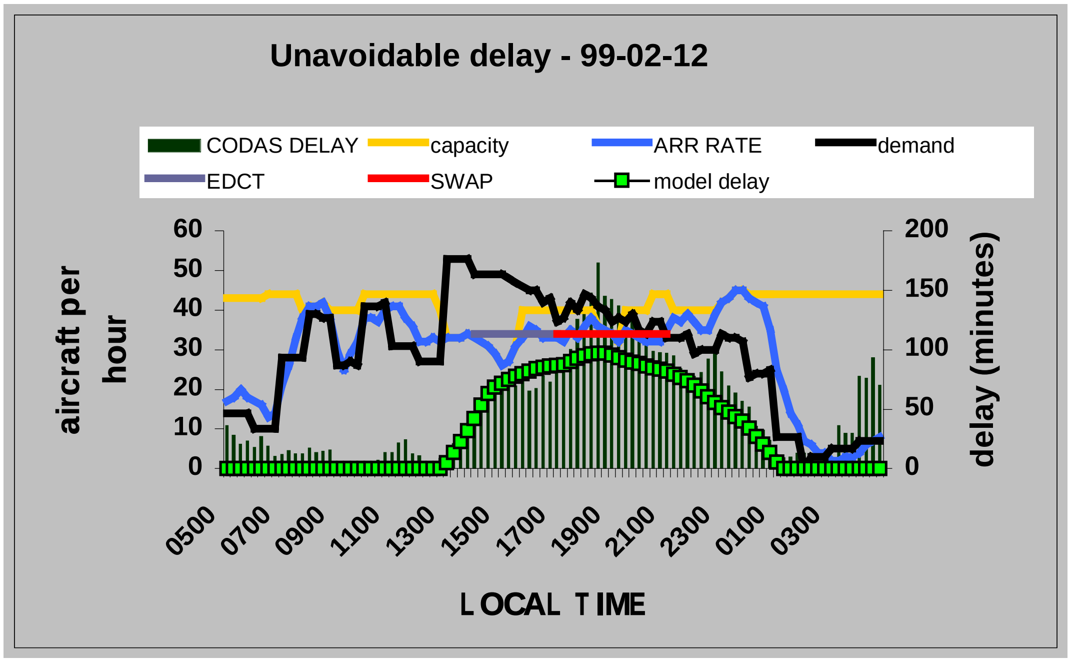

Figure 17. Delay information from the queuing model, assuming ideal engineered capacity. The period from 1830-1915 LT was adjusted to the actual arrival rate, due to a squall-line passage. CODAS delay is shown for comparison. The AAR for the EDCT program is also shown (EDCT/SWAP for reference.

6.4 Other Potential Avoidable Delay Benefits

Using the model and capacity method described above, we obtained avoidable delay statistics for a more typical day of low C&V conditions at EWR. On 19 May 1999 conditions improved to VMC earlier than forecast, and the implemented GDP lasted for 90 minutes beyond the end of IMC. It was estimated that by ending the GDP at the time conditions improved to VMC, nearly $240,000 would have been saved. While it is beyond the scope of this paper to consider the specifics of all 53 C&V cases, an estimate of potential savings can be derived. If this result were extrapolated to all 53 cases, the potential savings would be over 12.5 million dollars. More realistically, if only half of the cases are considered, the savings is still greater than 6 million dollars. Furthermore, this estimate only takes into account 90 minutes of increased capacity after IMC. Additional savings could be realized in some cases by increased accuracy of GDP rates in relation to true airport capacity during the IMC event.

At LGA, GDPs are implemented nearly as often as EWR due to restrictive runway configurations. Low ceilings and/or winds often force them into single runway operations. If we apply the result at EWR to LGA, a savings of $480,000 could be realized at the two airports by properly timing the GDPs to match low C&V conditions. This is not an unreasonable assumption, since LGA daily traffic counts are only slightly lower than EWR. These estimates do not consider JFK, which occasionally has GDPs, though not as often due to much higher capacities in IMC.

It should also be noted that while we have referenced both ITWS and TCWF at several points within this report, only ITWS was available to users during most of the analysis time considered in Sections 5 and 6 (as TCWF became operational only during the last month of this study).

7. CONCLUSIONS

This study examined delays at New York from September 1998 through August 2000 to determine:

- Benefits realized through the use of ITWS/TCWF at New York
- Major causes of the delay which occurred during the first year of ITWS use
- Delays that occurred with ITWS in operation that were "avoidable" if enhanced weather detection and prediction capabilities were added to the NY ITWS/TCWF system

All of these major objectives were achieved in the study.

