Project Report
ATC-305

An Analysis of the Impacts of Wake Vortex Restrictions at LGA

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16 September 2002

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16. Abstract

Wake vortex restrictions at New York's La Guardia airport cause a significant reduction in capacity when aircraft land on runway 22 and depart on runway 31. This report presents an analysis of the annual delay cost at LGA associated with the wake vortex restrictions. We find that the delay due to these restrictions exceeds 4000 hours annually, and that these restrictions cause a significant workload increase to controllers at both La Guardia and the New York TRACON. If traffic levels were to increase 10% from their February 2001 levels, the corresponding increase in delay due to the wake vortex restrictions would rise from 30 hours a day to over 400 hours a day in this runway configuration. It is also found that for a meaningful increase in passenger capacity in this runway configuration to be achieved as demand grows, restrictions must be reduced from their current levels. If the percentage of heavy/757s doubled at LGA, there would be no increase in passenger capacity while daily delays in this runway configuration due to current wake vortex separation standards would increase by 250 hours.

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ABSTRACT

Wake vortex restrictions at New York's La Guardia airport cause a significant reduction in capacity when aircraft land on runway 22 and depart on runway 31. This report presents an analysis of the annual delay cost at LGA associated with the wake vortex restrictions. We find that the delay due to these restrictions exceeds 4000 hours annually, and that these restrictions cause a significant workload increase to controllers at both La Guardia and the New York TRACON. If traffic levels were to increase 10% from their February 2001 levels, the corresponding increase in delay due to the wake vortex restrictions would rise from 30 hours a day to over 400 hours a day in this runway configuration. It is also found that for a meaningful increase in passenger capacity in this runway configuration to be achieved as demand grows, restrictions must be reduced from their current levels. If the percentage of heavy/757s doubled at LGA there would be no increase in passenger capacity while daily delays in this runway configuration due to current wake vortex separation standards would increase by 250 hours.

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1. INTRODUCTION

It has been recognized for many years that vortices generated from the wingtips of airborne aircraft are a safety hazard to trailing aircraft that may encounter these vortices. The vortices are transient in nature and almost always invisible to the human eye, making it difficult for pilots to know when or where they may encounter them. Eventually they may dissipate, sink, rise, or drift out of the path of the trailing aircraft.

The danger presented by these vortices led to Federal Aviation Administration (FAA) imposed wake turbulence (vortex) separation standards to ensure that safety is not compromised, thus significantly lowering airport capacity. Although it has yet to be proven, many years of research suggests that the relationship between wake vortex behavior in IMC may not be different than in VMC [1]. Measurements taken over many years show that the current separation requirements are overly conservative in many weather conditions and that more precise weather measurements and forecasts could substantially increase lost capacity due to wake vortex restrictions [2].

The lost capacity causes significant delay at busy airports that operate near or at capacity much of the time. New York's La Guardia airport (LGA) operates within possibly the busiest and most congested airspace in the world. Its two intersecting runways present an additional capacity limitation because of wake vortex spacing. A potential wake hazard exists for the arriving aircraft that follows a B757 or heavy aircraft (hereafter heavy/B757) that departs and is airborne over the intersection of the arrival and departure runway. This standard is applied when landing runway 22/departing runway 31 and landing runway 13/departing runway 4. The separation standard of 6-8nm is imposed between the departing heavy/B757 aircraft and the next arriving aircraft, depending on its weight class.

In concert with AIR-21 legislation and the removal of slot restrictions in the late summer of 2000, LGA regularly had daily operations exceeding 1400 aircraft, running at or above capacity from early morning until late evening. It was the most delayed airport in the United States during calendar year 2000, with the result that slots were re-introduced in early winter 2001 to limit operations to around 1250 aircraft per day. Because of its proximity to downtown Manhattan and popularity with both passengers and airlines, there is a critical need to understand the impact of wake turbulence separation at LGA to make the most efficient use of the airport while not increasing delays.

The effect of wake vortex spacing on capacity at LGA when landing runway 22 departing runway 31 (hereafter referred to as 22/31) is not well understood. This runway configuration is used almost 20% of the time. Controllers prefer to use other configurations when possible because of the need to coordinate with the New York TRACON (also known as N90) the creation of gaps in the arrival stream to meet wake turbulence separation standards. A runway intersection wake vortex constraint also exists when the airport is departing runway 4 and arriving runway 13, but since this runway configuration is rarely used this configuration was ignored in this analysis.

Past research has examined the wake vortex problem at La Guardia and what could be done to increase lost capacity due to wake turbulence separation standards. Eberle [3] examined two factors in reducing the restrictions. One factor was how often a wake vortex encounter would occur at LGA in 22/31. The second factor was whether aircraft encountering a vortex on a flight path perpendicular to the aircraft generating the vortex would respond differently than an in-trail encounter. It was found [4] that encounters would be very rare in this runway configuration but could not be completely avoided. They also found that cross-vortex encounters by landing aircraft would not be hazardous provided there was time to alert a pilot who was trained for such encounters.

Personnel at the MIT Lincoln Laboratory field site in Garden City, NY visited and had several conversations with LGA and N90 controllers to observe and understand how wake turbulence separation standards impact daily operations when LGA is in the 22/31 configuration. In addition to these observations and conversations, a detailed capacity analysis was carried out. This paper gives results from this analysis and documents the economic and human factor impacts of the wake restrictions in this runway configuration. We show there is a substantial benefit to be gained at LGA if wake turbulence separation standards can be reduced without compromising safety.

The report has six sections. Section 1 is the introduction. Section 2 describes how LGA operates in 22/31. Section 3 describes how we estimated capacity while section 4 describes how we modeled and arrived at the cost of wake vortex restrictions. Section 5 discusses possible strategies of dealing with increasing demand and how wake turbulence separation standards would impact those strategies. Section 6 gives recommendations and conclusions.

2. LGA OPERATIONS IN 22/31

The weather at LGA when departing runway 31 and arriving runway 22 is nearly always fair. From a meteorological perspective this is because prevailing winds from the west or northwest usually mean a dry atmosphere and the presence of a nearby ridge of high pressure. Both dynamically and thermodynamically this is unfavorable for precipitating weather systems. The most common cause of IFR conditions when in the 22/31 configuration at LGA is when a front passes through. Winds switch to the west/northwest forcing a reconfiguration to 22/31, but the atmosphere does not immediately dry out leaving an hour or two of IFR conditions. In many cases where the airport is transitioning from IFR to VFR conditions, and runways are reconfigured to 22/31, the airport will have already been in a delay situation because of the weather. It may take an hour or two for delays to dissipate and arrival/departure rates to return to normal. An investigation of many of the days in this configuration also revealed that enroute weather rarely impacts LGA when in 22/31. This fact is helpful for this study, since capacity when in this configuration is usually independent of outside weather factors.

Demand at LGA remains high from early morning until late evening. A quick analysis revealed that over 80% of the time the ratio of arrivals to departures did not exceed 60:40. A tower controller will apply standard intersecting runway separation whereby a departure on runway 31 will be cleared for takeoff when the arrival on 22 passes through the intersection of runway 31. The runway 31 departure has to cross the intersection of runway 22 prior to the arrival crossing the landing threshold. Standard FAA spacing requirements are followed for the arrival stream provided there are no miles-in-trail (MIT)[1] or wake turbulence separations required.

Based on airline scheduling there are an average of three heavy/B757 departures each hour. Most of these are Boeing 757s along with a few B767-400s and A310s. To understand the impact of these aircraft on operations in 22/31 we visited both LGA and N90 to observe and discuss with controllers what was done. Heavy/B757 aircraft are commonly taxied on an inner taxiway to minimize interruptions to the departure queue (Figure 1). Interruptions can happen when the required extra spacing in the arrival stream does not materialize and the heavy/B757 cannot take off. If a single departure queue is being utilized all the jets in the queue must wait until the requisite spacing materializes. The typical sequence of events is as follows. Approximately ten minutes prior to a heavy/B757 departure the LGA controller calls N90 and requests that extra spacing in the arrival stream (a gap) be created in preparation for a heavy/B757 departure. This information is entered on the flight strip for the arriving flight (Figure 2). Occasionally compression on final approach, heavy arrival demand, or controller workload, leads to the gap not being created. Untimely gaps or miscalculation can lead to arrival airborne holding, which can cause ripple effects hundreds of miles from the airport. In rare cases a tower controller may ask an arrival to execute a go-around so that the heavy jet can get off the ground and not impact the departure queue. Assuming the

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[1] The term MIT refers to a type of restriction used by the FAA to meter volume over fixes or to limit the amount of aircraft in a piece of airspace at any given time. It refers to a required spacing in miles between aircraft. For example a 40 MIT restriction means aircraft must be spaced 40 miles apart.

