A SIMPLIFIED AIR TRANSPORTATION SYSTEM CAPACITY MODEL
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BACKGROUND

It has been asserted that the US is approaching a crisis in Air Transportation system capacity [Minneta, 1997]. This appears to be a credible assertion as one observes the increasing load factors on commercial airliners and the increase in airport crowds and delays. A review of Department of Transportation statistics [DOT, 1998] over the last 40 years sheds some light on why the hub and spoke air transportation system is running out of capacity. Figures 1 and 2 show the relative growth for both passenger and cargo transportation for several modes, compared to their levels in 1960, relative to growth in Gross Domestic Product (GDP). You can see that in both cases, the air mode has grown four to seven times faster than GDP or any other mode of transportation. This type of unconstrained growth cannot be sustained forever without a paradigm shift.

Figure 1. Modal Transportation Growth Relative to Gross Domestic Product-Passengers

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The FAA and the aviation community has had difficulty in arriving at a consensus on the best investments to make in order to alleviate the hub and spoke growth constraints. Part of this problem stems from the lack of a simplified equation that represents the characteristics of the air transportation system in a parametric way. The community has tended to develop detailed, event driven simulations that are useful in replicating the complex behavior of the system. Unfortunately, the air transportation system is so complicated and inherently nonlinear that attention to detail has not always added to a system level understanding of the problem. A recent study on the efficacy of the capacity enhancements at Dallas-Fort Worth Airport [Hanson, et.al., 1999] indicates that we need a better understanding of the real capacity constraints of the system. The best current understanding has led to the development of Free Flight in the United States [RTCA, 1998 and NAS 4.0, 1999] and 4-D control in Europe [2000+, 1998].

These two paradigms contain common elements with the Free Flight emphasis on enroute and pre-flight Collaborative Decision Making (CDM) and 4-D control emphasis on using the new aircraft Flight Management System (FMS) capabilities to accurately meter the arrival and departure flows. The difference in emphasis can largely be explained by differences in United States and European airspace constraints. This paper will concentrate on the Northeast Triangle of the United States which is very similar to the European airspace and therefore will emphasize the similarities rather than the differences.
In addition, the emergence of complexity theory and its seemingly successful application to a wide array of technical, and socio-economic problems [Axelrod 1997], calls for a parametric equation that provides insight into the growth response options and their consequences. In this paper, I propose an equation that captures much of the behavior of the air transportation system and provides system characterization parameters that can help policy makers conduct order-of-magnitude sensitivity analysis.

**MODEL DEVELOPMENT**

I must first of all provide a definition of system capacity. I define the capacity to be a transportation rate (in units of aircraft operations per hour)\(^2\). Furthermore, drawing from the international community’s concept of homogeneous air traffic management regions, I will define the equation for homogeneous regions that allow for a difference in system characterization parameters between airports and regions. I will also assume that the system is in steady state and that there are no sources or sinks of aircraft in the system\(^3\).

For a typical 1.0 to 1.5 nmi. runway it takes approximately 45 seconds from threshold crossing to high-speed taxi exit (a typical Runway Occupancy Time (ROT)). Therefore, one runway operation every 55 seconds (45 seconds plus a 10 second safety buffer) equates to a runway operational rate of \(\approx 65\) a/c hour. Figure 3 shows this idealized relationship between arrival and departures operations of one runway compared to the actual degraded operational capability observed at Boston Logan\(^4\) [Idris, 1998].

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\(^2\) For an airport this can be either a departure or an arrival.

\(^3\) This is not exactly correct, Seattle Washington, Toulouse, France and Wichita, Kansas are significant sources of aircraft whose airports have more departures than arrivals. Also, the southwestern desert of the USA has old aircraft storage areas that have more arrivals than departures.

\(^4\) Logan has 5 runways with the ability to use 3 at any one time. Therefore, they should be able to accommodate a maximum rate of 3*65=195 op/hr without degradation.
The runway capacity will be represented as:

\[ RW_{ijm} \approx 65 \text{ a/c ops/hr for the } m^{th} \text{ runway at the } j^{th} \text{ Airport in the } i^{th} \text{ region.} \]

The maximum airport’s capacity, therefore, can be represented by summing over the individual maximum runway capacity:

\[ AP_{ij} = \sum_{m}^{N} RW_{ijm}. \]

A third major assumption will be that the airspace volume consists of three layers of sectors 18,000 feet high (0 to 18,000 (low), 18,000 to 36,000 (high) and 36,000 to 54,000 (super-high) MSL.). The plan view of the sectors can be represented as 80 nmi. (low), 100 nmi. (high) and 120 nmi. (super-high) wide isosceles triangles (for mathematical convenience). Figure 4 shows this geometry for the high altitude sectors.