The methodology used in the study has considered major causes of delays (convective weather inside and well outside the terminal area, and high winds) that have generally been ignored in previous studies of capacity constrained airports such as EWR. We have found that the usual paradigm of assessing delays only in terms of IMC v. VMC conditions and the associated airport capacities is far too simplistic as a tool for determining which air traffic management investments will best reduce the "avoidable" delays.

Additionally, we have identified some major new benefit categories (especially, enhanced arrival and departure rates during convective weather and, high surface winds) that need to be considered in future studies of terminal weather information systems such as ITWS/TCWF.

The three principal results of our study are as follows:

1. The FAA user interview/delay modeling analysis showed that improved decision making by the FAA air traffic personnel at the NY TRACON and towers using ITWS/TCWF is providing primary delay reductions of over 27,000 hours, with downstream passenger savings of an additional 22,000 hours, resulting in a total monetary savings (using standard FAA values for airline direct operating costs and passenger time costs) of over $150,000,000 per year.

2. Analysis of two cases revealed that during one convective event at EWR, over $2,000,000 in delay could have been avoided, and that during a typical C&V event, proper timing of termination of the GDP could result in a saving of $240,000 at EWR. Applying the same result to LGA suggests that savings of approximately $480,000 per event could be realized through proper timing of termination of GDPs at NYC airports.

3. Convective weather was related to the largest percentage of arrival delay at EWR, while low C&V accounted for 27% of arrival delay annually. It was also found that strong surface winds are a major cause of delays at Newark that have generally been ignored in all of the New York airport delay studies. In addition, weather elsewhere in the nation was found to contribute to at least 14% of all EWR arrival delay.

These results suggest important areas for future research. Given the magnitude of avoidable delay found in our case study, future in-depth analyses of such events should be conducted to understand why benefits are not realized, and to determine what is needed to help traffic managers reduce delay that is avoidable. Such a study would need to involve detailed examination of traffic flows and weather conditions using movie loops, and interviews with traffic managers to understand decisions at all involved facilities.

We also recommend en route weather decision support initiatives that would help reduce delay at New York airports resulting from weather outside of New York airspace. We plan in the near term to extend the NY ITWS coverage out to Western Pennsylvania by creating a three radar NEXRAD mosaic that uses the State College, PA NEXRAD.

Our findings on the magnitude of delay at EWR resulting from low ceiling/visibility and high winds also suggest that future research at New York should include the development of ceiling/visibility and surface wind prediction products that would aid in properly timing GDP programs and setting their AAR rates. The TCWF appears to have some skill in predicting the onset of low ceilings and visibility from winter precipitation and may be an appropriate candidate for a near term operational demonstration.

We would also note that the results of this study are very important for studies of the effectiveness of changes made to the U.S. aviation system (e.g., procedures changes, new controller displays, traffic automation software, traffic flow management systems, etc) to reduce delays at airports such as Newark. In these studies, one must normalize for the differences between the weather prior to the change under study, and the weather after the change was made. To accomplish this normalization, one must have a very good understanding of the principal causes of delay and appropriate models for computing the delay due to weather of various types.

The results in this report have shown that there are very important weather phenomena (especially, thunderstorms at distances greater than 100 nmi from the terminal area, high surface winds, and sheared winds aloft) that can be significant causes of delay that are not captured in the usual data bases (including CODAS) which focus only on ceiling, visibility and thunderstorm observations at the airports. Additionally, many previous studies have not properly accounted for differences in traffic mix between the periods under study as well as the times during which adverse weather occurs. This is particularly important where there are queuing delays such as account for the bulk of the delays at Newark.

APPENDIX A
DELAY DAYS AT NEWARK INTERNATIONAL AIRPORT
(SEPT 1998-AUG 1999)