N90 controller can create the gap, the heavy/B757 on the inner taxiway will start its takeoff roll just as the arrival at the front of the gap crosses the intersection. Regulations state that for intersecting runway restrictions, when a heavy departure crosses the intersection the separation standards in Table 1 apply. Controller interviews confirm that not only do these restrictions limit airport capacity, but that there is a significant increase in controller workload both at LGA and N90.

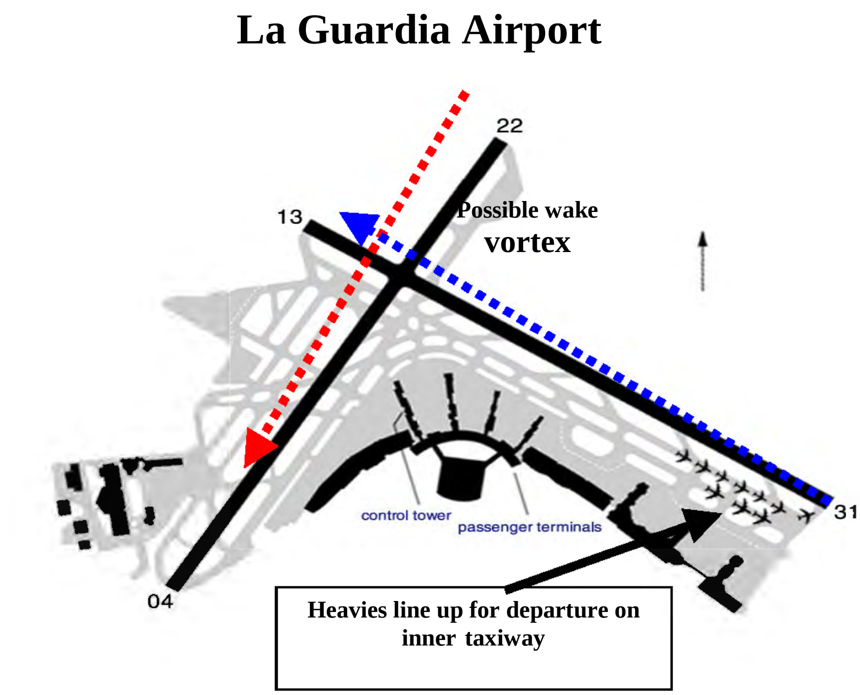

Figure 1. La Guardia Airport operating with arrivals landing runway 22 and departures departing runway 31.

TABLE 1

Spacing criteria for arrivals following a heavy/B757 departure crossing the runway intersection.

Arrival	**Arrival Spacing requirement (nm)**			
	Departure			
	Heavy	***B757***	***Large***	***Small***
Heavy	***4***	***4***	***2.5 – 3***	***2.5 – 3***
B757	***4***	***4***	***2.5 – 3***	***2.5 – 3***
Large	***5***	***4***	***2.5 – 3***	***2.5 – 3***
Small	***6***	***5***	***4***	***2.5 - 3***

Restrictions in 22/31 are possible due to external factors such as weather in enroute airspace, MIT restrictions on aircraft bound for LGA, or internal factors such as airport congestion. These other restrictions make it difficult to isolate the effects of a single restriction like wake vortex spacing. This task was attempted by directly comparing arrival and departure rates in the 22/13 configuration with the 22/31 configuration. The 22/13 configuration is the most favored configuration (Table 2), and if wake turbulence restrictions were not an issue the 22/31 configuration would have comparable but slightly less capacity than the 22/13 configuration. Data were only used where the arrival/departure rate ratio was similar and where there were no known major internal or external factors present such as weather or airport gridlock.

TABLE 2

Capacity numbers supplied by N90 that are used as guidance when setting Ground Delay Program rates for LGA.

LGA Arrival Rates (Favors arrivals)						
Runway			**Capacity**			
Arrive	***Depart***		***IFR***	***MVFR***	***VFR***	***VFR optimum***
22	**13**		**34**	**36**	**39**	**44**
22	**31**		**30**	**32**	**34**	**39**
4	**13**		**29**	**35**	**37**	**41**
31	**4**		**27**	**30**	**35**	**39**
31	**31**		**22**	**27**	**29**	**34**

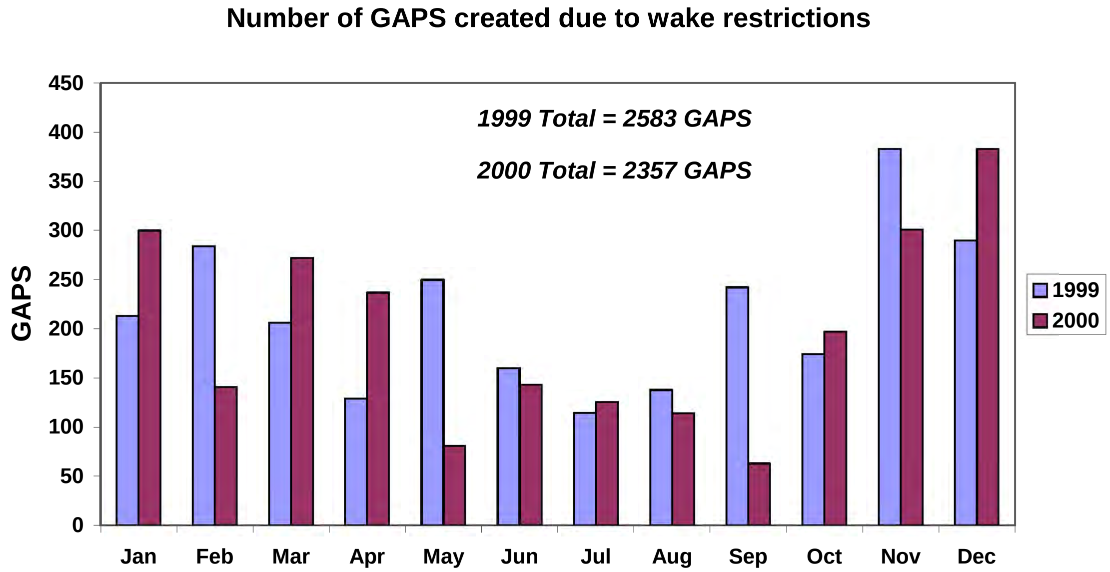

Figure 2. Monthly number of wake vortex restriction gaps recorded on flight strips.

3. ESTIMATING CAPACITY IN 22/31

3.1 DATA SOURCES

Aviation Data Systems collects all flight strips from EWR, LGA, JFK, and TEB and enters them into a consolidated database called Collection and Analysis of Terminal Records (CATER). This data set is the most comprehensive set of operations data available for LGA. It contains runway configuration, weather, aircraft type, comments, and many other types of information for each aircraft at these airports and is the primary source of information for this study. Like all other data sets it has limitations. Flight strip data are hand entered into the database and this may introduce some human error. Human error may also occur on the flight strips themselves. It has the advantage, however, of including every operation at LGA and not just those on the Official Airline Guide (OAG) schedule.

A queuing model [5] was used to assess the delay impact of wake restrictions. This model needs only two inputs, demand and capacity. Demand was taken primarily from the OAG schedule. Capacity, detailed in a later section, was derived from the CATER data set. Any weather information was also taken from CATER, which includes archived weather observations from Automated Surface Observation System (ASOS) for all airports in the database.

3.2 DETERMINING CAPACITY IN VFR CONDITIONS

Capacity varies according to runway configuration, local weather, enroute weather, controller efficiency, local airspace limitations, spacing restrictions, etc. There are several approaches to estimating capacity. One approach is to use a model that takes into account the physical and operational characteristics of the airport. An example of this is the George Mason University Macroscopic Model [6]. Another approach is to estimate the runway capacity of the airport by looking at the capacity of the airport system. Welch [7] looked at Consolidated Operations and Delay Analysis System (CODAS) airborne delay as an indicator of the system capacity. An airport may have many runways and high runway capacity, but due to dense enroute traffic may never be able to utilize that runway capacity. Even if demand does not reach the runway capacity, short spurts of arrival traffic result in airborne aircraft queues and airborne delay. System capacity takes into account the inability of the airspace to keep airborne queues from forming. The FAA also recently published its benchmark capacity report [8] for 31 airports, taking into account peak achieved traffic rates, the FAA's airfield capacity model[2], and the airline schedule. The estimated benchmark capacity for LGA was 80 operations per hour (arrivals plus departures). This was based on the best configuration without impacting weather.

Our study derived LGA capacities empirically based on actual arrival and departure rates. This method can only be used at those airports where the demand continuously meets or exceeds the airport's runway capacity. The time period used was September-December 2000. During this period all slot restrictions

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[2] "Upgraded FAA Airfield Capacity Model (User's Guide)," FAA-DF-81-001A, May 1981

were lifted at LGA, and the airport ran operations at or above published capacities from early morning until late evening. Figure 3 shows the delays that resulted from the lifting of these slot restrictions.