**Figure 4. Diagram of the Northeast Triangle and the idealized sectors used in this analysis.**

Within these triangles, aircraft are nominally separated by 1000 feet in altitude and 7 nautical miles\(^5\) at a given altitude below 18,000 ft and 2,000 ft. vertical separation above. Furthermore, within these idealized sectors, the nominal speed of transiting aircraft is assumed to be 400 knots and the human factor aircraft density limit \(\rho_h\) is assumed to be 15 aircraft per sector\(^6\). These parameters can be varied for sensitivity analysis. This triangle is

\(^5\) This is a conservative estimate. FAA states 5 nmi. but controllers frequently use 7 nmi.

\(^6\) FAA order 7210.46 dated 4/16/1984 defines the Operational Acceptable Level of Traffic (OALT). For a sample day (7/7/1997) at Washington Center, the 100% OALT was 46 aircraft/hour/sector. The average
defined by 1000 nmi. legs between Boston, MA, Minneapolis/St. Paul, MN, and Tallahassee, FL.

The combination of these factors produces an equation for the nominal volumetric flow rate through a sector of the form:

\[ SV_{ik} \equiv (\text{# altitude layers/sector}) \times (\text{sector area/aircraft buffer area}) \times (\text{aircraft speed/avg. sector dia.}) \times \text{Human Productivity Factor} \approx 45 \text{ aircraft operations/hour} \]

\[ SV_{ik} \equiv 9 \text{alt} \times \left[ \frac{0.5(50\text{nmi.} \times 87\text{nmi.})}{\pi (3.5\text{nmi.})^2} \right] \times (400\text{kn}/60\text{nmi.}) \times \text{HPF} \approx 45 \text{ ops/hr} \]

where HPF is defined to be the Human Productivity Factor.

\[ \Rightarrow \text{HPF} \approx 0.015 \text{ (i.e. 1.5%)} \]

where

\[ SV_{ik} \equiv \text{sector flow rate of the } k^{\text{th}} \text{ sector in the } i^{\text{th}} \text{ region.} \]

We now can write the following equation for the total system capacity:

\[ C_{\text{TOTAL}} = \sum_{i=1}^{R} C_i, \text{ and} \]

\[ C_i = \sum_{j=1}^{A} \alpha_{ij} A\rho_j - \sum_{k=1}^{S} \beta_{ik} SV_{ik}; \]

Where:

\[ i=1\ldots R(\text{number of homogeneous regions}); \ j=1\ldots A(\text{number of airports in the } i^{\text{th}} \text{ region}); \ k=1\ldots S(\text{number of sectors in the } i^{\text{th}} \text{ region}); \ m=1\ldots N \text{ (number of 6,000 to 10,000 ft. runways in the } j^{\text{th}} \text{ airport).} \]

\[ \alpha_{ij} = \text{Airport Degradation Matrix} \text{ and,} \]

\[ \beta_{ik} = \text{Airspace Degradation Matrix.} \]

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aircraft traversal time was measured to be 11 minutes (with a range from 7 min. to 16 min.) and an average of 5.4 controllers/sector at peak load (i.e. 945 ac/hr @ 217 controllers = 4.4 aircraft/controller).

7 The airspace has a vast capacity for aircraft even at 7 nautical mile and 2000 ft. separation. The human ability to control traffic limits the capacity to about 1.5% of its potential.

