

**Testimony before the US House of Representatives  
Committee on Science  
Subcommittee on Space and Aeronautics**

**Hearing on the FY2001 NASA Budget Request: Aerospace Technology Enterprise  
Tuesday, April 11, 2:00pm, Rm. 2318 Rayburn Office Bld.**

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Professor of Systems Engineering and Operations Research  
School of Information Technology and Engineering  
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**Abstract**

The US Hub and Spoke air transportation system is approaching a serious capacity crisis. Both safety and capacity are intertwined. NASA and the FAA are working hard at coordinating their research agendas, even though they have very different missions and cultures. NASA has set some very ambitious goals that may not be technically achievable without a fundamental rethinking of the air transportation mode. Specifically, the increase in system throughput by a factor of three is not achievable using large aircraft at hub airports. A reduction in accident rates by an order of magnitude is an equally daunting goal. Pending the availability of funds, NASA could do more in the operational demonstrations of automatic collision avoidance, development of a national, broad-band, wireless transportation Internet, and noise/emissions reduction research. Automatic collision avoidance is routinely discussed in the context of the FHWA ITS program, where it is extremely difficult to implement, and seldom discussed for aviation where the technology is much more mature and the problem is much more tractable. This technology will be required in the future to increase both the safety and the capacity of the air transportation system. Substantial funding to NASA and the FAA will be required if these stated goals are to be achieved.

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Mr. Chairman and honorable members of the committee, it is a privilege to appear before your committee this afternoon to testify on the NASA Aeronautics research program and the Fiscal Year 2001 budget. There are extremely important issues that depend on this research agenda. NASA is assuming an increasingly important mission to lead the research that will be used by both industry and the FAA to implement new airborne and ground systems that will be required to improve both the capacity and the safety of our air transportation system. Before I comment on specific elements of the FY 2001 budget submission, I would like to set the background for my programmatic comments.

### **Background**

It is widely recognized that air commerce, i.e., the transportation of people and goods throughout the United States and overseas for business or leisure purposes, is strongly linked to the nation's economy [1]. Since 1960, DOT statistics indicate that the air mode of transportation has grown at 4 (passenger) to 7 (cargo) times the rate of GDP growth. This is also 4 to 7 times greater than any other mode of transportation. *Thus, any indication that the air transportation system might constrain future air travel because of the inherent capacity or safety limitations of the National Airspace System (NAS) is a justifiable cause for concern.*

Such indications exist. Captain Russ Chew of American Airlines, in a study referred to in the National Civil Aviation Review Commission report [2], put forth an analysis suggesting that the limited capacity of the NAS would lead to unacceptable delays by approximately 2010, only a decade from today. According to Chew, these delays could significantly disrupt airline schedules, bringing into question the efficacy of the current hub-and-spoke system that most major airlines use. Figure 1 [3] supports this hypothesis and shows that the system is currently at 58% of maximum capacity (at current aircraft separation technology). Table 1 [4] shows how this capacity fraction is distributed throughout the United States. At current growth rates, it is predicted to reach 70% of

maximum capacity by 2010. The nature of transportation queues leads to a predicted hyperbolic growth in delays as indicated in Figure 2 [4].

The resulting consequences in increased inconvenience and cost to the flying public are expected to significantly reduce the public's incentives to fly, thereby stifling further growth in the airline industry. While the resulting impact on air travel is hard to quantify, the *predicted annual growth in passenger enplanement of 3-4% is unlikely to occur without a major insertion of new technology and operational concepts*, with significant consequences for both the airline industry and tourism within the United States [1].

However, predictions of serious problems with the NAS, with airline schedules, or with truncated demand for air travel should not be taken out of the context within which they are made. Many of the predictions about growing delays at specific airports will not occur because they are already operating at maximum capacity. Common sense tells us that the airlines using that airport would adjust their schedules and fleet mixes to "manage" their operations and avoid unnecessary delays caused by unachievable demand for additional access. And common sense also tells us that airport authorities will seek to expand airport capacity, to the extent they can, when demand so dictates. However, recent analysis by Hansen, et. al. [5] indicate that adding runways and redesigning the airspace may not be, by themselves, adequate to satisfactorily mitigate the increasing delays at most large hub airports.