We calculated capacity for two runway configurations, arriving runway 22 and departing runway 13 (hereafter 22/13), and arriving runway 22 departing runway 31. Table 1 shows guidance capacities used by the FAA for these runway configurations.

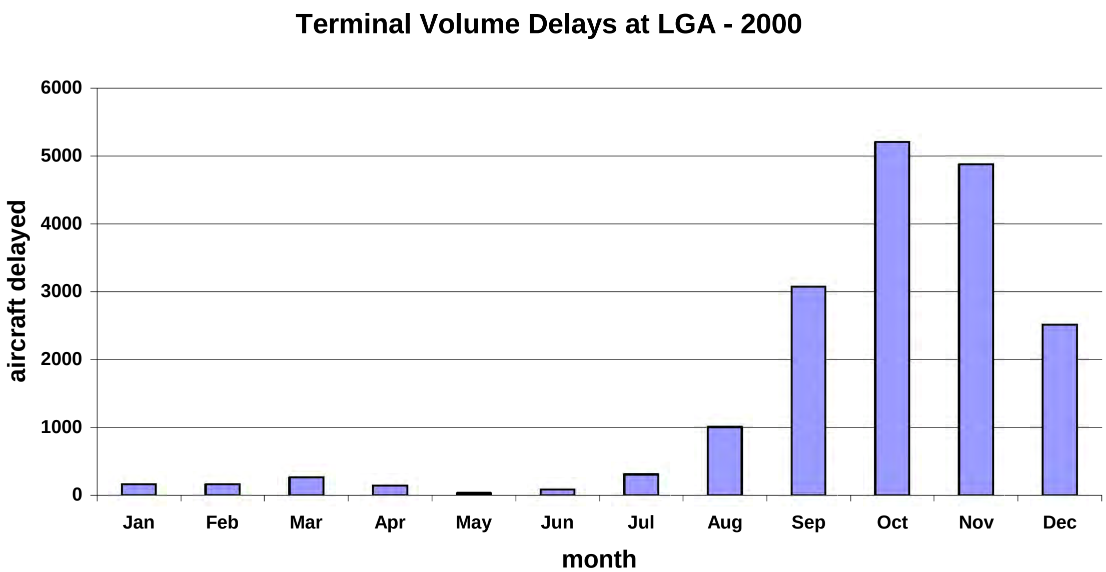

Figure 3. Monthly number of aircraft delayed due to volume at LGA during 2000. Source: OPSNET data at www.fly.faa.gov.

We calculated 60-minute arrival and departure rates at 15-minute intervals for each day the airport was in either the 22/31 or 22/13 configuration. No hours were included where other configurations were in use. For each runway configuration, we subdivided the database of hourly arrival and departure rates into six categories based on the number of heavy/B757 departures during each hour. These categories were 0,1,2,3,4, or 5 or more heavy/B757s. There were not enough hours with more than five heavy departures to justify further categories. Finally, only those hours where the ratio of arrivals to departures was between 40:60 and 60:40 were included in the database. A brief analysis showed that this accounted for 87% of all hours between 7:00am and 10:00pm for the four month period we examined. For each category (e.g. all hours with 3 heavy/B757 departures and traffic mix between 60:40 and 40:60) of heavy/B757 departures, the cumulative probability distribution of arrival and departure rates for that category was calculated.

Figure 4 shows the arrival cumulative probability distribution for each category in the 22/31 configuration, as well as the cumulative probability distribution for the 22/13 configuration (not stratified by hourly heavy/B757 departure rate). One can see that the 22/13 curves very closely approximates that of the 0-heavy/B757 and 1-heavy/B757 curves of the 22/31 configuration. One can also see that the 5+ heavy/B757 curves in the 22/31 configuration shows much lower achieved arrival rates than the 22/13 configuration.

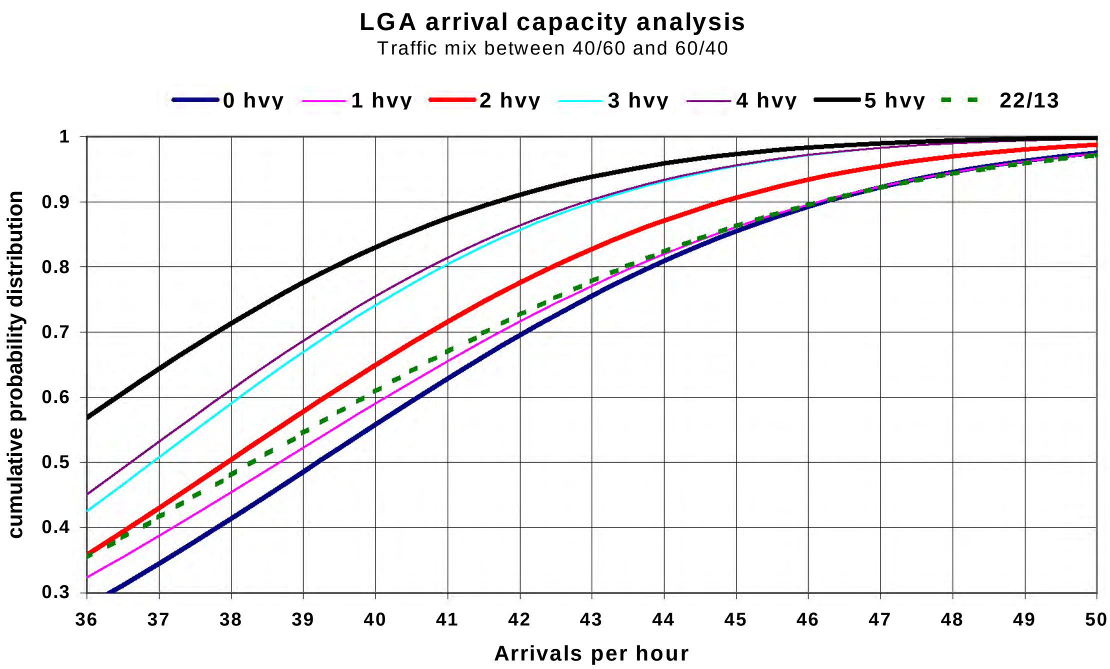

Figure 4. Cumulative distribution functions for hourly arrival rates at LGA calculated at 15 minute intervals when arriving runway 22 departing runway 31. All curves accept the dashed curve (representing arrivals on runway 22 and departures on runway 13) represent hours stratified according to the hourly number of heavy departures.

Figure 5 is the same as figure 4 except for departure rates. One can clearly see that the 22/13 departure rates are consistently higher than in 22/31. However, there is not a clear relationship between the number of heavy/B757 departures and the departure rate itself. For instance, when considering the top 30% of all hourly departure rates, there were just as many hours with 5+ heavy/B757 departures as there were with 0-1 heavy/B757 departures. More research is needed to understand why the relationship is less clear for departures.

An independent analysis by Leo Prusak, FAA Manager of LGA control tower, showed that taxi-out times for heavies are longer than for non-heavies in the 22/31 configuration. He examined CATER data for the three month period of May-July 2001 and compared taxi-out times for B757/heavies and all other aircraft. Figure 6 shows the distribution he calculated for taxi-out times for the two classes of aircraft for all hours where the arrival rate was greater than 36. The shape of the heavy/B757 curve shows that there is a greater probability of higher taxi-out time for heavy/B757s than for other aircraft. A calculation of the median value of taxi-out time for the two classes of aircraft confirmed a higher median taxi-out time for B757/heavies than for smaller aircraft. The analysis suggests that heavy/B757s at LGA wait a longer period of time on the inner taxi-way (see Figure 1) than do other aircraft in the departure queue on the inner taxiway. The additional taxi-out delay would not be present in other runway configurations where wake vortex restrictions are not needed.