8 For practical purposes, this will include all class B, C and D airports (i.e. all public, tower controlled airports with at least one runway 4,000 ft. or longer. There are over 400 airports in the US in this category. This paper will focus on just the class B and major Class C capacity in the Northeast Triangle.
Now let us define the system parameters that make up the airport and airspace degradation matrices. The airport degradation matrix has a value that ranges between 0.0 and 1.0 and is calculated as follows:

\[ \alpha_{ij} = S_{ij} G_{ij} W_{ij} X_{ij} N_{ij} W_{ij} M_{ij}, \]

where

- \( S_{ij} \) = surveillance degradation factor (i.e. a non-dimensional separation time (distance) under VMC conditions) \( = 55 \text{ sec.}/\tau_{VMC} \) (aircraft separation over the runway threshold in seconds) for the \( j \)th airport. Measurements taken at DFW [Denery and Erzberger, 1997] indicate that today’s separation rules yield, \( 220 \geq \tau_{VMC} \) (sec) \( \geq 70 \) or \( 0.8 > S_{ij} > 0.25 \), with an average of 110 sec.
- \( G_{ij} \) = ground movement degradation factor, to first order it can be approximately \( \approx \) \( (# \text{ Gates}_{ij}/T_{ij})^{9} \) airport acceptance rate, for the \( j \)th airport. [Hanson, et. al 1999 and Idris, et. al., 1998] have shown this to be an extremely important parameter in capacity degradation. Data at DFW indicate that this factor may offset many of the gains from the addition of new runways and airspace design at large hub airports.
- \( W_{ij} \) = Weather degradation statistics, usually reflected by an increase in separation distance under IMC conditions for the \( j \)th airport (i.e. \( \approx 83 \) seconds./\( \tau \), \( 300 \geq \tau \) (sec.)\( \geq 83 \) );
- \( X_{ij} \) = Runway configuration factor (nominally between 1.0 and 0.5 depending on whether the runways are parallel and independent\(^10\) or if they are crossing and arriving/departing aircraft must be interleaved) at the \( j \)th airport;
- \( N_{ij} \) = Noise degradation factor (nominally, between 0.5 and 1.0 depending on the location of the airport and the local community noise sensitivity) for the \( j \)th airport. This parameter is usually a function of time of day or could be represented by a maximum number of arrivals/day restrictions (or both).
- \( W_{ij} \) = wake vortex separation factor \( = 83 \) (sec.)/\( \tau \) wake vortex separation time for the \( j \)th airport (this time is determined by the aircraft-in-trail weight matrix distribution and the weather state statistical distribution [Dasey, US/EC, 1998]). Nominally, \( 166 \geq \tau \) (sec.)\( > 83 \).
- \( M_{ij} \) = Maintenance degradation factor (i.e. runway closed for resurfacing, etc.) for the \( j \)th airport.

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\(^{9}\) Gates, in this case, refers to both Gates and ramp parking spaces. \( T_{ij} \) represents average gate residence time+taxi in and out time. This parameter may range from 3600 to 7200 seconds.

\(^{10}\) Parallel runways are considered to be independent if they are more than 4300 feet apart.
Each of these degradation matrices is non-dimensional and has a value that ranges between 0.0 and 1.0. Separation distance is an extremely important parameter in this model. It is a fundamental restraint on system capacity and is directly a function of the aircraft type, speed\(^{11}\) and the air traffic control system time constant (\(\tau\)).

\[
\tau = \tau_{\text{Surveillance}} + \tau_{\text{HF}} + \tau_{\text{A/C}} + \tau_{\text{ROT}} + \tau_{\text{WV}}
\]

where,

\[
\tau_{\text{HF}} = \tau_{\text{Human}} + \tau_{\text{Communications}} + \tau_{\text{IMC}}
\]

For a terminal radar system requiring two 5 second sweeps to estimate position and velocity, \(\tau_{\text{VMC}} \geq 83\) seconds\(^{12}\). For the man-in-the-loop human operator annunciation time, \(\tau_{\text{HF}} \geq 15\) seconds\(^{13}\).

Similarly, for the Airspace Degradation Matrix:

\[
\beta_{ik} = 0 \text{ if } V_{a/c} \rho_{ik} \leq SV_{ik} \text{ and } \beta_{ik} = (V_{a/c} \rho_{ik} - SV_{ik})/SV_{ik} \text{ for } V_{a/c} \rho_{ik} \geq SV_{ik}
\]

Where

\[
\rho_{ik} = \text{number of aircraft in the } k^{th} \text{ sector of the } i^{th} \text{ region, and}
\]

\[
V_{a/c} = \text{average velocity of aircraft in the sector.}
\]

The airspace degradation matrix penalizes the regional system capacity in direct proportion to the number of aircraft that exceed a sector aircraft density limit. Air Traffic Control may put these aircraft in a holding pattern until the sector density is reduced enough to allow the aircraft to proceed on its route of flight. Table 2 indicates that this is a factor in about 22% of measured delays. For the rest of this paper, transiting aircraft and inter-region non-linear effects are assumed to be negligible until further research can determine their values.