The overall capacity of the NAS is a function of a variety of important factors, including the design and operation of the airspace itself and the equipment that facilitates that operation. At present, NASA and the FAA are engaged in substantial efforts to modernize the equipment and procedures to enable significant changes to both how the available airspace can be more efficiently used and how safety can be enhanced. In addition, new operating concepts (e.g., "free flight") are under consideration; and new decision support tools for the controllers promise to open opportunities for better adaptation to congested airspace situations, while augmenting the controller's ability to handle a greater number of aircraft safely. *It is still a matter of debate, however, about whether these actions will successfully deal with the capacity and subsequent delay problems.*

In a recent set of papers by Donohue and Shaver [3] [4], we describe how the NAS capacity might be evaluated and what might happen if technology and new procedures are not put in place to ameliorate the expected growth in NAS congestion. As a minimum, we expect the airlines to respond by changing their schedules, increasing block times between city-pairs, increasing ticket prices and (hopefully) purchasing larger aircraft. If the airlines were left to handle this problem on their own, the result for the passengers and air commerce in general would be serious—reduced access, increased prices, reduced convenience, and somewhat increased delays. Our analysis indicates that the future cost of air transportation will not be determined by the cost of designing or building large commercial aircraft but by ticket-price-setting (yield-management) software in a largely unregulated supply and demand market. Unfortunately, the supply of hub and spoke aircraft operations is technically limited (i.e. runway occupancy time, wake vortex separation, and surveillance accuracy) and the demand for high-speed transportation is steadily increasing.

Any policy on how to make investments to ameliorate NAS congestion must recognize that there are a number of important stakeholders. For the U.S., the six principal stakeholders are the FAA and NASA, the airlines, the aviation industry, the airport authorities, Congress, and (perhaps the most important) the flying public. Others include foreign Civil Aviation Authorities (CAAs) and the international organizations (e.g., International Civil Aviation Organization (ICAO)) that oversee and (to some degree) regulate global aviation activities. Each of these stakeholders have their own incentives regarding responses to NAS congestion. The incentives motivating one stakeholder are often not parallel to those of the others. Worse, they are occasionally diametrically opposed.

The primary motivation of an airline is to make money. While airlines do make long term investment decisions (especially regarding fleet sizing and mix), most of their focus is on near-term profitability, i.e., return on investment. ***Through experience, most of the major airlines have found that hubbing is an economical way to make the best use of their fleet.***<sup>ii</sup> Passenger convenience, measured by serving a wide variety of cities with frequent flights from their hubs, has proven to be a reliable way to gain customer loyalty, repeat business and a steady revenue stream. Hub domination (i.e., one major carrier serving the hub) has often been the result, with mixed blessings for the flying public.

The current manifestation of this strategy is airline investments in small and mid-sized aircraft (***many built offshore***), suitable for frequent flights to and from the major hub airports. The convenience this provides to those flying from smaller regional cities to major urban areas (and in the future, directly from one mid-sized city to another) is substantial, and has spurred the recent remarkable growth in regional jets in the United States. ***It is noteworthy that the average number of seats per commercial airliner has been dropping in the last couple of years and is expected to continue to drop for several more years. This airline behavior is exacerbating hub congestion and has implications for the new NASA SATS initiative.***

Airports are also interested in making money. Profitable customers (the airlines) are critical to their success. They benefit from frequent flights, and only secondarily suffer from the costs of congestion. They benefit from growth in passenger enplanements. For the most part, major airport expansion happens only when the airline(s) operating from the airport threaten expansion elsewhere or the dominant airline feels expansion will not threaten its hub monopoly position. Once an airline has established itself as the dominant carrier at the hub, incentives for expansion are lessened unless that dominant carrier can see further growth. ***In most cases, airport expansion is significantly limited by environmental factors (noise, pollution), and requires local public support and approval. Recently, such approval hasn't been forthcoming [6]. This has important implications for the NASA noise and emissions initiatives.***