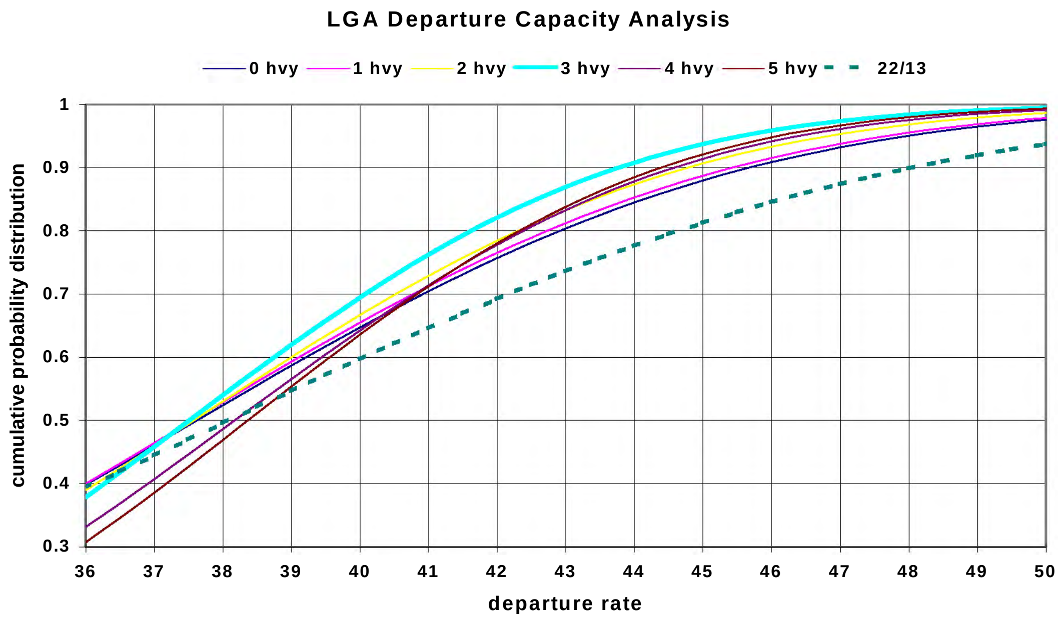

Figure 5. Same as in Figure 4 except for cumulative distribution functions for departure rates.

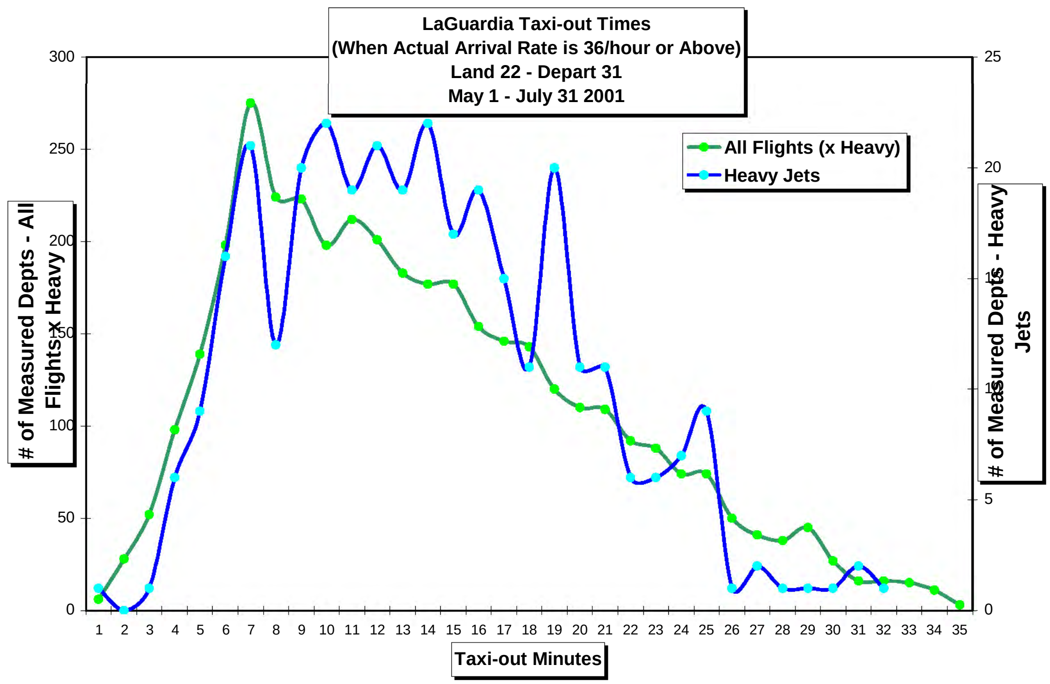

Figure 6. Taxi-out time distributions for B757/heavies (blue curve) and all other aircraft (green curve). Data based only on hours where arrival rate is 36 or above.

It was assumed for the purposes of this study that departure capacity was affected by wake restrictions in the same way arrival capacity was affected, even though the effect could not be captured cleanly in the data. For the top 30% of all hourly departure rates, the rates in 22/31 are consistently between 2-3 aircraft per hour less than rates achieved in 22/13, providing partial evidence that the wake vortex restrictions are having an effect on departure capacity. We know that if the first plane in line for departure after a heavy/B757 takeoff must wait extra time for his takeoff roll because of wake vortex restrictions, there will be extra departure delays for the entire departure queue.

Suppose we assume the sustainable arrival capacity corresponded to the cumulative probability of 0.8 on the distribution curve in figure 4. If there were no heavy departures in a given hour, the capacity would be taken to be 44 arrivals. Figure 7 shows that the arrival capacity at LGA when in 22/31 (and we will assume departure capacity as well) varies almost linearly as a function of the number of heavy/B757 departures. For the purposes of this study, we will define the linear capacity model to be:

$$C_{22/31}(t) = C_O - C_1 * h(t) \quad \textbf{(1)}$$

Where $C_{22/31}(t)$ is arrival or departure capacity in the 22/31 configuration for hour *t*, C_O is the sustained achieved capacity with no wake vortex restrictions, C_1 is a constant taken to be 1 based on figure 7, and h(t) is the number of heavy departures for hour *t*. The question of setting the value of C_O will be discussed in a later section.

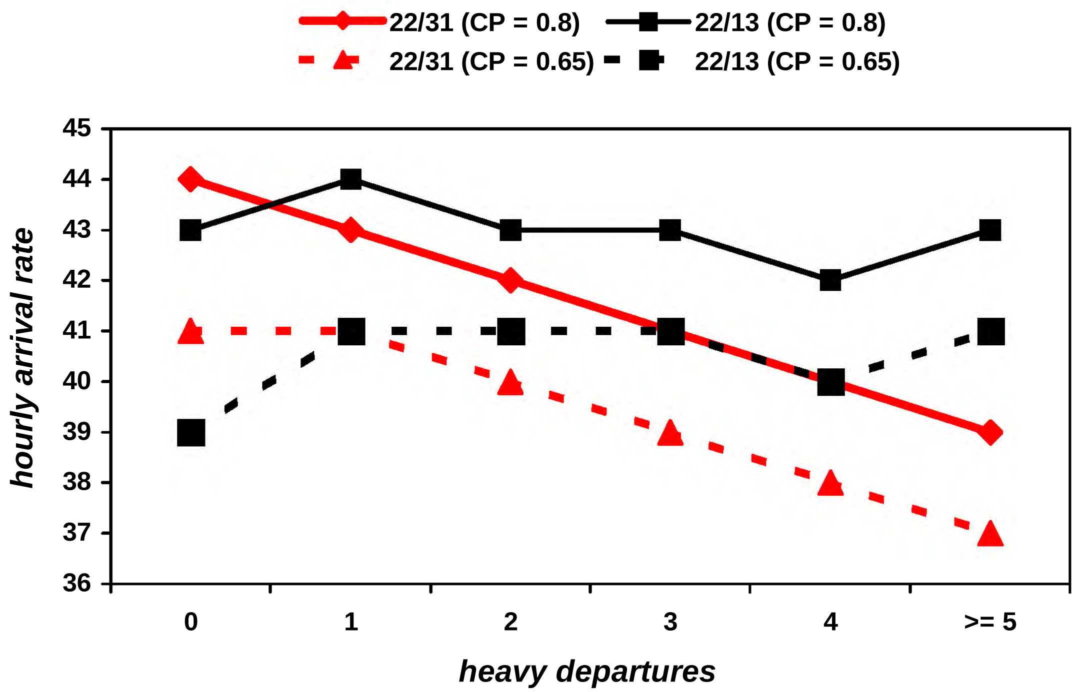

Figure 7. Plotting hourly arrival rates as a function of the hourly heavy departure rate based on a cumulative probability (CP) of 0.8 and 0.65 in figure 4. Rates are rounded to the nearest integer.

3.3 DETERMINING CAPACITY IN IFR CONDITIONS

Capacity was also examined at LGA under IMC conditions. Because low-IMC conditions (defined as ceilings less than 1000 ft and visibility less than 1 mile) were so rare when in this runway configuration, only marginal VMC conditions (ceilings between 1000-3500 feet and/or visibility less than 5 miles) were considered. Methodology was the same as the clear weather analysis in section 3.2, with the distinction that hours were not stratified according to the number of heavy/B757 departures. There were not enough hours with marginal VMC conditions to (hereafter M-VMC) construct a realistic probability distribution based on the number of heavy/B757s.