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\(^{11}\) Speed over the threshold is a function of aircraft type. It ranges from 135 knots (heavy), 125 knots (large) to 120 knots (small). This analysis will use 130 knots as an average. Small GA aircraft go as slow as 65 knots over the threshold and thus produce severe capacity limitations at hub airports.

\(^{12}\) One of the major advantages of moving to an Automatic Surveillance Broadcast (ADS-B) system is the improved positional accuracy and the improved surveillance and pilot reaction time constant that could be on the order of one to two seconds. At an outer approach speed of 180 knots, a \(\tau (\tau_{\text{Sur}} + \tau_{\text{HF}})\) of 15 seconds equates to 3nmi./min.*0.25min.=0.75 nmi. (4,500ft.) displacement. (Note that the FAA considers 4,300-ft. separation adequate for simultaneous, parallel IFR approaches.) Whereas ADS-B surveillance/data-link displacement equates to 3*0.04=0.12 nm (720 ft) displacement.. See [Shepherd, R., et.al.,1997].

\(^{13}\) The actual values and distributions of these time constants need to be determined. For the purpose of this paper I will assume that \(\tau_{\text{Sur}} = 10\) sec., \(\tau_{\text{A/C}} = 10\) sec., \(\tau_{\text{ROT}} = 45\) sec., \(\tau_{\text{WV}} = 8\) sec., \(\tau_{\text{Com}} = 5\) sec., \(\tau_{\text{Human}} = 5\) sec., \(\tau_{\text{IMC}} = 30\) sec.
This equation and its representation of the system performance parameters is the beginning of a different modeling approach to the air transportation system capacity estimation problem. In some sense, its’ usefulness should be analogous to the radar range equation. It is not intended to be exact but to shed light on the larger issues and to identify the important parameters of the problem. Each of the degradation parameters can be modeled in terms of a cost function based upon either technologies or policies that can reduce the capacity degradation. This formulation is particularly suited to optimization techniques and provides statistical metrics that can be measured (or estimated) as a function of each airport and selected high-density airspace sectors.

**MODEL EVALUATION**

At this point we can make some crude approximations to the systems maximum capacity. There are about 730 sectors in the US airspace, at 45 enroute aircraft operations per hour, the current volume capacity should be about 33,000 aircraft aloft flights per hour. This number is far in excess of the typical 5,000 to 7,000 IFR aircraft aloft flights per hour that are currently experienced and thus, to first order, not a capacity limitation. Obviously, the system does not load all sectors uniformly and therefore work needs to concentrate only on the sectors where the aircraft density is approaching 15 to 20.

There are 100 major airports (out of a total of ≈ 450 tower-controlled airports) that accommodate approximately 95% of all US commercial traffic [ACE,1998]. Assume that each of these 100 major airports airport has at least 2 active runways in use at any one time (i.e. N= 2 and A=100). If $\alpha_{ij}=1.0$, then $\sum C_i = 200 \times 65 \text{ a/c op/hr} = 13,000$. Clearly, at 55 seconds intervals(≈ two-mile) separation, there is ample capacity for 6,000 aircraft aloft during peak system load (i.e. approximately 12,000 arrival and departures per hour). Let us now look at the simple case where $\alpha_{ij}=S_{ij}$ and there is 83 seconds (≈ 3 mile separation) [Denery, et.al. 1997] between aircraft in the terminal approach. This results in 13,000 IFR ac op/hr * 55/83 = 8,600 (i.e.4,300 aircraft aloft)! This number is very close to the average current load of IFR aircraft and shows that aircraft separation over the runway threshold is an important limiting parameter to the air transportation system capacity. Obviously, if any other parameter, like weather, gate availability, or runway taxi time were to come into play, the system should experience a severe capacity problem at peak load and this is in fact observed. At the macro level, the equation seems reasonable.

