The U. S. Air Transportation System: A Bold Vision for Change

A White Paper prepared for the Commission on the Future of the U.S. Aerospace Industry

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1.0 EXECUTIVE SUMMARY

The World Wide Air Transportation Network System has become indispensable to domestic and international trade. It has been known for some time that the US balance of trade is heavily dependent on the export of civil aircraft parts and services. The recent events of terrorism against the United States and the subsequent severe reduction in US air transportation services gave us a vivid example of the economic dependency of both regional economic activity and the entire world on these services. The growth in air transportation over the last 40 years has been an important ingredient in US economic growth. The rapid migration of the airlines to a hub-and-spoke system after deregulation in 1978 led to a significant rise in service frequency and price competition. The inherent efficiencies of this new regulatory environment resulted in a rapid rise in the utilization of the air transportation mode. Today, we are at the cross-roads of inefficient utilization of national airport infrastructure and an outdated air traffic control paradigm. These factors will severely limit the continued growth of air transportation unless modern technology and a new regulatory environment are put in place.

At the beginning of the 21st century, there are approximately 60 major airports in the United States owned and operated by local municipal governments with a maximum capacity of about 32 million operations per year. Current forecasts predict that the future demand for air travel will significantly exceed supply and delays will increase over the foreseeable future. In general, the National Airspace System (NAS) modernization and runway improvement programs that are being fielded are indicating substantially less than predicted performance increase. It is becoming increasingly clear that several important non-linear effects are complicating the NAS modernization program.

We could increase the NAS capacity in the USA to over 70 million operations per year by migrating from the use of radar surveillance to the use of aircraft broadcast Global Positioning System (GPS) satellite navigation fixes over a wireless digital data link. This important transition would also utilize the significant computer-based flight management systems that have been incorporated into virtually all of the commercial aircraft over the last 20 years. Over the last 7 years, we have observed a rapid growth in the use of small (e.g. less than 50 passenger) regional jets and privately operated business jets in the NAS. A co-dependent two tier air transportation system may be required to take maximum advantage of the different flight characteristics and operational profiles that these aircraft present the NAS. A new regulatory scheme including airport slot auctions will need to be implemented to take advantage of these technology advancements and encourage optimal safe use of the nation’s airport infrastructure.

Just as the Alaska Capstone Operational Evaluation has led to a significant advancement in our understanding of the safe use of some of these new technologies and operational procedures, a bold step must now be taken in concert with the Cargo Airlines to integrate the new equipment and procedures into the mainstream of the nation’s air transportation management system.
2.0 BACKGROUND

2.1 Air Transportation and the Aerospace Industry

The World Wide Air Transportation Network System has become indispensable to domestic and international trade. It has been known for some time that the US balance of trade is heavily dependent on the export of civil aircraft parts and services. The recent events of terrorism against the United States and the subsequent severe reduction in US air transportation services gave us a vivid example of the economic dependency of both regional economic activity and the entire world on these services. This paper will attempt to describe the characteristics of the complex air transportation system and explain why the system is in trouble. This understanding should help the policy community to become more proactive in shaping the future of the US air transportation industry.

Richard Golaszewski [1] has provided a disturbing picture of national aerospace industry dis-investment in his recent testimony before congress. Table 1 provides an estimate of the economic importance of the aviation industry to the US Gross Domestic Product. The role of government and industrial research in producing this element of national GDP is illustrated in Figure 1. Unfortunately, the amount of both government and private funds invested in this market segment has been decreasing steadily over the last decade, as seen in Figure 2. This has led to a steady decrease in US world market share as seen in Figure 3. Figure 4 provides a breakdown of the various components of US aerospace products by transportation sector and shows a 9 year market potential of over $800 billion. Almost 75% of this market is in civil air transportation.

Table 1. Economic Importance of the air transportation Industry and Government Investment. Golaszewski [1], data source [2] pg. 8.

<table>
<thead>
<tr>
<th>Economic Impact of Aviation Industry</th>
<th>($billions 1999)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Total Output</td>
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<tr>
<td>Air Transportation</td>
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<tr>
<td>Aircraft Manufacturing</td>
<td>$134</td>
</tr>
<tr>
<td>Tourism</td>
<td>$94</td>
</tr>
<tr>
<td>Agents/Forwarders</td>
<td>$3</td>
</tr>
<tr>
<td>Government</td>
<td>$2</td>
</tr>
<tr>
<td><strong>Total Impact</strong></td>
<td><strong>$438</strong></td>
</tr>
</tbody>
</table>

N/C = Not calculated
Figure 1. Relationship Between Air Transportation Research and Economic Growth. Golaszewski [1]

*Companies classified in SIC codes 372 and 376, having as their principal activity the manufacture of aircraft, guided missiles, space vehicles, and parts. Data in constant 1996 millions of dollars.


Figure 2. The U.S. Has Reduced R&D Funds for Industrial Research and Development in the Aerospace Industry. Golaszewski [1]

2 This commission study is also including SIC codes 381, 451, 452, 458, 489, and 96. Economic activity in these sectors is not included in figure 2.

Figure 3. US has been Steadily Reducing it’s share of Aerospace Products over the last 2 decades. Golaszewski [1]

Figure 4 Air Transport Aircraft represent the majority of US Aerospace Industry Output. Golaszewski [1], source data [2] pg. 13.
The growth in air transportation over the last 40 years has been an important ingredient in US economic growth. All segments of transportation are important to any nation’s economy but Figure 5 shows that only air transportation has consistently grown at a faster rate than GDP growth. This data is taken from DoT statistical data and the growth rate in each mode is normalized by it’s activity level in 1960 and the GDP growth rate. A value of 1.0 represents a transportation growth rate equal to GDP growth rate. It can be seen in Figure 5 that the growth in US air transportation was stagnating in the late 1970’s until deregulation of the US airline industry. It was recognized at that time that a Federally controlled, highly regulated air transportation system was inefficient. The rapid migration of the airlines to a hub-and-spoke system after deregulation led to a rapid rise in service frequency and price competition.

The inherent efficiencies of competition and hubbing strategies led to another rapid rise in the utilization of the air transportation mode. Beginning in about 1990, however, we begin to see a gradual drop in this growth rate due to a growing lack of available transport capacity at the major hubs. The large excess of airport and Air Traffic Control (ATC) System capacity that existed in the post war era, lulled policy makers into the mistaken assumption that this growth could continue forever. Today, the nation’s air transportation network is seriously overloaded in the major cities that support airline hub operations. This unregulated overload is leading to a gradual decrease in the US air transportation system safety and a need for a new regulation mechanism that retains the benefits of deregulation that we have experienced over the last 25 years but allows the system to continue to grow by taking advantage of underutilized national infrastructure that has been provided with a heavy investment of taxpayers funds.

Figure 5. US Transportation Growth for Major Modes normalized to 1960 levels and GDP growth. Source US Department of Transportation Statistics [25].
2.2 Brief History and Description of Air Traffic Control

The invention and development of the jet aircraft in World War II has led to the use of aircraft as a major mode of both domestic and international transportation. Since 1960, the year that the US Department of Transportation began collecting statistics, the air mode of transportation has grown over four times faster in passenger traffic and seven times faster in tons of cargo than any other mode of transportation in the United States. The International Civil Aviation Organization states that more than one third of all international cargo by value was shipped by air in 1998. It should come as little surprise that both the technical and physical infrastructure is feeling the strain of this sustained growth rate.