Figure 8 shows that the achieved arrival rates in the 22/31 configuration are about 2 aircraft per hour less than the 22/13 configuration. Traffic managers generally follow capacity guidelines as given in Table 1 to set Ground Delay Program (GDP) Airport Arrival Rates (AAR) when M-VMC conditions exist and this would tend to bias the data. However, the guidance rates that are followed are based on the assumption that wake vortex restrictions do lower capacity in the 22/31 configuration. Achieved arrival rates in IMC conditions are thus not only a reflection of planned arrival rates but of the expected impacts of restrictions.

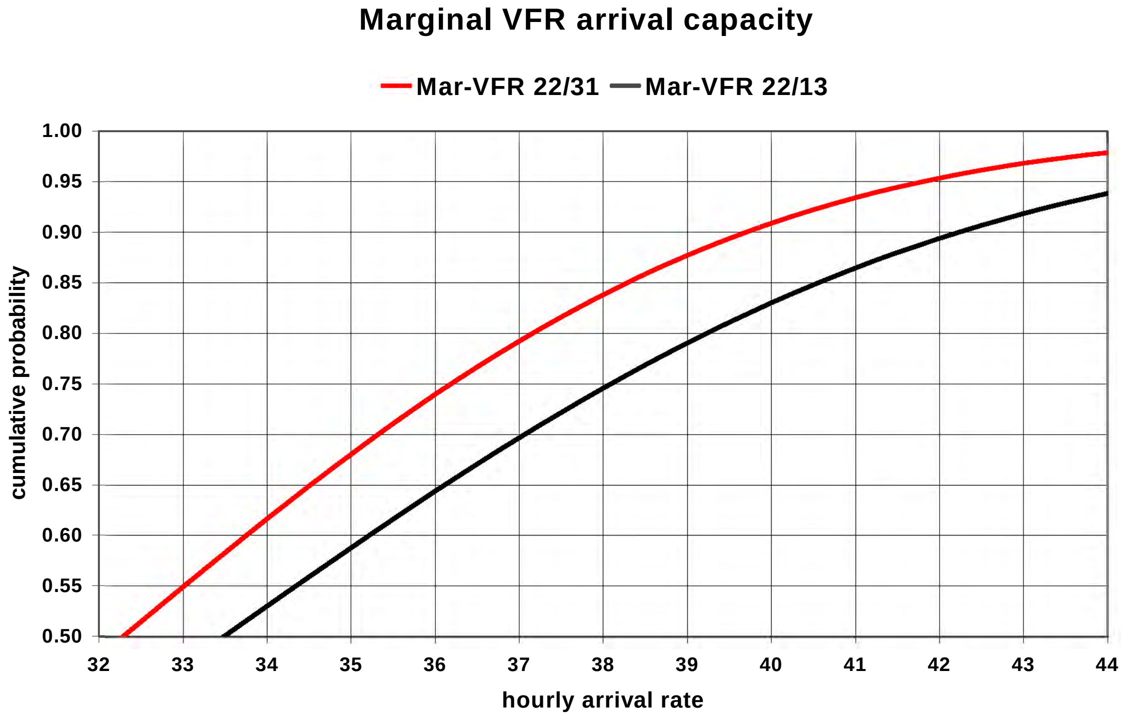

Figure 8. Same as in Figure 4, but with distribution curves for arrival rates in marginal VMR conditions.

4. MODELING THE ECONOMIC COST OF WAKE VORTEX RESTRICTIONS

4.1 MODELING APPROACH

The model used in this study was a queuing model (see [9] for more details). This type of model lends itself naturally to an airport like LGA which generally faces demand that meets or exceeds capacity from early morning until late evening. Any time the demand exceeds the capacity a queue will form either on the runway or as an airborne queue, with the resulting delay quite nonlinear and greatly enhanced as the gap between demand and capacity gets larger.

The model only requires two inputs—demand and capacity—to estimate delay. The previous section described in detail our capacity analysis of LGA. What we did not address was what point on the probability distribution curve to pick as a capacity. Picking 1.00 is misleading because it represents a single 1-hour period of unsustainable maximum landing/departure rates. A controller who is able to land 46 aircraft one hour may be unable to sustain that throughput over several hours. An arrival throughput of 46 one hour may be followed by 40 the next hour. Assuming constant demand on the airport, an average of achieved arrival throughputs for different controllers over several hours on different days gives an approximation of arrival capacity. Different controllers have different experience and skill levels and this is a factor in what throughput rates are achieved.

Our approach to estimating the no-heavy capacity was to use the queuing model with several different capacity numbers (based on the linear model in equation 1) to find a delay profile that best matched the actual delay data. By restricting ourselves to airborne delay, the major factors that one would have expected to contribute to that delay were upper-air winds, volume, MIT restrictions, and other restrictions such as wake vortex restrictions. The sum of the delay due to all such factors should equal the total airborne delay for the day. Delay due to upper-level winds should be relatively constant throughout the day, assuming there are no major shifts in the jet stream. We would also expect to find some small amount of airborne delay even on days with no wake vortex restrictions due to the congestion of the airspace in the Northeast. We would expect the airborne delay on a day in the 22/31 configuration to be greater than the delay in the 22/13 configuration. We would further expect the modeled delay, which takes into account only wake vortex restriction delay, to be less than the airborne delay (which includes delay from factors other than wake vortex restrictions).

4.2 CONSTRUCTING CAPACITY AND DEMAND FOR 7 FEBRUARY 2000

February 7, 2001 was a day with runway configuration 22/31, perfect weather conditions, relatively benign upper-level winds, and very few MIT restrictions or volume related problems (based on Traffic Management Unit (TMU) logs). This day was modeled using the queuing model both to determine the amount of delay due to wake vortex restrictions, and to determine the capacity that yielded the model delay profile most similar to the actual airborne delay profile.

A significant challenge was to construct an accurate hourly demand of 7 February 2001. For our purposes we wished to know the LGA hourly arrival demand that the N90 controllers expected in a given hour prior to implementing gaps in the arrival stream. More simply stated—we needed to know the demand while it was still independent of wake vortex spacing restrictions, since it was the delay due to those same restrictions we were attempting to measure. Using actual 22/31 arrival rates as demand does not work because those rates are dependent on the wake vortex restrictions. Another possible way of defining demand was to use the OAG schedule, since it is independent of wake vortex restrictions. It does not include, however, cancellation information, nor is it a comprehensive set of all military, civilian, general aviation, and transport aircraft. As a baseline demand, the OAG schedule was used and cancellations subtracted out. A detailed comparison was then carried out between the OAG schedule and the CATER arrival/departure rates. It was not expected that the hourly profiles would be similar because of the difference between scheduled and achieved traffic rates. As an example, if the capacity between 8:00am and 9:00am was 40 arrivals and the schedule called for 43 arrivals, the three extra aircraft would be pushed into the count of traffic for the 9:00am to 10:00am period. Assuming reservoirs of excess capacity will eventually absorb all aircraft, we would eventually expect to see the average schedule and achieved traffic counts to be similar. To do this, we compared two periods of time that began and ended with reservoirs of excess capacity big enough to absorb any traffic queues. At LGA there are traffic lulls after the morning push and in the early afternoon. We compared OAG data to CATER data during these periods. It was found that CATER and OAG were similar for arrival counts until noon, but that CATER had 6% more traffic on average after that. We added a 6% constant in arrival traffic to OAG for all hours from noon until midnight. This accounts for the extra military, civilian, general aviation, and transport aircraft not in the OAG. For departures the differences were more substantial. It was found that CATER had 15% fewer departures than OGA on average between 6:00am and 9:00am, but afterwards CATER showed 10% more departures on average. Recalling that cancellations were subtracted from the OAG departure count, the schedule was reduced by 15% before 9:00am but increased by 10% thereafter. One key input to the queuing model—demand—was in this way obtained.

With a credible demand constructed, it was fairly straightforward to determine capacity. The hourly heavy departure rate was computed at 15-minute intervals. We then plugged in hypothetical values of the optimum capacity into **(1)** to obtain hourly capacity profiles. In Figure 9 it can be seen that using an optimum capacity of 40 aircraft gives more delay than actually occurred on that day. When we modeled actual delay with an optimum arrival capacity greater than 41 we found that too little arrival delay was produced (greatest average hourly delay was two minutes for an optimum capacity of 42). Modeling an optimum capacity of 41 yielded more realistic values of arrival delay (up to 3-4 minutes on average during peak demand hours) that closely resembled actual airborne delay experienced at LGA when in the 22/13 configuration. For modeling purposes we assumed an optimum hourly arrival/departure capacity of 41 aircraft.