The flying public wants both the convenience associated with frequent flight schedules and the current low airfares. As demand grows and congestion becomes worse, the leisure flyers will be most impacted as they are highly sensitive to the almost certain rise in airline ticket prices resulting from the increased demand to supply ratio. They constitute approximately 70% of the current passengers, and are the primary beneficiaries of airline deregulation. Business travelers, on the other hand, are likely to continue to fly in growing numbers as they are far less sensitive to price, often paying “full fare”. They

are considered essential to the profitability of most airlines. *Consequently, airline revenues are likely to continue to rise, and their interest in alternative hubbing strategies will be limited to cities that can provide a solid business-flying base. This also has implications for the importance of the new SATS initiative.*

Finally, Congress has the joint incentives of supporting the nation's interest while also serving the needs of its constituents. Occasionally, these incentives are in conflict, with shorter-term needs and local priorities often getting the largest share of a tightly constrained federal budget. Long range research investment and planning, something needed to successfully deal with the NAS congestion problem, is often the victim.

## **Implications for the Future**

Despite claims to the contrary, it is unlikely that the impending NAS congestion problem will lead to total gridlock or the economic dismantling of the airlines. The airlines will adapt their behavior to ensure their economic viability, and the flying public will modify their demand for air travel as the convenience and cost of such travel changes. The consequences are higher ticket prices, less convenience for the travelers, and a curtailing of the anticipated growth in air commerce. *This implication for the U.S. economy is that the growth in U.S. Gross Domestic Product (GDP) will be negatively impacted.*

What does this mean in terms of policy implications for the United States Government? First, it is important to understand that it is unlikely that the Government will dictate how airlines or the various airport authorities will respond to congestion. Also, congestion is not necessarily bad for either. While greater NAS capacity would offer opportunities for more growth, it seems likely that many of the airlines will still be able to retain their profitability under conditions of moderated growth bounded by capacity problems. To some extent, the higher airline operating costs implied by a congested airspace will be offset by the likely percentage increase in business travelers who pay on the average significantly higher fares per trip.<sup>iii</sup> The airports would also benefit financially from increased traffic and may even benefit from the increased delays where the number of passengers within the airports at any time is likely to grow, increasing opportunities for the selling of food and other merchandise at the airport. The semi-monopolistic status of specific airlines at many major hubs will also add to the inertia resisting change.

Second, as noted at the start, neither NASA nor the FAA has any magic response they can take to solve the congestion problem on their own. Modernization of the NAS can help ameliorate the problem, deferring the date when the airlines and the air transportation system as a whole will be forced to react. But without complementary actions by the FAA, the states, the airports, the airlines, and the traveling public, that deferral could be short-lived.

Perhaps the most straightforward way to think about how the three major actors could productively work together to meet everyone's interest is ask who is going to pay the cost of mitigating the impacts of congestion. For the airlines, it is clear that the passengers will pay for whatever changes the airlines must make to adapt. For airports, it is also true that the passengers will, for the most part, pay for airport improvements, albeit indirectly through the airline tickets, Passenger Facility Charges (PFCs), and services and merchandise they buy at the airport. For the FAA, there is at present no direct tie to the passengers, but the ticket tax that they pay can be considered to be the principal source of

FAA funding for both NAS modernization and operation. Thus, whatever the cost of mitigating the growing congestion, the passengers are going to pay most, if not all of it. Thus, it only makes sense to look for the combination of actions undertaken by the traveling public, the airlines, the airports, the FAA and NASA that adds to the lowest total cost to the passenger.<sup>iv</sup>

## **NASA Aero-Space Technology Enterprise Programs**

I will restrict my comments to NASA programs that involve improvements to the US/International air transportation system safety, affordability or capacity. First, I want to compliment Administrator Golden on the adoption of the Global Civil Aviation Pillar as one of the central pillars of NASA's Aeronautics mission. Six of the ten Aero-Space Technology Enterprise goals relate to this pillar. *Unfortunately, I would also note that less than 7% of NASA's budget is devoted to achieving these goals. Substantial success may be difficult to achieve.*

I want to address each of these goals in turn. Many of these goals are inherently related to each other. The interrelationships of individual technologies are incredibly complex and my comments will, therefore, be inherently oversimplified. As such, I will fail to mention many important NASA technical activities, which relate to my main messages.