In the United States, there are over 10,000 aircraft in commercial service at the turn of the century. Roughly 60% of these aircraft are powered by high bypass ratio fanjets, the rest are powered by either jet or piston driven propellers. The fanjet aircraft prefer to fly above 30,000 feet in altitude, whereas the propeller aircraft prefer to fly below 24,000 feet. Aircraft flying above 12,000 feet are usually pressurized due to the lack of adequate oxygen required for passenger comfort and/or survival. The US operates approximately 40% (i.e. operational rate) of the world’s commercial air transportation. In addition, the US uses aircraft for private transportation to a considerable extent.

There are over 150,000 registered private aircraft in the US with over 600,000 registered pilots. On any given day, there are over 5,000 aircraft in the air (between the hours of 10:00 and 22:00) under positive separation control by the Federal Aviation Administration (FAA) Air Traffic Control (ATC) system. Of this amount, approximately one fourth are involved in private transportation. There are also approximately three times this amount of private aircraft in the air that are not under FAA positive control. Europe operates an air transportation system that is approximately 65% of the operational rate of the US system, but with very little private air transportation activity. Africa, South America and Australia operate a considerable amount of private air transportation in addition to commercial air transportation because of the large intercity distances and lack of substantial ground transportation infrastructure.

There are roughly 15,000 aircraft in the US military fleet that come under operational control of the FAA, a civil agency, while in transit to military operational areas. Only a small fraction of these are in the air at any given time. This is somewhat unusual since many countries use a separate military ATC system to control their military aircraft in partitioned airspace. In time of war, the FAA can come under operational control of the US Defense of Defense.

In the USA, the ATC system equipment is owned and operated by the Federal government. Increasingly, governments are turning this function over to private or government owned corporations so that the rapid changes in technology (and subsequently required increased access to investment capital and rapid depreciation rates).

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3 There are approximately 55,000 scheduled flights and over 12,000 private, non-scheduled flights each day in the US under positive air traffic control.
can be incorporated into the ever-changing ATC systems that will be required in the future. Federally operated systems are typically financed by a combination of user taxes and general tax fund contributions. The newly privatized (e.g. Canada) or quasi-privatized systems (e.g. Germany, Australia or New Zealand) are totally supported by user fees and have access to private financial capital. Telecommunication companies typically replace their entire computer switching systems every six years. This is impossible for the US government due to the governmental separation of powers decision making system (consensus between executive and legislative branches) and the planning, programming and budgeting system. The failure of the federal government to provide capacity and safety growth potential will impact not only national GDP growth but will severely depress the requirement for the airlines of the world to purchase new aircraft, avionics and aerospace services. The health of the civil aviation industrial base is directly linked to the national defense industrial base, as well.

2.3 Government Services and Responsibilities

After World War II, in 1944, the International Civil Aviation Organization was formed as part of the United Nations to regulate international civil aviation. There are approximately 180 member countries at the beginning of the 21st century. Each member country must have a Civil Aviation Authority (CAA) to provide Communications, Navigation, Surveillance and Air Traffic Management (CNS/ATM) services to internationally accepted standards. For the United States, this agency is the FAA. In addition to the provision of CNS/ATM services, each country must provide aircraft safety oversight for the certification of aircraft airworthiness and aircraft operation. Until recently, these two functions (CNS/ATM and safety oversight) have been supplied by the same government agency. Since 1990, there has been a trend to privatize (through different means ranging from wholly owned government organizations to complete privatization) the provision of CNS/ATM services and retain government safety oversight. As currently designed, the US FAA has an inherent conflict of interest between the provision of both transportation capacity and safety.

The CNS/ATM function has evolved from the 1920’s provision of primitive navigation and communications services to a highly computerized ATM system with Central Flow Control Management (CFCM) or Traffic Flow Management (TFM) utilizing space-based communications and navigation equipment as shown in Figure 6. With the advent of radar in World War II, the surveillance function was added to the CAA’s provision of services in the late 1950’s. The physical limitations of radar at that time set the aircraft separation standards that are still in use today. These separation standards (in conjunction with the number of runways that are available) set the maximum operational capacity that the air transportation system can support. These separation standard are typically 5 nautical miles (9 km) in high altitude airspace (i.e. above 18,000 feet) and 3 nautical miles (6 km) in low altitude airspace (typically within 60 nautical miles (110 km) of an airport). Airspace that does not have radar surveillance must maintain procedural separation using aircraft onboard navigation position fixes and ATC communications. These separation standards usually exceed 60 nautical miles (110 km) and are used in oceanic airspace and in under developed countries that lack radar services.
Figure 6. This is a pictorial of the many components and subsystems that exist in the current US National Airspace System (NAS) and is typical of a modern Air Traffic Management System. Note the similarity to a private-service telecommunications system. (Source the US Federal Aviation Administration NAS 4.0)

The radar physical properties that dictate these standards are beam width and sweep rate. In practice, the aircraft are routinely maintained at 7 to 30 miles (13 to 56 km) separation due to air traffic controller cognitive workload limitations. A typical controller can maintain situational awareness on from 4 to 7 aircraft at a time. When airspace sector loading exceeds this amount, controller teams work to maintain aircraft separation. These teams can be as high as three controllers per sector. In the US, there are over 730 en-route sectors and in Europe there are over 460 sectors. The number of sectors that are available to high-density airspace in the US and Europe is limited to the number of communication channels that are available to the CAA. The number of communications channels available is dictated by the technical efficiency in which the allocated radio spectrum is utilized. The radio spectrum is allocated and controlled by the International Telecommunications Union (ITU), also a United Nations charter organization. The FAA is allotted a significant amount of very valuable radio spectrum that is sought by the FCC for auction to the rapidly growing wireless telecommunications market. The failure of the FAA for over 20 years to migrate to a spectrally efficient, digital communications system is limiting growth potential in both industries.

Unlike the USA, where the FAA operates the entire airspace ATC (from airport tower to upper altitude airspace), Europe has formed a central, trans-European organization called
EUROCONTROL to coordinate the national provision of ATC services and operates the CFMU and upper airspace over central Europe. Both the USA and Europe have experienced considerable delays in introducing new technology over the last 20 years due to the difficulty of developing complex computer software that can demonstrate extreme levels of safety. This software is needed to greatly increase the level of ATC automation in order to reduce air traffic controller workload. Aircraft manufacturers have been much more successful in introducing computerized Flight Management Systems (FMS) that reduce pilot workload and provide on-board Aircraft Collision Avoidance Systems (ACAS). Much of the increase in air transportation safety and productivity over the last 20 years has been attributed to the introduction of these aircraft automation systems.

![Normalized Cost per Operation](image)

**Figure 7.** A relative comparison of Productivity Trends for the US Air Traffic Control System and both US and European Airlines Post Deregulation [26].