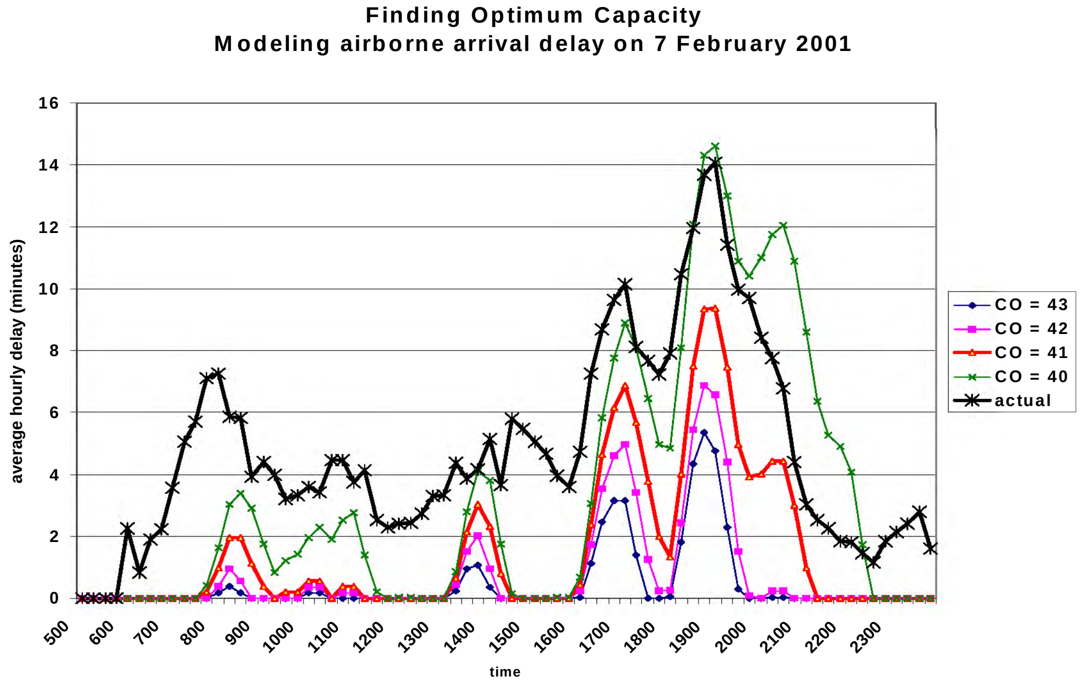

Figure 9. Delay profiles obtained from the queuing model using arrival demand from 7 February 2001 and different optimum capacities plugged into equation (1). C0 stands for optimum hourly arrival capacity. The heavy black curve represents actual airborne delay from ASPM.

4.3 COST OF WAKE VORTEX RESTRICTIONS ON ARRIVAL DELAY FOR 7 FEBRUARY 2000

To obtain the cost in delay minutes of wake vortex restrictions on 7 February 2001, the queuing model was run twice. The first run used the arrival demand outlined above and a constant optimum arrival capacity of 41. All rates were hourly and calculated in 15 minutes intervals. The delay from the first run was assumed to be unavoidable delay. The model was then run a second time with the same demand profile and a variable wake vortex capacity value based on the linear capacity model of **(1)**. The delay difference was calculated between the two queuing runs and taken to be the cost in minutes of the wake vortex restrictions. Figure 10 shows the modeled arrival delay, demand profile and actual airborne delay for 7 February 2001. The total cost of wake vortex restriction delay was 15 hours. If we had chosen a capacity of 42, the cost would have been 6 hours, while a capacity of 40 would have sharply increased the cost to 36 hours. This demonstrates the sensitivity of modeled delay to the chosen optimum capacity.

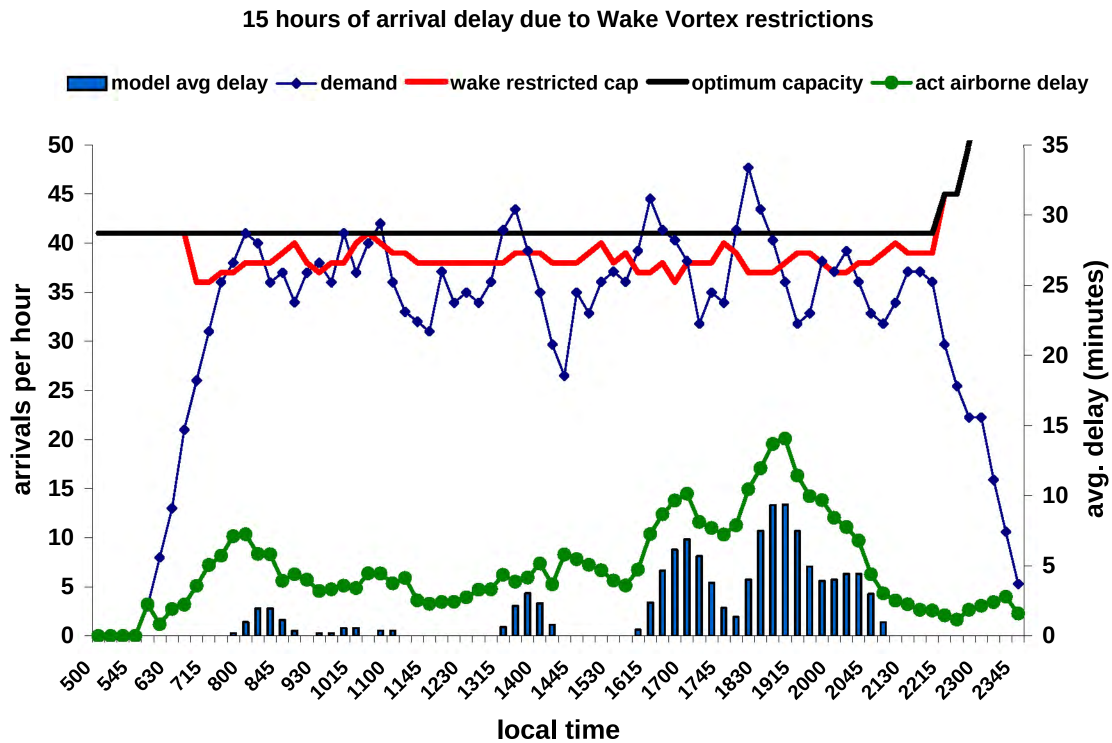

Figure 10. Average arrival delay in minutes (blue bars) calculated using the queuing model and subtracting out delay from a model run using constant optimum capacity of 41 (black line). Demand and capacity are based on 7 February 2001.

4.4 COST OF WAKE VORTEX RESTRICTIONS ON DEPARTURE DELAY FOR 7 FEBRUARY 2000

Figure 11 is the same as figure 10 but for departure delay. We compared modeled delay with Aviation System Performance Metrics (ASPM) taxi-out delay. This is reasonable since aircraft must wait extra time in the departure queue on the taxiway when a heavy/B757 takes off. The total modeled cost of wake vortex restrictions for departures was calculated to be 33 hours. Choosing a capacity of 42 would have decreased the modeled cost of the restrictions to 18 hours, while a capacity of 40 would have increased the modeled cost of delay to 65 hours.

33 *hours of departure delay due to Wake Vortex restrictions*

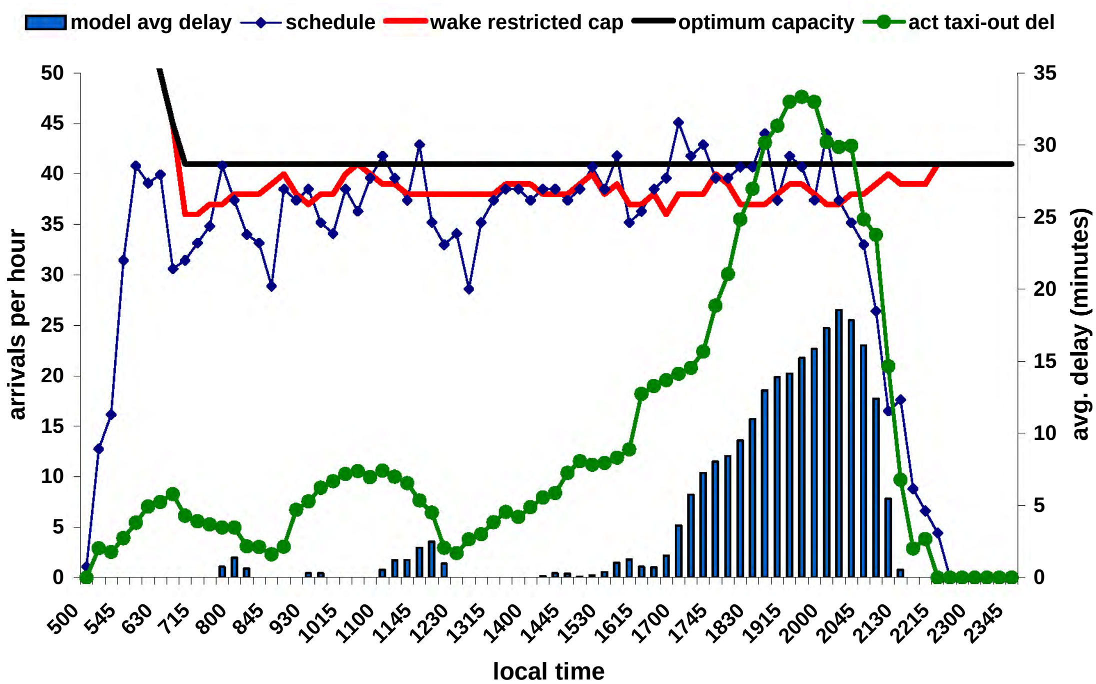

Figure 11. Same as in Figure 10 but using demand data for departures on 7 February 2001. The green curve represents average hourly taxi-out delay from ASPM.