Table A-1
Thunderstorm

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS	HOURS OF IMC DURING DELAY PERIOD	HOURS OF VMC DURING DELAY PERIOD
1999-05-24	31633	81	22	9.0	6.0
1999-08-26	31219	65	18	11.0	5.0
1999-07-22	25761	38	0	11.0	5.0
1999-04-09	25450	32	3	6.6	5.5
1999-01-18	24103	59	32	8.0	1.0
1999-04-16	22492	17	0	4.0	6.0
1999-06-29	21510	46	5	0.0	13.0
1999-06-28	21409	43	0	0.0	11.0
1999-07-30	20553	37	10	0.0	12.0
1999-08-20	20421	21	0	3.0	8.0
1999-08-14	20396	34	7	6.5	4.5
1999-07-28	20199	21	14	0.0	14.0
1999-08-13	20024	55	7	6.0	6.0
1999-06-13	19238	15	0	9.0	3.0
1999-07-19	18612	35	16	1.5	9.5
1998-09-07	17872	30	2	3.5	7.5
1999-07-06	17159	35	2	0.0	12.0
1999-03-03	17146	40	20	9.0	2.0
1999-05-08	16109	21	3	12.0	0.0
1999-07-02	15626	25	1	0.0	11.0
1999-06-07	15596	34	2	0.0	10.0
1999-04-11	15376	4	2	8.5	0.5
1999-07-24	14595	29	1	0.0	11.0
1999-07-18	14080	12	0	0.0	10.0
1999-06-14	13682	24	7	0.0	8.0
1999-08-05	12936	12	4	0.5	13.5
1999-07-25	12563	18	0	0.0	7.0
1999-07-29	12189	37	0	0.0	7.0
1999-07-17	11636	12	7	0.0	13.0
1999-08-08	11499	7	0	0.0	5.0
1999-08-11	11481	5	13	0.0	6.0
1998-09-02	10966	26	15	0.3	4.7
1998-09-27	8150	12	2	0.0	7.0
1998-09-22	6268	14	2	1.0	2.0
1999-04-06	5668	11	0	0.0	4.0
1998-09-21	4405	17	1	1.5	0.5

Table A-2
Ceiling/Visibility

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1999-07-01	32273	43	5
1999-05-07	28732	22	1
1999-01-08	28375	106	4
1999-04-23	27007	44	7
*1999-02-12	26763	39	6
1999-02-02	25927	50	3
1999-05-19	23571	48	1
*1999-01-03	20341	37	2
*1999-01-14	20055	136	10
*1999-01-15	19326	85	2
1998-10-09	19153	9	1
1999-01-22	18531	41	1
*1999-01-28	17772	27	0
1998-12-21	17728	22	2
1998-12-29	17593	14	0
1999-01-09	17380	18	9
1999-05-18	16626	27	0
*1998-12-08	16334	26	0
*1999-03-14	15954	33	11
1999-05-03	15913	9	1
1998-10-08	15867	10	2
1999-05-23	15438	6	2
1999-05-04	14041	25	0
1998-11-20	13979	8	0
1999-01-23	13858	69	39
1999-02-28	13645	23	2
1999-04-01	13613	6	0
1999-08-21	13212	12	7
1999-05-06	13129	20	0
1999-06-17	13095	14	0
1999-02-18	12735	26	0
1999-02-17	11785	32	0
1999-01-13	11404	43	6
1999-04-20	11402	13	0
1999-01-21	11306	25	1
1999-02-04	11234	13	1
1998-12-23	11010	16	1
1998-11-17	10921	20	0
1999-04-22	10705	23	0
1999-06-21	10080	8	0
1999-01-25	9801	24	2
*1998-11-10	9689	18	0
*1999-03-06	9463	27	2
*1999-03-21	9442	4	4
1999-06-09	9141	13	1
1999-08-15	8868	13	0

Table A-2 (Continued)
Ceiling/Visibility

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1999-06-12	8165	13	0
1999-01-24	7978	18	0
1999-02-25	7345	18	0
1998-09-30	6839	6	2
1999-03-28	6127	2	1
1998-10-10	5853	3	1
1999-02-07	4005	21	1

* Days that also featured strong vertical wind shear

Table A-3
High Wind

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1998-12-22	26864	10	0
1999-03-18	26287	29	6
1998-12-30	24623	21	4
*1999-03-15	16679	64	0
1999-04-14	15694	16	6
1999-01-04	15400	20	0
*1998-11-11	14090	14	0
1999-03-04	12670	42	1
1999-03-12	12483	9	0
1999-03-07	12370	15	0
1999-04-08	12146	9	5
1999-08-30	11275	7	2
1999-05-20	10889	7	0
1999-04-13	9995	9	4
1999-03-22	9822	18	2
1999-03-11	9765	9	1
1998-12-01	9456	6	0
1999-02-26	9253	10	0
1999-04-29	9024	5	0
1999-04-26	8195	14	1
1999-02-13	7984	17	1
1999-03-08	7519	26	1
1998-10-01	7357	6	0
1999-03-19	6643	3	0
1999-01-01	6302	7	0