Let us do a more detailed calculation of the Northeast triangle of the United States to show how the equation can represent dynamic regional capacity. For the purpose of this example,

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14 If one takes a nominal peak national load and just divides it by the total number of air traffic controllers on duty at any one time, one gets an average of approx. 4 aircraft per controller. Obviously, sectors around Chicago, Dallas-Fort Worth and New York City are running closer to 20 aircraft per controller at peak load.

15 If one divides the total number of aircraft arrival and departures per year (≈64 million) by 365 days and by 18 hours/day and by 5000 A/C avg. aloft \( \approx 2 \) multiplier between arrivals + departures and A/C aloft.

16 FAA data indicate that VFR aircraft represent approximately 10% to 20% of the total aircraft operations in the terminal airspace. Many of these aircraft are operating at reliever airports, however, that are not represented by the 100 largest commercial airports used in this example.

17 For example, increasing the spacing from 3 nm. to 6 nm. in IMC would further degrade the airport’s capacity by 50%.
I will use only class B and major class C airports in the triangle shown in Figure 3. Table 1 shows the 33 airports in this region that represents 17% of all United States operations and a majority of the congested airports in the United States. It also represents an operational region very similar to European airspace. For the purpose of this example, I will set the noise, maintenance, weather and wake vortex degradation factors equal to 1.0. There is no readily available public source of data on airport gate/ramp capacity and I set them equal to an amount that would not constrain the operational rate at the airport’s current average runway capacity (i.e. $\tau = 110$ sec. or 4 nmi. separation)$^{18}$ Also, the runway configuration factor is my own initial estimate of operational degradation due to airport layout geometry and needs to be empirically determined for each airport. These are extremely important airport capacity metrics.

The airports in Table 1 are initially grouped as local geographic homogeneous regions with over a million operations per year $^{19}$[ACE, 1998 and Hill, 1998]. The next major grouping represents more isolated major hubs with over 400,000 operations per year. The remainder are major class C airports in the region with over 120,000 operations per year. These airports also represent the majority of delays experienced in the United States air transportation system. The first column represents all of the active runways at the airport in excess of 5,000 feet in length. The second column represents the author’s best guess at the current number of aircraft turn points (i.e. either gates or parking ramps) at the airport. The next five columns represent my initial estimates of the airport degradation factors for each of these airports. These metrics may provide a good relative measure of an airport or regions relative contribution to total air transportation system capacity. The eighth column gives the model’s prediction of the airport’s maximum hourly operation rate. The sum of this operational rate over the Northeast Triangle region gives an estimate of the total regional capacity (for the base case this is equal to 2,700 operations per hour).

In order to see if this is a reasonable estimate of the regional capacity, column nine lists the actual number of operations for each of these airports conducted in 1997 [ACE, 1998]. An hourly rate is estimated by dividing this operational rate by 365 days/year and 18 hours/day to get an hourly estimate shown in column ten. Summing this rate over the entire region gives an estimated average hourly rate of 1,600 aircraft takeoff + landing per hour in this triangular region. This would indicate that on average, the region is operating at 60% (i.e. $1,600/2,700=0.60$) of its current maximum capacity under favorable Visual Meteorological Conditions (VMC).

Extrapolating these estimates to a national value can make a further check for reasonableness. According to FAA statistics [ACE 1998], these 33 airports represent 17% of all IFR operations in 1997. Dividing these combined arrival and departure rates by 2 to get and estimate of hourly aircraft aloft and by 0.17 to get a national aircraft aloft estimate yields and average of 4,800 with a maximum of 7,900. Current FAA Aircraft Situation Display data (i.e. as monitored by Dimensions International, Inc. Flight Explorer software) show this value to nominally be in the 4,000 to 6,000 aircraft range. This is quite encouraging for the use of this simple methodology as a capacity meter.

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$^{18}$ This produces more A/C turning points than I suspect many of these airports currently have and they may be turning point constrained before they become A/C separation constrained.