4.5 ANNUAL COST OF WAKE TURBULENCE SEPARATION STANDARDS AT LGA

To find the total amount of time that LGA operates in the 22/31 configuration in a year, we first calculate that on average LGA is in IMC conditions 25 days a year. A runway usage chart was then calculated taking a two-year average of the frequency of all LGA runway configurations between 1999-2000. Figure 12 shows that the 22/31 configuration was used 19% of the time, which translated into approximately 70 full days per year. Subtracting the 25 days with IMC conditions, we obtained the result that the average annual total number of hours with VMC conditions in the 22/31 configuration at LGA was equal to about 45 days per year. Using the earlier queuing model results, we found that wake turbulence separation standards on these days cost 48 hours of delay per day, giving an annual delay of 2160 hours.

Runway use at LGA 1999-2000

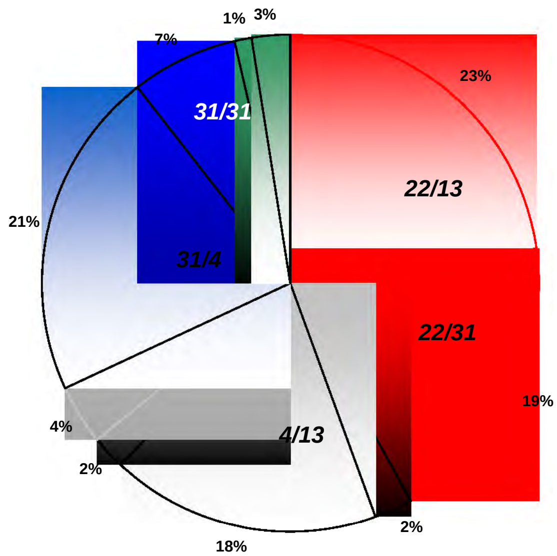

Figure 12. Runway usage frequency at LGA based on a two year average of 1999-2000. Data source is CATER.

To complete the analysis of the cost of wake turbulence separation standards at LGA, we modeled the cost of restrictions during M-VFR conditions at LGA with a 22/31 configuration. Our previous analysis of capacity in VMC at LGA showed a capacity that corresponded to 0.65 on the cumulative distribution curve in figure 4. It was assumed that for M-VFR at LGA, the same point on the cumulative distribution curve for M-VFR arrival rates (figure 8) would give a reasonable representation of capacity in M-VFR at LGA. This yielded a capacity of 36 arrivals per hour without wake turbulence separation standards and a capacity of 34 arrivals with wake restrictions. This was considerably higher than the chart guidance (table 1) and led to a very conservative estimate of the cost of the restrictions.

It was calculated that M-VFR at LGA occurred approximately 25 times per year in the 22/31 configuration, and that the average M-VFR event in that configuration lasted two hours. There were 16 two-hour M-VFR periods considered from 6:00am until midnight (e.g. 6-8,7-9,8-10 etc.). It was assumed that there was an equal probability that M-VFR could occur in each time period. Each time period was modeled using the queuing model, and an average of the delays for the 16 different M-VFR periods was taken. The analysis was done for both arrivals and departures. The total amount of delay computed using this approach (arrival + departure) was 75 hours. A check of ASPM delay data for several of these M-VFR events confirmed that the approach was very conservative, with many of the events causing well over 200 hours of delay at LGA. Multiplying the 75 hours by 25 events gave 1875 hours of delay due to wake turbulence separation standards during M-VFR conditions.

One delay savings that may be significantly underestimated in this analysis is the case where there is a thunderstorm passage over the airport and the runways are reconfigured to 22/31. If there has been a significant backlog in arrivals built up due to a ground stop, airborne holding, or ground delay program, any increase in capacity such as a reduction of wake turbulence separation standards would greatly increase delay savings. This is because of the non-linear nature of the queuing model.

The official FAA value for the cost of an hour of delay to the airlines is $3,093 in direct operating costs (DOC) (Hoffer et al., 1998). We calculated the annual cost of wake vortex restrictions in the 22/31 configuration at LGA to be:

DOC to airlines: **[2160 hrs (VFR) + 1875 hrs (M-VFR)] * $3,093 ~ = $12,000,000**

The 4035 hours delay at LGA due to wake turbulence separation standards does not include downstream delay or cost to passengers.

5. IMPACTS OF INCREASING DEMAND AND CHANGES IN FLEET MIX

5.1 DELAY GROWTH FOR INCREASING DEMAND

Following the tragic events of 11 September 2001, demand dropped by 20-30 percent at the major NYC airports. Most people in the aviation industry expect traffic levels to rebound to where they were prior to the terrorist attacks and to eventually climb to record levels during the next decade. When slot restrictions were imposed again in February of 2001 at LGA, traffic levels fell by about 10%. As a result, the daily GDPs were dropped and delays lowered dramatically.

Because delay is so sensitive to the amount that demand exceeds capacity, the effect of wake turbulence separation standards on delay grows rapidly as daily demand grows at LGA. We modeled the difference in daily delay growth between the 22/31 configuration and the 22/13 configuration with hypothetical demand growth at LGA. Figure 13 shows that as demand grows by 8% above spring 2001 levels, there is only a small increase in the amount of daily delay in the 22/13 configuration. However, assuming the lowered capacity profile of this study in the 22/31 configuration, figure 13 shows that delay grows almost exponentially in the 22/31 configuration, with the difference in delay hours between the two runway configurations about 300 hours with daily operations of 1318 aircraft. This difference grows to 450 hours as daily traffic rises a further 2% to 1342 aircraft, about where it was during the fall of 2000. These results suggest that reducing wake turbulence separation standards would allow traffic levels at LGA to rise without a corresponding large increase in delay.

5.2 INCREASING THE PERCENTAGE OF HEAVY/B757S IN FLEET MIX

Traffic levels experienced during the fall of 2000 at LGA made it clear that the airport was unable to accommodate that level of traffic without massive increases in delay. There simply is not enough runway capacity. There is motivation, however, to increase the overall passenger throughput of the airport because of its close proximity to Manhattan. One strategy is to increase the size of aircraft. Heavy jets and B757s currently account for about 10% of the overall traffic mix at LGA. What would happen if the percentage of heavies/B757s were to increase?

We assumed the linear capacity model of equation **(1)** to determine the relationship between airport capacity and the number of heavy/B757 departures each hour. Figure 14 shows that if the percentage of heavies were to double, delays would rapidly become unacceptable because of the corresponding loss of capacity. We did not account for the increased probability of a heavy/B757 arrival following a heavy/B757 arrival, since the reduction in spacing to 4nm with this leader-follower pair would not have a significant impact with a doubling or tripling of the percentage of heavy/B757s. An analysis of passenger capacity was also made to determine if passenger capacity would increase as a result of such a strategy. An analysis of CATER data showed the average non heavy/B757 aircraft at LGA has a capacity of 120 passengers, while the average capacity of a heavy/B757 is 220 passengers. Figure 15 shows that passenger capacity would not increase with such a strategy because of the corresponding loss of arrival/departure capacity as a result of increased wake turbulence separations. It would be significantly better for airlines to maintain the current schedule than to pursue a strategy of more heavy/B757s. However, figure 15 also shows that if wake turbulence separations were eliminated or reduced it would make sense to increase the percentage of heavy/B757s. Passenger capacity would significantly increase without a corresponding large increase in delay.