* Days that also featured strong vertical wind shear

Table A-4
Weather Elsewhere

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1999-08-27	17586	34	3
1998-12-24	17079	19	0
1999-07-21	15861	17	1
1999-06-10	15051	21	0
1999-07-23	14718	36	1
1999-06-11	14715	23	0
1999-06-27	14414	7	1
1999-06-25	12643	12	0
1999-06-02	11600	20	0
1999-08-12	11246	10	1
1999-06-24	10746	12	0
1999-07-07	10431	18	0
1999-06-04	10092	13	1
1999-07-09	9990	17	1
1999-04-15	9814	8	1
1999-08-01	9582	6	0
1999-06-08	9456	18	0
1999-06-23	9281	18	0
1999-06-22	9210	14	0
1999-01-02	9034	49	0
1999-01-11	9029	35	0
1999-07-31	8869	20	1
1998-12-17	8811	5	1
1999-08-24	8752	13	0
1999-08-25	8594	15	0
1999-06-16	8372	12	1
1999-02-11	8343	32	1
1999-03-09	8227	33	0
1999-05-12	8066	21	0
1999-05-17	7805	22	0
1999-08-23	6919	6	0
1999-03-05	6403	20	0
1998-11-30	6014	4	0
1998-10-02	5722	7	0
1998-12-06	5632	5	0
1999-07-10	5576	7	1
1999-06-26	5422	5	1
1999-05-31	5005	1	0
1999-07-11	4922	1	0
1998-09-20	4827	11	0

Table A-5
No Weather

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1999-01-05	11840	17	2
1999-01-06	10623	19	0
1999-08-17	10561	4	1
1999-05-10	10295	20	0
1999-05-26	8640	11	0
1999-04-30	8356	7	1
1999-04-28	8296	5	0
1999-07-08	8235	9	0
1998-10-29	7159	10	0
1998-12-18	7101	3	0
1998-11-05	7064	8	0
1999-06-03	7019	11	0
1998-09-04	6712	23	1
1999-05-28	6711	2	1
1999-07-15	6576	9	1
1998-09-25	6463	29	1
1999-01-10	6375	8	0
1998-10-19	6304	6	1
1998-10-28	6287	3	0
1999-05-02	6280	3	0
1998-10-22	6131	6	0
1998-11-24	6110	3	0
1998-11-12	6064	8	1
1999-08-29	5816	3	1
1998-11-06	5780	9	6
1999-05-16	5555	2	0
1999-04-21	5548	7	0
1999-06-20	5149	9	1
1998-10-21	5055	3	5
1999-08-28	5039	2	1
1998-12-07	5029	8	2
1999-03-27	4422	3	1
1998-10-25	4420	3	0

Table A-6
Unknown Cause

DATE	TOTAL DELAY (min)	CANCELLED ARRIVALS	DIVERTED ARRIVALS
1999-05-25	9064	21	1
1999-05-05	8478	17	0
1999-06-30	8324	14	1
1999-07-20	8012	22	0
1999-06-01	7477	9	1
1999-08-19	7431	9	1
1998-12-28	7384	10	0
1999-07-26	7348	15	0
1999-06-15	7251	21	0
1999-07-27	6990	7	1
1999-06-06	6989	7	0
1998-10-05	6787	20	0
1998-10-18	6647	5	0
1999-05-13	6573	12	0
1999-07-05	6299	8	0
1998-10-23	6243	6	1
1999-08-22	6144	3	0
1999-08-04	6079	16	1
1999-03-25	5797	8	0
1999-02-01	5551	18	1
1998-09-11	5398	20	0
1998-10-04	5088	5	0
1999-05-09	4540	4	0
1999-03-13	4047	5	0

APPENDIX B
PREVIOUS ANALYSES OF ITWS OPERATIONAL BENEFITS

The approach used to assess the ITWS/TCWF benefits at New York that is described in the main body of the report was derived from an earlier study of ITWS benefits at Orlando, FL and Memphis, TN conducted in 1994-95 by a team from the Volpe Transportation Center and MIT Lincoln Laboratory. The basic approach was essentially identical to the approach used here:

- Interviews were conducted with operational users of the products to determine the operational decisions that had been improved by use of the ITWS products,
- Results of the interviews were then utilized in the benefits models described in Chapter 2 to determine quantitative benefits

However, a number of the beneficial operational decisions that were described by the FAA ITWS users at Memphis and Orlando are rather different from the beneficial decisions discussed in Chapter 4. Since the Memphis/Orlando operational decisions have been the principal basis for estimating ITWS operational benefits for the national deployment of ITWS, it is useful to discuss the differences between the findings of the two studies.