$^{19}$ The Boston/Providence RI cluster is an exception with only about 600,000 operations per year.
A question has been frequently asked about how important aircraft separation is to overall system capacity. This model can provide a very simple insight to the answer to this question. The base case maximum capacity estimate used a 110-second aircraft separation over the runway threshold (i.e. approximately 4.0 nmi. at 130 knots landing speed as observed at DFW [Denery, 1997]) value. If we increase this value to 166 seconds average (i.e. 6.0 nmi. as one might encounter in bad weather) we reduce the national maximum capacity estimate from 7,900 to 5,200 (roughly the current average flight aloft operational rate)! Obviously, aircraft separation distance in the terminal airspace is central to system capacity. Equally obvious from this analysis is that the simple addition of a few runways will have little effect on overall system capacity. In fact, a recent analysis of the Dallas-Fort Worth (DFW) runway addition and airspace re-design [Hansen, et.al.1998] showed virtually no change in aircraft delay. It is hypothesized that the lack of aircraft turn capacity (i.e. gates and parking ramps) and increases in taxi time offset increased runway capacity and airspace design. This would suggest that there is a maximum desirable size to a hub and that the growth of regional virtual hubs may provide a better capacity enhancement strategy as suggested by [Hill, 1998] (i.e. IAD/DCA/BWI).

Although I set the weather degradation matrix and the wake vortex degradation matrix equal to 1.0 in this base case example, they are also extremely important capacity limitation factors. Wake vortex separation alone sets separation from three to six miles (83 to 166 seconds) depending on the type of adjacent aircraft. Most of the time, however, this is an overly restrictive criteria since runway cross winds and atmospheric boundary layer turbulence convect and disrupt the coherent vortices that are of concern. The new detailed micro-weather monitoring and forecasting system called the Integrated Terminal Weather System will be able to provide valuable information that can help reduce the wake vortex separation. This system will also provide faster airport weather response time. The combination of wake vortex avoidance information and airport runway turn prediction for weather shifts could help minimize the largest contributors to delays in the system today. The use of self-separation under IMC using ADS-B would also provide significant gains in IMC capacity by minimizing the human factors and surveillance time constants. Table 2 summarizes the distribution of delays by cause and is taken from the 1998 FAA Aviation Capacity Enhancement (ACE) Plan.

**TABLE 2. Estimate Primary Causes for System Delay**

<table>
<thead>
<tr>
<th>CAUSE</th>
<th>DISTRIBUTION (Delay &gt; 15 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>68%</td>
</tr>
<tr>
<td>Terminal Volume</td>
<td>22%</td>
</tr>
<tr>
<td>Center Volume</td>
<td>0%</td>
</tr>
<tr>
<td>Closed Runways/Taxiways</td>
<td>3%</td>
</tr>
<tr>
<td>NAS equipment</td>
<td>3%</td>
</tr>
<tr>
<td>Other</td>
<td>4%</td>
</tr>
<tr>
<td>Total Operations Delayed</td>
<td>245,000</td>
</tr>
</tbody>
</table>
Table 3 (taken from CODAS data and shown in the 1998 ACE Plan\textsuperscript{20}) gives a further breakdown of delay by phase of flight from the 15 congested airports of the 33 airports shown in Table 1.

**TABLE 3 Estimate of the Amount of delay in different Phases of Flight**

<table>
<thead>
<tr>
<th>PHASE OF FLIGHT</th>
<th>AVERAGE DELAY (min/flt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi-out</td>
<td>5.6 \textsuperscript{21}</td>
</tr>
<tr>
<td>Airborne</td>
<td>4.0</td>
</tr>
<tr>
<td>Taxi-in</td>
<td>1.7</td>
</tr>
<tr>
<td>Total</td>
<td>11.3</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A new simplified air transportation model is proposed that provides reasonable estimates to both today’s system capacity but also offers the potential to provide easily measured, meaningful system capacity metrics. The understanding that this model and it’s metrics bring to the modernization debate may help the community reach a consensus on system modernization priorities that may help alleviate the gridlock predictions that this and other models are predicting.

This preliminary analysis indicates that the best return on investment (ROI) to increase the air transportation system capacity (and therefore minimize delays) should be found by: 1) Reduce aircraft separation under all weather conditions in the terminal area by the use of ADS-B\textsuperscript{22} and allowing the pilots to self-separate and maintain 83 second (3.0 mile) separation over the runway threshold on final approach (wake vortex conditions permitting). This is probably the most important application of data link technology (i.e. aircraft to aircraft and aircraft to ground). Safe Flight 21 and Capstone demonstration/validation experiments that are just beginning will tell us how much of these gains can be achieved [NAS 4.0]. It may be that the cargo airline hubs may be the first beneficiaries of this technology do to their ability to totally equip all of the aircraft operating at their hubs during the night cargo hub turn. The FAA/NASA sponsored CTAS program that will be implemented in Free Flight phase I will greatly aid the sequencing and timing to the metering fix (which now has a +/− 180 second variance [Weidner, 1998]. CTAS may not be able to improve the timing over the threshold, however, do to the surveillance, communications and human factor contribution to the system time constant in this phase of flight.