It is interesting to compare the relative productivity change in the US government provided Air Traffic Control services to that of both the US airlines and the European airlines after deregulation was put in place. The airline data was obtained from an analysis conducted in 1997 [27] and the FAA data was obtained while the author was at the FAA in 1998. The FAA data is plotted assuming that the government controller salaries were fixed and adjusted for cost of living annually (a conservative assumption). Note the large dip in FAA cost per operation in 1981, the year of the FAA air traffic controller strike. This apparent large increase in productivity is deceptive since it was accompanied by a significant reduction in flights due to the aggressive use of Ground Delay Programs and the use of military controllers. The GAO has observed that a large number of the new air traffic controllers hired in 1982 through 1985 will become eligible for full retirement benefits in 2007 and may leave the work force.
2.4 A Typical Flight

For regularly scheduled commercial service, a flight is typically scheduled for 3 month time blocks. These schedules are not regulated and bear no relationship to an airports maximum safe capacity. This schedule is published in the Official Airline Guide (OAG) every 90 days. Whether it is a commercial flight of a B777 for a major airline or a private pilot flying his own airplane, a specific flight begins with the flight planning activity 1 to 6 hours before the flight. FAA regulations require the pilot-in-command, or his designated representative, to check all factors (especially weather) that may affect the safety of the flight, including the status and availability of navigation aids and the status of the runways at the destination airport. For flight under instrument flight rules (all commercial flights essentially fly under instrument flight rules) a flight plan must be filed with the country’s Civil Aviation Authority and this information is entered into a computer that is connected to the entire international Air Traffic Control system. An Air Operations Center (AOC), which begins a planning and re-planning dialogue with the ATC system throughout the flight, performs this function for a major airline. The airline owned and operated AOC is taking on an increasing role in the Traffic Flow Management function of the FAA.

After the ATC tower controller authorizes the aircraft to depart on the designated runway, the pilot contacts ATC departure control (located in a control facility know as a TRACON or Terminal Radar Control Facility) upon lift-off. The TRACON facility may be located many miles from the airport and will typically handle several airports simultaneously. The ATC controller in this facility will guide the pilot throughout the climb phase to a cruise altitude of over 30,000 feet (or approximately 10 kilometers). At altitude, the pilot is turned over to an ATC controller at an en-route center. In the United States, there are 20 en-route centers, which will handle traffic from approximately 6 to 10 TRACONs (as a measure of comparison, the United Kingdom and Australia have two en-route centers). As the aircraft travels through a multitude of en-route sectors and centers, he/she is continually transferred to different controllers on different VHF frequencies. Upon approach to the airport and at top-of-decent, the pilot is handed to the ATC approach controller in the TRACON that controls the destination airport airspace. The approach controller assigns a runway for landing and a landing sequence to the arriving aircraft. Within about 10 miles of the airport, the pilot contacts the ATC tower controller and is guided to aircraft touchdown. After clearing the active runway, the pilot contacts ATC ground control for taxi instructions to the gate. Upon shutting the aircraft down, the active flight plan is terminated and the computer file is closed. Throughout the flight, a typical commercial aircraft of a major airline is in constant communication with the airline AOC via a commercially provided VHF digital data link.

In the event that the ATC system should experience an equipment failure, backup VHF radios are available to instruct the aircraft to separate using procedural separation techniques. In addition, since 1990 in the US, large passenger carrying aircraft have used onboard, computerized collision avoidance equipment internationally referred to as Aircraft Collision Avoidance System (ACAS). This system has matured over the last ten years and ACAS is planned to be introduced as standard equipment in aircraft throughout
the world by 2005. The acceptance of this system by the FAA and industry in the US was mandated by congress, for safety reasons, after initially strong resistance from the FAA air traffic control organization and union. One should observe the significant amount of human involvement in this system. This is in sharp contrast to the Telecommunications system which has undergone significant automation over the last 20 years. The international, privately operated, telecommunications system is a close commercial analogue to the US Air Traffic Management System.

Except for the ACAS and commercially provided Aircraft to AOC VHF digital data link (ACARS), this aircraft separation and control system is virtually unchanged from its development over a half century ago and is reaching its capacity limit. Considerable international debate is ongoing on how this system will evolve over the next 15 years. A particular concern is the significant air traffic controller retirement activity that will be taking place over the next 5 to 7 years. This will occur within a relatively short period of time due to the rapid hiring of the current set of controllers in 1982-87 as a result of the controllers strike in 1981. The GAO and the FAA are debating the severity of the situation. It presents a potentially unique opportunity to make significant changes in the system over the next 5 years, however. A central Technical Issue is how to modernize the system and increase capacity while increasing safety at the same time.

2.5 System Capacity and Aircraft Separation

Most of the world allocates air transportation routes through government agencies. In the US, prior to 1978, the Civil Aviation Board (CAB) controlled the allocation of routes that commercial air carriers could provide. In 1978, the US government deregulated the air transportation industry and allowed economic forces to shape the air transportation network. This system evolved very quickly to a hub and spoke network. At the beginning of the 21st century, there are approximately 60 major airports in the United States owned and operated by local municipal governments with a maximum capacity of about 32 million operations per year [3]. Current forecasts predict that the future demand for air travel will significantly exceed supply and delays will increase over the foreseeable future [4][5][21]. As an example of the system maximum capacity sensitivity to aircraft final approach spacing, decreasing aircraft separation in the final approach to a runway from an average of 4 nautical miles between aircraft to 2 nautical miles (Figure 8) could increase this capacity in the USA to over 70 million operations per year.

This increased capacity could be achieved by migrating from the use of radar surveillance to the use of aircraft broadcast Global Positioning System (GPS) satellite navigation fixes over a wireless digital data link. This is referred to as Automatic Dependent Surveillance – Broadcast or ADS-B [3] and can be used to maintain aircraft separation. Technology like the NASA developed Passive Final Approach Spacing Tool (pFAST) can be used for optimal aircraft airport approach sequencing. This capacity increase can not be realized, however, without a change in the en-route separation procedures used by air traffic

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4 As will be shown in Figure 10, these technologies may increase both separation safety and arrival efficiency but have offsetting effects on increasing net capacity without modification of the current static wake vortex separation standards.
controllers due to human cognitive workload limitations [5]. At individual high-density airports, these average delays can be as high as 10 minutes per aircraft at airport capacity fractions > 0.7. Increasingly, a central flow control function is being used to institute ground delay programs to anticipate these delays and hold aircraft on the ground at the point of origin rather than in the air at the point of destination. In the US, these delays are frequently triggered by a weather event effecting one or more of the hub airports.

Figure 8. Runway Arrival Rate per Hour as a function of aircraft spacing and arrival speed. Decreasing arrival spacing from an average of 4 nmi. to 3 nmi. increases system maximum capacity by 34% [5].

There are five main actors that control the utilization of the air transportation system: 1) the Civil Aviation Authorities in the provision of regulations and aircraft separation / flow control standards and services; 2) the airlines in their utilization of aircraft enplanement capacity, advanced avionics and the utilization of ATM information in their Air Operations Centers; 3) the airport operators in their provision of airport infrastructure, 4) the private aircraft operators in their provision of advanced aircraft avionics and non-interfering airspace utilization and 5) the US military. In order for the capacity and quality of service to increase in the 21st century, each of these players will have to make substantial capital investments in new equipment and significantly revise their operational procedures.

2.6 A Safety – Capacity Crisis is Emerging

There is a growing consensus over the last 3 years that the capacity of the US National Airspace System is finite and currently approaching critical saturation limits. The first U.S. national air transportation capacity estimate was published in 1999 [3][5]. It assumed that the air transportation system is a linear system and therefore it’s capacity is the sum of the total airport capacities. The non-linear effects were included as the second
term in the capacity equation and were not estimated. Further analysis found that the delays experienced at the major hub airports correlated to a predictable growth in delays using simple queuing theory and the airport operational capacity fraction [4]. Further examination using better delay data from both the USA and Europe indicated that the linear model is inadequate to explain all of the observed behavior and non-linear effects such as airline schedule and route structure, en-route airspace restrictions and ground delay programs are important in determining accurate capacity and delay estimates [6].