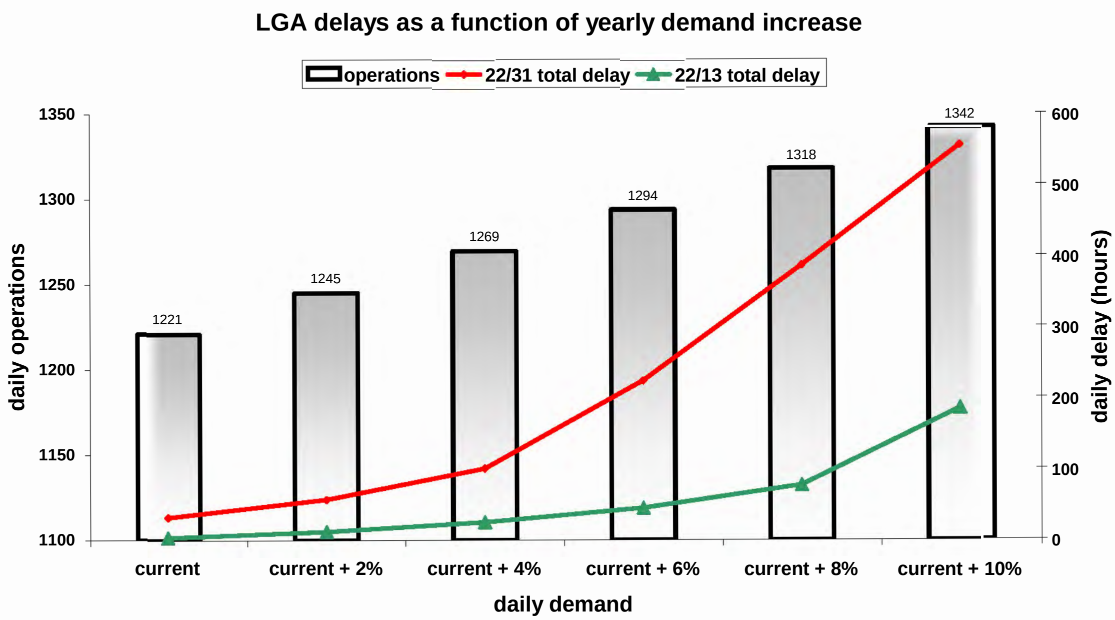

Figure 13. LGA delays as a function of yearly demand increase at LGA. The current demand is based on 7 February 2001 and is the sum of arrivals and departures. Results are based on the queuing model.

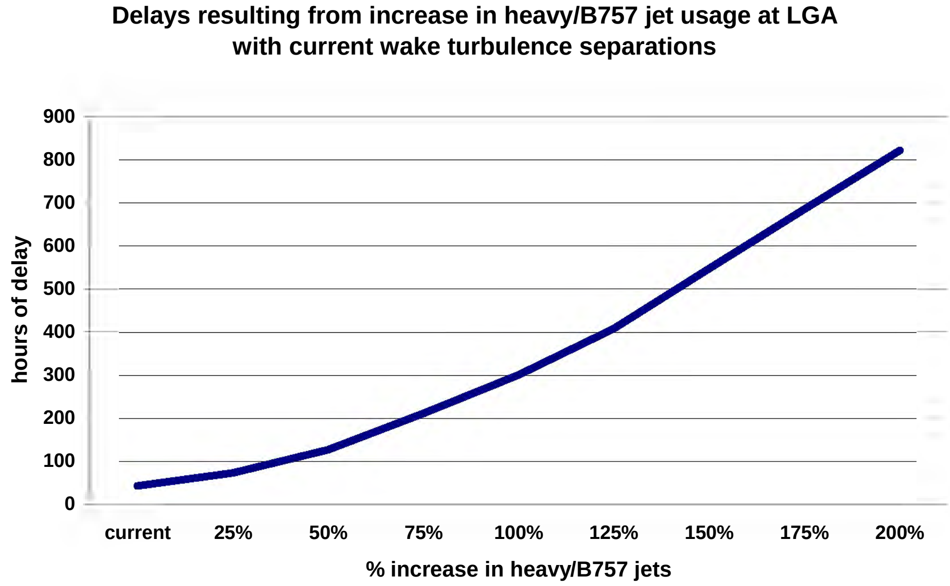

Figure 14. Hourly delay at LGA that results from increased percentage of heavy/B757 aircraft.

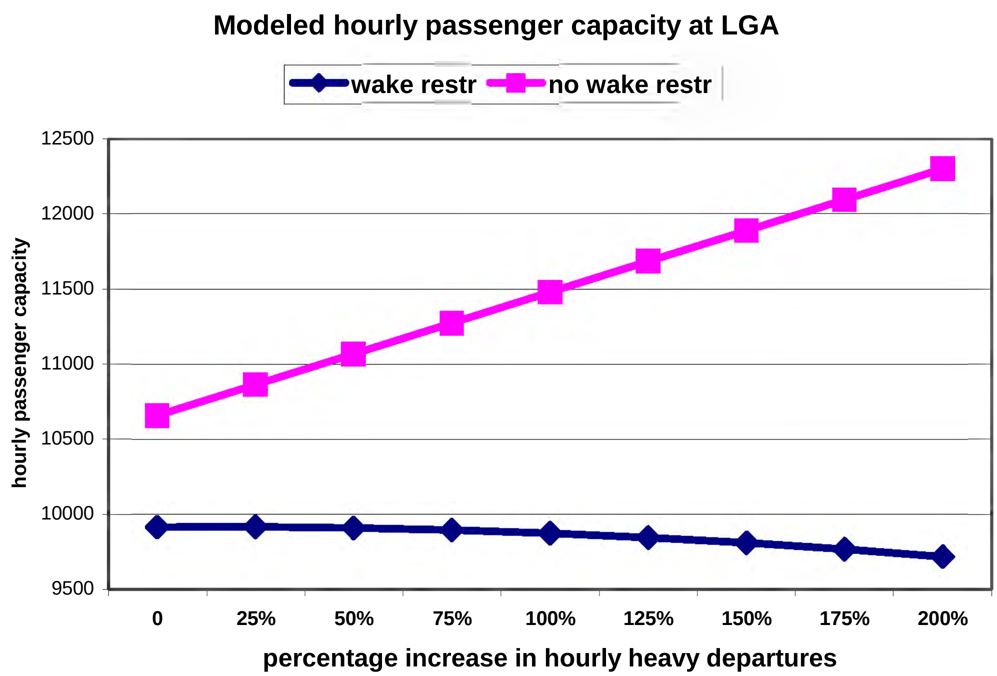

Figure 15. Hourly passenger capacity at LGA as a function of the percentage increase in hourly number of heavy/B757 departures.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This paper described a detailed methodology to determine the economic impact of wake turbulence separation standards at LGA while operating in the 22/31 runway configuration. It also described the cost of delay associated with wake restrictions as demand increased above pre-September 11 2001 levels, and what would happen to capacity in the alternate scenario that a greater percentage of heavy/B757 aircraft were used. Some of the key findings were as follows:

1. The annual DOC of wake turbulence separation standards at LGA is approximately 4000 hours or $12,000,000. This is a very conservative estimate and does not take into account downstream impacts.

2. There is a significant burden on both LGA and N90 controllers associated with the coordination of arrival stream gaps in the 22/31 runway configuration.

3. For every heavy/B757 departure, there is a loss in capacity of one departure and one arrival per hour during high demand hours.

4. If there were no wake restrictions, delay would remain at an acceptable level if traffic were to increase 10% above current levels.

5. With current wake separation standards at LGA, increasing the percentage of heavy/B757s would substantially increase delay without any increase in passenger capacity. The increase in passenger capacity would be much larger without a corresponding large increase in delay if the current turbulence separation standards were reduced.

6.2 RECOMMENDATIONS

To understand the amount of the wake induced delay that can be recovered requires that a measurement program be undertaken to understand the departure wake life times in the 22/31 configuration. Most wake data are for wakes generated well above ground effects. It is expected that wakes generated near the ground will decay more rapidly than those generated at a higher altitude. Current standards assume a wake life span of about two minutes. If it is found that the wakes from the departing heavy aircraft always decay in some shorter time, say 90 seconds, a significant fraction of the delay can be avoided simply by reducing the size of the required gap in the arrival stream to make room for a heavy departure. It may turn out that a reduction in spacing requires that the wake life span be predicted from knowledge of atmospheric dynamics, such as turbulence or eddy dissipation rate, or it may be that such a prediction will give an additional benefit. A limited amount of data should be taken and analyzed to determine the feasibility of reducing spacing either as a blanket change to the current spacing standard or by using weather dependent standards.

GLOSSARY

AAR	Airport Arrival Rates
ASOS	Automated Surface Observation System
ASPM	Aviation System Performance Metrics
CATER	Collection and Analysis of Terminal Records
CODAS	Consolidated Operations and Delay Analysis System
DOC	direct operating costs
FAA	Federal Aviation Administration
GDP	Ground Delay Program
LGA	New York's La Guardia airport
OAG	Official Airline Guide
TMU	Traffic Management Unit

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