Table B-1 shows the benefits assessment for Orlando that would correspond to the benefits discussed in Chapter 4. We see that there are differences in both high benefits decisions and the magnitude of the benefits associated with some common decisions. For example, anticipating weather impacts on the arrival gates into the terminal area is the single highest benefit decision identified in the Orlando usage whereas the New York highest benefits are associated with departure rates and the use of the terminal winds; neither of which were significant benefits factors for Orlando (terminal winds was not tested in Orlando due to the excess runway capacity at the airport and generally benign winds aloft).

These data reflect the major differences in airspace available and runway usage at Memphis and Orlando versus New York. It is very difficult to reroute aircraft at New York from one arrival fix to another when a fix is blocked, and the New York airports typically have demands exceeding the runway IFR capacity whereas both Memphis and Orlando typically have excess IFR runway capacity and, considerable freedom to re-route aircraft in the transitional en route airspace.

In 1995, the expected benefits for the New York airports were estimated on the basis of extrapolation from the Memphis and Orlando experience to be on the order of $30,000,000 per year[9] for delay reduction during thunderstorms. This estimate is much lower than the $100,000,000 for thunderstorm delay reduction shown in Chapter 4, and illustrates the problems of extrapolating the results from airports and airspace which are not highly congested to highly congested airport complexes such as New York.

The good news is that airport complexes such as New York which appear to have intractable delay problems due to the congestion and complexity of the terminal area can in fact achieve very significant delay reductions when provided with appropriate decision support tools such as ITWS/TCWF.

One of the interesting issues to be resolved in the next few years will be the extent to which other major terminal complexes such as Chicago and Washington DC are like New York or, whether they are more like Memphis and Orlando. It should be noted that Dallas appears to be similar to Memphis and Orlando in terms of the operational decisions that are most significantly enhanced by the ITWS/TCWF products.

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[9] This delay estimate includes a correction for the frequency of thunderstorm impacts that was developed in 1998.

Table B-1
Orlando ITWS Delay Reduction Benefits Estimates
(1994 KDP-3 numbers with 1998 climatology corrections)

Benefit Category	Hours Saved	Direct Operating Cost	Passenger Delay Cost	Total Delay Savings
DTA Closure Anticipation	152	$68,399	$311,596	$379,995
DTA Traffic Balance	84	$38,000	$173,109	$211,108
Runway Shift Anticipation (TSTM)	32	$22,166	$64,916	$87,082
Shorter Terminal Flying Distances for Departures	12	$11,856	$25,584	$37,440
Runway Shift Anticipation (GF-MIGFA)	0	$0	$0	$0
Recognize that one runway will remain open	1056	$1,002,760	$2,163,850	$3,166,610
ATA Reopen Anticipation	477	$453,517	$978,642	$1,432,159
Recognize that ATA will remain clear	469	$445,673	$961,716	$1,407,389
ATA Closure Anticipation	398	$377,931	$815,535	$1,193,466
Land planes before event rather than hold them	370	$351,969	$759,511	$1,111,480
Airport reopening anticipation	127	$120,331	$259,662	$379,993
Position holding aircraft for quicker landings	79	$75,207	$162,290	$237,497
More arrivals before AAR reductions	23	$21,375	$46,125	$67,500
Hold Jets Higher	0	$5,675	$0	$5,675
Better Recognition of Advantageous Ground Stops	0	$25,333	$0	$25,333
Fewer Diversions before airport shutdown	0	$1,646,637	$0	$1,646,637
Fewer Diversions near airport reopening	0	$633,322	$0	$633,322
Call Necessary Diversions Sooner	0	$1,583	$0	$1,583
Fewer first tier ground stops	95	$42,749	$194,747	$237,496
Shorter ground stops	222	$99,748	$454,409	$554,157
Airline Dispatch avoids specifying alternate airport	0	$75	$0	$75
Improved Fueling estimates in marginal wx	0	$281	$0	$281
Improved handling of priority connecting flights	0	$31,666	$0	$31,666
Fewer missed connections at hubs	0	$346,930	$0	$346,930
Fewer occasions of ramp gridlock	52	$23,418	$106,681	$130,099
Total Primary Delay	3,648	$5,846,602	$7,478,373	$13,324,975
Downstream Passenger Delay	2,918	$0	$5,982,698	$5,982,698
Total Benefit	6,566	$5,846,602	$13,461,071	$19,307,673

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