Subsequent to these papers and DoT Inspector General congressional testimony on national capacity limitations, the FAA and the Department of Transportation have issued an Airport Capacity National Benchmark Report [7]. In addition, the FAA has released 3 reports on the measured efficacy of the NAS modernization efforts referred to as Free Flight Phase I [8][9][10].

A number of issues are now coming into focus.

1 The capacity of national air transportation systems at major hub airports is becoming arrival rate limited. Addition of new runways to these airports experience dis-economies of scale and the addition of new runways at reliever airports tend to be underutilized due to airline economic realities. Both new technology and new regulations need to be introduced to address the safety and economic issues.

2 Two simultaneous and co-dependent air transportation control paradigms are emerging in the US air traffic management system.
   a. A hub-to-hub, high capacity airways network that is limited by major airport capacity (e.g. minimum aircraft separation, number of runways, number of gates, airport security system, automobile parking spaces, service road access, etc.) and the size of the aircraft. Aircraft flying between these 60+ airports are relatively organized, sequenced and fly at roughly the same altitudes. These aircraft could be very closely spaced in 4-D tubes, to reduce ATC Controller workload, between these airports given the addition of aircraft self-separation technology. The aircraft would all be equipped with enhanced flight management systems that allow minimum flight technical error, high flight path conformance and permit Required Time of Arrival (RTA) within 10 to 30 seconds of scheduled runway threshold crossing time.
   b. Direct, increasingly on-demand, low-capacity aircraft flying between lower population density communities and scheduled, low-capacity aircraft flying between the lower population density communities and high population communities. Many of these low-capacity aircraft fly at lower airspeeds and frequently, lower altitudes than the high-capacity aircraft. The airports at the low population communities are typically not capacity

5 These four dimensional “virtual tubes” would link the primary hub airports, much like the interstate highway system [27]. Large commercial aircraft that operate within these tubes would be self-separating and the ground based control system would move the tubes in space as weather required. This should greatly reduce the ground controller workload in the enroute domain. The traffic would have time separation arrival spacing based upon demand management schedules and DoT/FAA safety standards.
constrained, but the carriage of relatively few passengers per flight leads to increased en-route controller workload. Also, many of the low population community airports do not have air traffic control towers or radar separation services, thus limiting all-weather travel predictability. In order for this air transportation system to mature, low-cost, unmanned terminal weather and aircraft separation facilities need to be developed and certified. At low arrival rates (e.g. <10 aircraft/hour), suitably equipped aircraft may be able to self-separate without a ground based system in IMC to a decision height of 400 feet. En-route autonomous aircraft separation technologies and procedures also need to be certified in new low-occupancy vehicle corridors so that ATC controller workload does not limit this transportation option.
3.0 CAPACITY, SAFETY AND DELAY

3.1 US Airline Schedules are not limited by Safety Relationships

Although rarely discussed, it is obvious on theoretical grounds that air transportation capacity and safety are related [11] [12]. Figure 9 illustrates an estimate of wake vortex accident rate for a single runway using an European wake encounter model (S-Wake assuming a 50% random mix of B747 and B737 aircraft). Note the rapid decrease in predicted safety between 33 arrivals/hr to 60 arrivals/hr.

![Single Runway Estimated Wake Vortex Accident Rate](image)

**Figure 9. Estimated relationship between System Safety and Capacity**

For this assumed high enplanement capacity aircraft mix, the predicted wake vortex encounter rate goes from over 2,000 years for a Hazardous wake encounter to less than 3 years for a Catastrophic wake encounter. **This represents less than a Doubling of the Runway capacity.**

The recent publication of arrival-departure pareto frontier data by the US DoT indicate the very high operational rates that are being accommodated by the FAA ATC system under both Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) conditions. Figure 10 shows the data for LaGuardia Airport. Figure 10a shows the number of arrivals scheduled for each 15 minute interval throughout the day. A similar graph would show an equal number of departures with a slight time shift since departures must equal arrivals when averaged over the entire day. Note that the scheduled arrivals exceed even the good weather nominal arrival rate of 10 arrivals/15 minutes. The FAA nominal arrival rate is reduced to about 8 arrivals per 15 minutes in bad weather or IMC as shown in Figure 10a.

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6 Data derive from the Netherlands Aeronautics Laboratory (NLR) Calculations.
Figure 10a. LGA Scheduled Number of Arrivals in 15 minute increments compared to the FAA estimate of safe aircraft operational separation of 8 (32 Arrivals / Hr.) under Instrument Meteorological Conditions (IMC) [7].

Figure 10b. LGA one-hour Arrival-Departure Operation Rates for April and October 2000 [7]. Notice that Arrivals in excess of 33 Arrivals per Hour imply average aircraft separations of less than 3 n mi or 80 second separation.
In Figure 10b, actual arrival and departure rates are plotted for a one hour period in April and October of 2000. Note that the average is around 33 arrivals and departures per hour (4 nmi. or 109 seconds average separation). Peak operational rates were recorded up to 45 arrivals and departures per hour (3 nmi. or 80 second average separation), however.

Recent aircraft inter-arrival time data obtained by Haynie [13] at LaGuardia Airport (LGA) indicate that both wake vortex separation and simultaneous runway occupancy criteria are being compromised in the interest of accommodating an over scheduling of airport capacity. Although the FAA ATC tries to meter the aircraft at the 33/hr. rate, uncertainties and inaccuracies in the current technology create a + 50 to - 30 second time spread that results in both loss of capacity efficiency and potential loss of safety. Figure 11 illustrates this separation problem showing arrivals at wake vortex separation time separations of less than 0 seconds (Arrivals less than 0 seconds represent arrivals that are at risk of a hazardous wake vortex encounter or a runway occupancy violation.. Aircraft arriving at times in excess of 0 seconds represent inefficient sequencing and separation that reduce the maximum achievable capacity of the airport.).

The unfortunate excessive congestion at LGA in the fall of 2000 was the result of dramatic excessive scheduling of the airport due to congressional relaxation of slot controls at LGA. A lottery was temporarily put into place to restrict the flight schedule at LGA until a more rational system was established to restrict flight activity. Safety has not been identified as a concern, however. Only the flight delays associated with high congestion and high community noise levels have been raised as a reason for flight rationing. The data shown in Figure 11 illustrate that new regulations concerning over-scheduling of airports should also be based upon safety constraints. Both technology additions to aircraft operating into high capacity airports and economic incentives need to be the foundation for maximizing the safe capacity of major hub airports.

Figure 11. Aircraft Separation Histogram at LGA of 124 Arrivals (20 sec. bins) on 13 March 2002 (Average Arrival Rate=33 arrivals/hour). Negative Values represent current Wake Vortex Separation violations operating at 100% IMC capacity [13].
Figure 12. Number of Near Midair Collisions (NMAC), Runway Incursions and Loss of Legal Separation Reports filed at 4 airports over the last 13 years correlates with the capacity fraction the airport was operating at the time the incident occurred [13].