The second and equally important contribution to increasing system capacity is in airport operations and design. Therefore, 2) improve airport design by adding more gates and better

\*\textsuperscript{20} This data underestimates the actual delay since the airline schedules have been designed to incorporate system delays in order to provide better predictability and DoT reporting data.

\*\textsuperscript{21} [Idris, et.al., 1998] estimates that roughly 65% of all airport delay is incurred in the departure runway access Que.

\*\textsuperscript{22} Automatic Dependent Surveillance – Broadcast (ADS-B) provides ubiquitous surveillance information to both pilots and ground controllers based upon the broadcast of each aircraft’s state vectors, derived from GPS data, every second over a digital data link. It is significantly more accurate and covers more search volume than radar.
ground flow to and from the runway. The Surface Movement Advisor (SMA) identified for introduction in Free Flight Phase I should also help in this regard. It may be, however, that some of the existing major hub airports have reached the point of diminishing returns. This analysis suggests that there may be a number of existing airports that are operating significantly below capacity and are candidates to becoming new hub airports. Also, the emergence of virtual mega-hubs with multiple regional airports (perhaps specialized) netted together may be in the future as suggested by [Hall, 1998]. Finally, 3) Improve wake vortex separation criteria by using the ITWS to take advantage of cross wind conditions and provide wake vortex separation alerts.

Other elements of Free Flight Phase I are also important. The augmentation to the United States Global Positioning System (GPS) by the Wide Area Augmentation System (WASS) is a vital enabling technology to any civil system that is based upon GPS [JHU, 1999], such as the ADS-B system. Also, the User Request Evaluation Tool (URET) and enroute data-link are important ingredients to reduce controller workload in high capacity sectors, thus allowing an increase in the OALT. This technology will primarily effect the Airspace Degradation Matrix $\beta_{ik}$ which will be studied in more detail in future research.

This is clearly work in progress and much more needs to be done. The current research is focusing on improving the understanding of the airport turn and taxi problem and airspace sector degradation analysis. I am indebted to my students in the University of Maryland systems engineering program for invaluable discussions and insights that have helped me arrive at this formulation. My current students at George Mason University (who are working on parameter estimation for the Washington DC metropolitan homogeneous region) will allow us to do more than the simple limiting calculations that have been possible in this paper.
## TABLE 1. NORTH EAST TRIANGLE AIRPORT (33) DEGRADATION MATRIX

<table>
<thead>
<tr>
<th>AIRPORT</th>
<th># R/W</th>
<th># A/C TURN</th>
<th>S</th>
<th>G</th>
<th>W</th>
<th>X</th>
<th>W V .</th>
<th>#OPS/</th>
<th>#OPS/YF</th>
<th>1BHR</th>
<th>RANK</th>
<th>RANK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago (ORD)</td>
<td>7</td>
<td>180</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.7</td>
<td>1.0</td>
<td>158</td>
<td>892,665</td>
<td>136</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Chicago Midway (MDW)</td>
<td>5</td>
<td>90</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>81</td>
<td>251,511</td>
<td>40</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Milwaukee Wis (MKE)</td>
<td>5</td>
<td>90</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
<td>81</td>
<td>209,378</td>
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2684 1637

| VMC SEPARATION TIME seconds (4.0 nautical miles)| 110 |
| IMC SEPARATION TIME seconds (@130Kts) | 110 |
| WAKE VORTEX SEPARATION TIME (@83sec. Min.) | 110 |

| TOT REGIONAL CAPACITY | 10,756,447 |
| Nat. Max. Estimated A/C Aloft | 7,891 |
| Nat. AVG. Estimated A/C Aloft | 4,814 |
| CAPACITY FRACTION | 0.61 |

17 %TOTAL US Operations.
REFERENCES


Bureau of Transportation Statistics, 1998 (http://www.bts.gov/)