Figure 12 illustrates that pre-cursors to accidents happen more frequently at a selected number of airports studied [13] as the aircraft arrival rate increases. These curves look very similar to the theoretical delay curve shown in Figure 14. These reports are principally voluntary pilot reports and are probably an underestimate of actual incidents. This data might suggest that continuing to operate the system as a stochastic arrival system with unregulated schedules should set an airport maximum capacity at roughly 50% of its maximum capacity on safety grounds. On the other hand, moving to a schedule synchronized by time-window slot auctions, and using the new aircraft equipment that will allow time-based separation could utilize significantly more of the available maximum runway capacity.

Figure 11 also illustrates an interesting problem in modernizing the ATC system. New optimum arrival sequencing software and new accurate aircraft spacing technology could, in principle, eliminate aircraft over or under separation. Since the current system is erring on both sides of the static wake vortex separation ideal, the net result on increased capacity would be almost zero! This illustrates not only that the static wake vortex separation system must be improved and the average aircraft separation standards must be reduced, but it illustrates the non-linear relationships between the ATC technology and
procedures modernization program (i.e. deploying individual technologies in a build-a-little, test-a-little fashion may not show any improvement until many new interacting systems are deployed).

3.2 FAA Operational Evolution Plan: Capacity and Delay

In general, the NAS modernization and airport runway improvement programs that are being fielded and analyzed are indicating substantially less than predicted performance. It is becoming increasingly clear that several important non-linear effects are complicating the NAS modernization program [7] [8] [9] [10]. These effects have been observed in the results of numerical simulations using network codes such as the MITRE DPAT and LMINET codes but have not been widely recognized as significant to date.

As an example, one noteworthy study [23], used the LMINET model to estimate the capacity increases of the NASA research programs. These estimates were made prior to rigorous field data availability. Subsequent data indicate that human-computer interactions were underestimated in previous laboratory and early field tests. In addition, the LMI study assumed that these technologies would be applied to all 64 airports used in the model. Major non-linear system effects (which should be captured by this model) were masked by this assumption. For these reasons, this review emphasizes the results of FAA Free Flight Phase One—modernization deployment effectiveness analysis of the current NAS modernization efforts which show far less capacity increases than were predicted. These improvements are expected to be in place within the next ten years. Based upon current experience [8] [9] [10], the demand-capacity mismatch will be significantly worse than it is today with the resultant increase in queuing delays, Ground Delay Program holds and flight cancellations.

3.3 Delay, New Airports and Runways

Air transportation delays are governed by the same physics and are described by the same mathematical models as highway delays and telecommunications delays. Unregulated network traffic flows are described by queuing theory and the concept of maximum capacity is an important parameter. For air transportation, the maximum number of arrivals per hour for an airport is the relevant parameter. Currently, the absolute capacity limit for a single runway is about 60 arrivals per hour (ignoring aircraft wake vortex separation in clear weather) and is limited by aircraft runway occupancy (i.e. braking and turning) time of 45 seconds + safety margin. An airport is a complex addition of runways and the airport maximum capacity is typically less than the simple sum of the maximum capacity of its individual runways.

Figure 13 shows the top 18 airports of the US as a function of their capacity ratios. Simple queuing theory explains why the delays are so high and intractable for high demand airports that cannot fundamentally increase their maximum capacity. Increasing maximum capacity is not easy, however, without improving our aircraft spacing technology and decreasing our wake vortex spacing criteria. Adding new runways will help some but increasing the capacity of one effects all of the rest, sometimes in undesirable ways.
Figure 13. The Estimated Current Airport Operational Capacity Fractions for Major US Airports. Exponential Queuing Delays begin at about 60%.[18]

Figure 14 illustrates the theoretical relationship between an unregulated airport schedule (including the random effects of weather, aircraft maintenance and competing airline schedules) and expected arrival delay. This type of delay is experienced by us everyday in freeway traffic and in low-cost computer Local Area Network (LAN) systems. We have already discussed the fact that the maximum capacity of an airport can be determined by the maximum capacity of it’s runways. An airport can be modeled as a complex addition of runways (lumping the effects of runway/taxiway geometry and gates into a single capacity reducing term). Figure 14 shows us why the delays at our airports have been increasing since 1990. In spite of all the technology we have deployed over the last ten years, we have not fundamentally increased the airport maximum capacity and therefore, the delays have not gone down. Once an airport starts operating at an average (remember that airports frequently operate at significantly greater than average due to airline schedules and weather effects) over 70% of maximum capacity, delays increase to over 10 minutes per flight at an accelerating rate.
Figure 14. A theoretical delay increase for an airport that operates in an unregulated (i.e. non-time-slot controlled) fashion similar to current US practice.

The US has been attempting to add runways to major Hub airports for the last 20 years with limited success. Due to the large area that is needed for a runway to act as an independent runway the new runways either incur excessive taxi times or are closely spaced with taxiway chock points. Figure 15 shows the relative runway utilization for a number of the US major airports [5] with maximum operational capacity normalized by the number of runways at the airport and plotted as a function of the number of runways. One can clearly see that the normalized relative capacity decreases as the number of runways increases. This dis-economy of scale is the result of many factors including, weather effects, runway spacing, taxi-way designs and terminal geometry. Detailed simulations of airport operations have shown these same effects. In addition, runways that are constructed at airports that currently have only one or two runways do not increase the national network capacity because the economic incentives are not present for the airlines to schedule flights to these airports. Parametric studies using the MITRE DPAT model illustrate that the network is highly non-linear and significant network capacity can only be increased by increasing capacity at the major hub airports and these airports are frequently the airports that either have no land for expansion, experience significant political opposition to expansion or experience the diseconomies of runway scale shown in Figure 15.
Figure 15. Non-dimensional Runway Utilization of 9 US Hub Airports illustrating that airports with multiple runway frequently experience significant dis-economies of scale.

The “XG” factor in equation (2) represents the effectiveness of an airport’s runway, taxiway, and gate arrangements. An XG=1 is a perfectly efficient airport (i.e. San Diego, Phoenix) while San Francisco has an XG=0.4.

Once we understand the limiting factors of an individual runway on an airport’s capacity we need to look at the network of airports. Consider the concept of an air transportation network Total Operational Capacity (TOC). TOC is computed by summing the maximum airport operational capacities and subtracting the air traffic control restrictions.

\[ \text{TOC} = \sum_{i} \left( XG_i \cdot S_i \cdot R_i - \text{GroundDelayProgramFlightWithholds} \right) \]

Where \( XG_i = \) ith Airport Runway Design and Gate Capacity Efficiency Degradation

\( S_i = \) Security Queue Operational Efficiency Degradation at the ith Airport
And $R_i =$ Number of Runways at the $i$th Airport

$N =$ Number of airports in the Transportation Network (Approx. 60 for the US)

$60 =$ Maximum number of operations per runway per hour (Limited by aircraft runway occupancy time of approximately 45 seconds + 15 second safety margin).

It has been suggested by some that the mere addition of 50 miles of steel-reinforced concrete will solve the US capacity problem. This refers to the addition of 25 new runways to the US air transportation system. Unfortunately, this simple solution will not solve the problem.

The large size and complexity of the network has served to obscure several important characteristics of the system. A simple 3-airport network example is constructed to demonstrate the problem of increasing network capacity, one modernization system and one airport at a time. A recent study by Hansen, et. al. [14] illustrates how airport and airspace improvement programs can produce optimistic estimates of capacity increases at large hub airports. Of particular interest is the study by Hansen [19] that illustrates the free-market effect of airlines migrating to smaller aircraft. This effect is also a major determinant of decreasing passenger enplanement capacity in the future.

### 3.4 A Simple Network Example

The National Airspace System (NAS) is a large, non-linear, Complex Adaptive System (CAS) that is constructed from at least 60 major US airports and over 10 major airlines with independently scheduled transportation networks overlaid on the airport/airspace structure. The network is so large and complex that it is difficult to understand its basic nature. The large numerical simulation models that have been constructed to represent this complex network (with over 65,000 flights per day included in the simulations) have not been used to map out the non-linear Network Response Function to date. Recent work with the DPAT model at GMU is showing that practices such as independent airline scheduling and airline network interactions have a much greater non-linear impact on delays than was previously believed.

In order to understand why airport and NAS modernization programs are having less beneficial effects than would be predicted for a linear system, consider a simple 3-airline and 3-airport system$^7$ shown in Figure 16. Each airline is based in one of the three airports and produces an independent, uncoordinated schedule of flights.

For Case I, each airport has two independent runways operating at a maximum safe Visual Meteorological Conditions (VMC) separation capacity of 50 operations per hour

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$^7$ I am indebted to Prof. Ariela Sofer of George Mason University for suggesting such a simple model to explain the non-linear system behavior and to Ms. Lee Olson for suggesting and explaining the second Case II example illustrating airline interests in forming a Hub airport at A and keeping delays at airport A high and decreasing service between airports B and C.
per runway (i.e. 2.5 nmi. aircraft separation). One runway is used for departures and the other is used for arrivals. The maximum steady-state transportation system capacity that can be supported by this network is 300 operations per hour. This will be referred to as Total Operational Capacity (TOC). The capacity fraction of each airport runway is $50/60=0.84$ and therefore the delays are quite large at each due to the independent scheduling and asynchronous First-Come-First-Serve (FCFS) queuing system employed in the air traffic control system.

Case II represents a typical scenario where one airport authority (airport A) decides to add an extra runway to increase capacity and decrease delay at their airport. This runway must be used in a mixed operation mode since arrivals must equal departures in a steady state operation. This case has two variants.

Case IIa: Although the airport can now depart and accept 50 more operations per hour, the network cannot accept them because the other two airports cannot accept them. Therefore, this extra airport capacity is of little use to the system. The capacity equation sees this as an airspace loss term and it is manifested as an air traffic control gate hold or Ground Delay Program (GDP). The net result is that the TOC is still equal to 300 operations per hour. Delays are potentially decreased ($100/180 = 56\%$ capacity fraction) at airport A but not decreased at airports B and C. The arrivals and departures at airport A can now be balanced between three runways thereby increasing the average aircraft spacing, thus potentially increasing safety. Also, airport A may now have better adverse weather capability, thus weather over airport A will have less of an effect on airports B and C.

Case IIb: With the extra capacity at airport A, airline A chooses to operate Airport A as a hub. He changes his flight schedule to take maximum advantage of the increased capacity at airport A and no longer offers any flights between airports B and C. The delays at airport A are now the same as before the addition of the new runway and the Quality of Service (QOS) has decreased between airports B and C due to the increased time it takes to travel through airport A with high delays at the hub transfer point. The regional economy of city A will grow at the expense of cities B and C.

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60 arrivals per runway per hour represents a practical maximum arrival rate based upon aircraft runway occupation time (ROT) considerations [3]. Delay is a hyperbolic function of capacity fraction (cf) for a random arrival, random service system (i.e. delay $\sim$ cf / (1 – cf)).
Figure 16. Example of a 3 Airport Transportation Network.

**Case I: Base Case**
(TOC = 300 Operations/hour)

- Arrivals = 50/hr
- Departures = 50/hr
- (2 Runways)

**Case II A: TOC=300**
- 2R, 50A/50D
- 3R, 75A/75D

**Case II B: TOC=350**
- 3R, 75A/75D
- 2R, 50A/50D

**Case III: TOC=400**
- 2R, 50A/50D
- 3R, 75A/75D

**Case IV: TOC=450**
- 3R, 75A/75D
- 2R, 50A/50D
Case III now adds another runway at airport B. The system can now increase traffic between airports A and B. Each of these two can accept 25 more arrivals and 25 more departures. If the airlines decide to increase the route numbers between airports A and B, the TOC is increased to 400 but delays are not decreased if these 100 new slots are used! Delays between airports A and B should be significantly reduced if the airlines do not decide to use the extra capacity provided. Delays at airport C are not significantly affected. Airport B now gains the safety and weather benefits discussed in Case II.

Case IV finally adds a new runway to airport C. The TOC has now increased to 450 operations per hour. All airports now have equal increase in network capacity and can either use the extra capacity to increase safety and reduce delays by operating at a lower airport arrival capacity fraction (i.e. 50/90=0.56) or increase capacity at equal safety and delay.

If underutilized runway capacity is to be exploited, then new regulations will need to be developed to provide incentives for airlines to invest in hub airports that offer significantly less OD traffic than 50%. Many economists believe that a properly designed public-private auction system needs to be developed to properly load–balance the system to achieve both maximum efficient utilization of existing infrastructure and to achieve maximum safety by not over scheduling airport runways, as we saw in the case of LaGuardia in October of 2000.

3.5 A Two Tier Air Transportation System is Emerging

The NBAA has been observing the rapid growth in business class jet aircraft (GA) over the last 10 years [16] as shown in Figure 17. In addition, the growth in Regional Jet (RJ) usage has been nothing less than phenomenal over the same period.
This overall movement to smaller aircraft has been exasperating the nation’s major airport congestion problems by enplaning fewer passengers per aircraft over the last decade. The airline economic efficiency of using smaller aircraft at low operating costs, profitable load factors and utilization rates has led to this trend. As this trend continues, service to low population density regions will be serviced by an increasing number of small aircraft operating out of small and sometimes non-towered airports.

The US has a large number of airports that can be utilized by these aircraft. Figure 18 illustrates over 700 airports within a 1000 nautical mile radius of Washington DC. These airports are within a 30 minute drive from an urban population center and have a paved runway greater than 3500 feet in length. The majority of these airports are not equipped with an Air Traffic Control Tower, nor can they provide aircraft radar separation. Under IMC conditions, this lack of ATC infrastructure greatly reduces the value of these airports to provide reliable air transportation system capacity.

Figure 18. Distribution of Small Public Use Airports in the US Capable of supporting a Regional Small Aircraft Transportation System.

NASA should be investigating the use of new technology in both GA and RJ aircraft, combined with a new automated ground terminal facility to provide all weather reliable air transportation service to the communities served by these airports. The technology required for these airports is autonomous terminal aircraft sequencing and separation at up to 15 arrivals/hour (i.e. an average of 240 seconds separation) and continuous weather monitoring and runway occupancy surveillance. The design of such a facility is rather straightforward. High levels of availability can be achieved affordably by using a robust design of diverse and redundant surveillance techniques. Initial simulations of such a
system indicate that operational rates in excess of 12 to 15 arrivals per hour might require a manned air traffic control tower due to high rates of aircraft repositioning requirements.

The major problem with the expansion of a small aircraft direct service system is the relatively inefficient carriage of passengers. One can assume that the GA and RJ aircraft will enplane from 3 to 50 passengers per flight (much less than the average 130 passengers per flight now carried by the majority of commercial aircraft). This increase in flight activity places severe demands on the en-route air traffic controllers using the traditional role of the AT controller to separate aircraft. Simulations of suitably equipped aircraft conducting their own aircraft surveillance and separation, using on-board ADS-B and data-link technology suggest that the pilot workload and the number of aircraft repositioning events are significantly smaller than using a structured airspace, centralized ground controller based system [17]. A simple calculation of 15 aircraft departures/hour from 700 airports in the US Northeast triangle (as illustrated in Figure 18 and with an average flight duration of 2 hours) generates and ATC controller workload of over 21,000 aircraft aloft.

This compares with a typical national average of just over 6,000 today. Clearly, this cannot be accommodated with today’s en-route ATC paradigm. Transferring separation responsibility to the aircraft, using the new technology can handle this load assuming that a new digital communication system is adopted using a cellular telephone sector geometry similar to that shown in Figure 19 with up to 200 aircraft per 100 nautical mile triangular sector. The key problem in adopting these new technologies is the transition from today’s aircraft equipage to that needed to accommodate air transportation system expansion.

Figure 19. Hypothetical Low-Occupancy-Vehicle Sectors. Sector Size set by Digital Communication considerations.
Two DoT/FAA policy changes may be able to facilitate this transformation to a new NAS architecture. The first is the development of slot auctions at the nation’s top 10 airports. The auctions would be designed to find the most efficient market clearing price for arrival time slots that would be set at the maximum safe operating rate for each airport. The auction proceeds would be placed in a fund dedicated to offsetting airline technology equipment costs and encourage the maximum safe capacity increase as the FAA infrastructure and aircraft become properly equipped. The high capacity 4D tubes connecting the roughly 60 major airports in the US would utilize sequencing and separation tools such as TMA, pFAST, Wake Vortex Separation Alerts and URET to efficiently handle increased loads of large aircraft, perhaps flying in close closely spaced aircraft groupings. Even with all of this technology and new operational procedures, the number of large aircraft operating at these airports cannot increase from 6000 to more than about 9000 aircraft (unless simultaneous runway occupancy is allowed by the development of super-wide runways with formation landings). Most of the aircraft in this category over the next 20 years are already designed and many are already in service today (therefore must be retrofit with new self-separating avionics and data links).

The second policy change is required to accommodate the expected large increase in new GA and RJ class aircraft. Many of these new aircraft are still in design and most have not been produced. These large number of low-occupancy-vehicles will need to be equipped with self-separating avionics and high bandwidth digital data-links. The majority of these aircraft will be pressurized but they will fly relatively slow compared to the large aircraft serving the high population centers (i.e. the air transportation trunk lines). Due to the relatively low occupancy capability of these aircraft, they must be available at much lower cost, thus necessitating lower speed propulsion systems. Two new en-route altitude bands could be created. One from 13,000 ft. to 18,000 feet and one above FL 400. These corridors would be restricted to fully equipped aircraft and would be given flight clearance priority based upon their ability to self separate and operate in high density airspace.

All of the aircraft discussed above, must be equipped with an enhanced flight management system that is capable of negotiating and executing a 4D contract with a centralized ATM Flow Control function. The European PHARE Program demonstrated such technology in the late 1990’s and the NASA SATS research program may demonstrate a low cost version suitable for GA and RJ aircraft.
4.0 AIRPORT SECURITY

Increasingly, airport security will become a major capacity limiting factor. It is part of the serial queue structure that makes up the airport nodes of the air transportation system. As the requirement for 100% baggage and passenger screening becomes enforced, the large delays that will be associated with enplanement of passengers will directly impact overall system capacity. It makes little sense to decrease aircraft separation and increase runway operational rates if the passengers cannot get to the aircraft without substantial delays, thus decreasing the desirability for a high speed transportation system. A recent study by Shaver at the RAND Corp. [24] has estimated the amount of delay that will be incurred at a large hub airport.

Figure 20. Hourly Baggage Throughput at a Major US Hub Airport [24].

Figure 20 illustrates the magnitude of the problem that the congressionally mandated 100% Explosive Detection System (EDS) screening is facing. Just as the number of aircraft that transit the air transportation hubs create queuing delays, the enormity of the baggage transfer cannot be underestimated. One should recall that the major problem with commissioning the new Denver airport was not with the number of runways or the air traffic control system, it was with the baggage handling system. Denver had the advantage that the system they were installing was totally new and designed the space and flow paths for the enormous baggage exchange that the airport was designed to have with six independent runways!

As with all sensing and screening devices, the new EDS equipment are designed with a trade-off between a high probability of detection and a low probability of a false alarm. If the operator sets the detection threshold too low, in order to achieve a high detection probability, the false alarm rate rises and one must re-examine the false positive alerts – thus increasing the queue time with a redundant screening process. If the detection threshold is set too low, to decrease false alarm rates, there is a relatively high probability that an explosive devise will be missed in the screening process. Figure 21
illustrates the expected Hub airport queuing delays for a 100% detection reliability system (an ideal not to be achieved in practice) and a 90% reliability system (this would be an excellent system for any real deployable screening device) as a function of the number of machines deployed. You can see that a large number of machines will be required to minimize the expected baggage screening delays associated with 100% EDS screening. It should also be noted that with the possible exception of the new Denver airport, the existing hub airports were not designed with the space or logistics layout to accommodate this large number of screening devices, even if the manufacturing community could produce them in high quantities.

![Max Delays per Number of EDS Machines in Operation; All Flights at DFW, 1998](image)

**Figure 21. Estimated Baggage Delay as a function of the Number of EDS machines available [24]**

Using a reasonable screening system design for a typical airport, RAND [24] has calculated the expected increase in passenger delay time as a function of the number of dual channel screening machines deployed and the passenger’s willingness to board an airplane without his/her baggage making the aircraft departure time. As an example, assume: 1) that 40 machines were deployed and operating at this hub airport; and 2) A passenger is only willing to add one hour to his/her trip to assure baggage clearance. The calculations illustrated by the curves in Figure 22 would predict that there would be a 28% probability that the baggage would not accompany the passenger on the flight. This will either result in a new business for the cargo airlines to ship baggage or in an

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9 This refers to 10% of the EDS machines being unavailable for screening because they are temporarily out of service for maintenance or repair.
excessively long increase in passenger travel block time. This extra block time may dwarf hub delays and make travel by air less attractive for trip duration less than 3 to 4 hours. As an example in lost productivity, just one hour of extra travel time for 700 million enplanements per year (at $5/hr) would cost $3.5 billion in lost productivity.

Figure 22. Estimate of Increased passenger travel block time as a function of number of EDS machines deployed in a dual screening mode\textsuperscript{10} and as a function of missed bags [24].

There is no easy fix for this problem. Many security experts believe that a passenger identification system must be developed and that screening be done only for high risk profile passengers. Whatever is done to address this problem, screening every bag at hub airports is probably not a good idea. This is another example that the air transportation system is a total system and that fixing one problem without addressing others will frequently not provide a satisfactory solution [22][24].

Another potential consequence of this problem is the migration of the first class and business class passenger away from commercial air travel to private business jet service. With the advent of fractional aircraft ownership that allows an individual or companies to purchase air travel by the hour, many more executives are now traveling by private aircraft. This avoids the hub travel delay uncertainty caused by hub congestion and increasingly by security delays. There are two adverse consequences to this movement: 1) the airlines use a passenger yield management pricing system to match ticket price to passenger’s travel elasticity, thus maximizing income per flight. The loss of executive passengers to private air transportation will seriously effect the airline’s business model;

\textsuperscript{10} E.g. The number[17:24] refers to the ratio of primary EDS machines to secondary EDS machines required to examine the positive detection’s from the first machines that consist of true and false positives.
and 2) Movement of approximately 3 passengers per aircraft vs. 130 passengers per aircraft leads to a sharp increase in the expected number of aircraft aloft in the system at any one time. This increases controller workload to a point that the system may not be able to accommodate more aircraft in certain regions of the country, thus leading to excessive Ground Delay Programs for all classes of aircraft in the future. This is an area that the NASA Small Aircraft Transportation Program must address.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 The System is Already Changing under Pressure

If the air mode of transportation is to grow, a combination of technology, procedural change, regulatory change and economic incentives must be found to encourage and enable the transition of a system that has proven incredibly resistant to any significant modification over half a century. Never the less, change is beginning to happen. Hub congestion delays are becoming unbearable for business class passengers with incomes substantially over $100,000/year. The lost value of time due to delays becomes equal to walk-up business commercial air-fairs as fractional ownership of business class jets becomes more recognized. A large number of existing airports could be used to support this gradual migration of an important segment of air transportation users. The current airline business model relies on these business class passengers to pay for the majority of the flight cost. As these passengers migrate to private air transportation, the full cost of the air transportation costs will be transferred to the economy class passenger. The combination of increasing demand for air travel, constrained capacity and loss of the business class passenger will significantly change the current airline yield management system and increase the cost of air travel and decreased frequency of service. This increased cost will effectively suppress demand and have a profound effect on the nations culture and economy.

The majority of these new business aircraft do not mix well with large commercial air transports, however, due to speed differences and inefficient use of valuable hub airport runway capacity. Also, movement of larger numbers of passengers by small aircraft will exacerbate ATC controller sector workloads unless the new technology in aircraft based surveillance and collision avoidance is introduced. It is possible that introducing this technology through new generation general aviation aircraft, flying in relatively unused airspace between 13,000 and 18,000 feet and cargo aircraft may allow this transition to take place.

Congress should resist the temptation to make the air transportation system more secure than any other transportation mode or routine activity of US citizens. We should draw upon the experience of the Europeans and Israel [22], which have many years of experience in dealing with terrorist threats to aviation. The focus should be on identifying high-risk passengers and matching inspection technologies to these high-risk groups [22][24]. Another idea that may be worth pursuing would be the addition of a “state of security” message embedded within the ADS-B data-link message. This system could be evaluated in the Cargo Airline OPEVAL.
5.2 Slot Auctions at 10 Major US Airports

It should now be apparent that the current US air transportation system is already over-scheduled by the airlines at major airports and that this is leading to large systemic flight delays. Recent data at both LGA and ATL indicate that large delays may also be associated with an increasing number of aircraft that are exceeding current static wake vortex safe separation standards and therefore the problem is also becoming a safety problem as well. The current system is a random access, first-come, first-serve system. Until the system is regularized into a controlled Required-Time-of-Arrival system, the capacity and safety of the Hub-and-Spoke, major air transportation system will not improve. This problem is a familiar one to the economic community. The operational rates at the major US airports are overloaded because they are undervalued by the airline community. There is a large amount of hub-transfer airport capacity that is underutilized in the US today (e.g. Raleigh-Durham, Kansas City, etc.). These airports are underutilized by the airlines because their passenger fare yield management systems do not make it profitable to fly to these airports without a high Origin and Destination market (i.e. large number of walk-up business passengers paying high prices). Like other critical national infrastructure commodities (e.g. telecommunications spectrum and energy generation and distribution), airway access will need to be auctioned in the future.

The nature and the rules of these auctions are far from clear. As we have seen in both the spectrum and energy auctions, large damage to industry and the public can accrue from improperly designed auctions. If done properly, however, these auctions should find the optimum market clearing price for runway access and thus provide the maximum safe operating potential for our national airport infrastructure. The capital raised from the auctions could be required to be re-invested\(^\text{11}\) into airport expansion and even more urgently, equipage of large transport aircraft with the new avionics that will be required to safely provide aircraft self-separation (or station-keeping) and be able to execute an RTA within a 60 second time window.

5.3 A Proposed Transition Path

The air cargo fleets operate primarily at night, between 10 pm and 6 am. A typical night operation involves less than 300 cargo aircraft, ranging from small single engine propeller aircraft delivering mail to small communities to wide-body cargo jets with just two pilots’ on-board conducting transcontinental high-value freight delivery between major metropolitan regions to and from the air carrier trans-shipment hub. DoT, NASA, FAA and industry should form a government-industry team (to include the cargo airlines represented by the Cargo Airlines Association (CAA), Honeywell, Boeing and Lockheed Martin, etc.) to equip the majority of the cargo airline fleet with Flight Management Systems with ± 30 second Required Time of Arrival and Automatic Dependent Surveillance-Broadcast (Mode S) aircraft self-separation capabilities. These ~300 aircraft aloft at any one time represent over 90% of the entire night operation and would be representative of the future Air Traffic Management System as envisaged by Boeing, Airbus and most serious researchers, both in the US and Europe. Both the FAA and Eurocontrol have estimated equipment costs for cargo airline fleets of approximately 600

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\(^{11}\) Mr. Mike Lewis of NASA LaRC suggested the idea of using auction proceeds to provide the funds and incentives for the airlines to equip with the avionics required to modernize the National Airspace System.
aircraft to be less than $400 million dollars. These costs would be spread over 3 years. An additional cost of approximately $600 million would be required in system analysis, OPEVAL design, simulation, flight test and data acquisition and data analysis. The program funds should become available in FY 2004 and be planned through FY 2008.

Together, this team would analyze, plan, simulate, flight test and conduct a one year Operational Evaluation of the future Air Traffic Management Paradigm. The OPEVAL would be set for 2007 and would encompass an entire year of weather and operational loads to determine the actual RTA performance variability, uncertainty buffer design, hub efficiency and safety. The FAA would operate the system with a pre-flight conflict probe and flight trajectory resolution 4-D contract based upon 2 to 3 hour weather forecast from Central Flow Control. NASA would lead the OPEVAL design systems analysis and flight test data collection, post-operation analysis with DoT, FAA and industry evaluation. Pending satisfactory performance, the FAA and the Cargo Airlines would extend the system into routine night operations and the passenger airlines of the world would evaluate the benefits of equipping their fleets to extend the system to daylight operations. This OPEVAL would compliment the Airbus led European evaluation planned for 2007.

This is the natural next step beyond the FAA led Capstone and Safe Flight 21 experiments begun in 1997. This a significant step forward in the history of air transportation. It will require the highest level of government (executive and legislative branches) and industry support. The 2007 date corresponds to both a predicted serious air traffic controller shortage and the termination of airport slot controls. The current slot control legislation must be replaced with a new regulatory policy if the system safety is to be maintained. Slot auctions at the top ten US airports will require this type of aircraft technical capability and ATM operational system.

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