### **Reduce Accident Rates, 10X**

It is now well known that the commercial aircraft accident rate has been essentially constant for over a decade. Human factors have been the most significant elements in both commercial and private aviation safety for almost a half-century. The insertion of automation on the flight deck of commercial aircraft, although not without some problems and controversy, has been a significant factor in the dramatic decrease in commercial aircraft accidents over the last two decades. Accidents happen due to a complex sequence of events. Better analysis of existing flight data is required to understand these relationships. In my opinion, NASA has done a good job of coordinating the safety research effort with the FAA and is doing a reasonable job of trying to meet a very difficult goal within a very tight budgetary constraint. Also, due to funding limitations, the FAA has virtually eliminated its technical support and further development of the onboard aircraft collision warning system, Tactical Alert and Collision Avoidance System (TCAS II). This technology has saved countless lives since its introduction in the US in 1990 and is now being installed on aircraft worldwide. TCAS II v.7 is far from perfect and continued development is required. It is fundamental, in order for system capacity to grow, aircraft need to be spaced closer together. *Closing the loop from collision warning to collision avoidance has yet to be done.*

### **Increase System Throughput, 3X**

As my opening comments have suggested this is an extremely important goal. However, this goal cannot be accomplished within the constraints of the commercial hub and spoke operations alone (as shown in Figure 1). NASA and the FAA have been cooperating for

the last several years on technology that can improve aircraft arrival spacing, airport surface movement and wake vortex monitoring. There are four primary limitations to the current hub and spoke system:

1. **Aircraft spacing is limited by the surveillance system accuracy.** There is at least a one to two mile buffer that is added between aircraft so that these inaccuracies will not violate either runway occupancy time separation criteria or wake vortex separation criteria. NASA and the FAA are investigating the human factors of moving to a GPS/digital data linked surveillance system with a distributed control paradigm. The aviation community calls this system Automatic Dependant Surveillance–Broadcast (ADS-B). NASA has been emphasizing ground-based control using the CTAS program for evaluation and implementation. Although this program is addressing the central terminal capacity limitation, there is data to suggest that the time delays inherent in a radar-scan-controller-in-the-loop based system cannot significantly improve aircraft separation. It has, however, been very beneficial in aircraft sequencing and runway assignment at complex airports in simple airspace.

In addition to human factors concerns, a major barrier to the adoption of ADS-B has been the search for the correct wireless digital data communications system that meets wireless bandwidth concerns and international standards. NASA has been a small player in this debate but is seeking a larger role as they investigate the development of an aviation, wireless Internet follow-on. The FAA and ICAO have not made significant or satisfactory progress in this area and can use the technical talent that NASA can bring to bear. The funds that NASA has identified for this effort are insufficient to make a dent in this problem, however. I would recommend that NASA and the FAA should partner with DARPA's program to develop the broadband follow-on to the Internet. This future broadband Internet, with wireless tail circuits, can be designed to meet the stringent integrity, availability, security and time latency criteria required for aviation or ground ITS. *The need for a high integrity, wireless, broadband Internet is one of the major technical barriers to providing an order of magnitude increase in aviation system capacity and safety.*

2. **Bad weather causes the FAA Air Traffic Control system to increase separation** between aircraft, thus greatly reducing the system capacity during times of severe winter weather or spring / summer storms. The resultant delays are propagated throughout the NAS. NASA, the FAA and the National Weather Service are investigating better weather forecasting and weather data links to provide this data on the flight deck. There may be duplication of effort between agencies in this area.
3. **Wake vortex separation sets the closest that aircraft can approach on landing.** New technology is required to sense and monitor the location of aircraft wake vortices. NASA has a program in this area that needs more emphasis, including flight deck monitoring and display systems. This is an area that has received much rhetoric but little serious technical attention. Increasingly, this factor will set the maximum capacity of the air transportation system. The FAA does not have significant technical expertise in this area and I applaud NASA for continuing to pursue research

into determining aircraft wake vortex location. It has been observed that frequently, the preceding aircraft wake vortex has been convected away from the succeeding aircraft flight trajectory by the atmospheric boundary layer. For this reason, the current FAA wake vortex separation criteria are extremely conservative. This was not a concern when the system capacity was operating below 50%. *Even a simple flight deck computer estimate of wake vortex location could help to significantly increase capacity at today's operational loads.*

- 4. Enroute sector loading constraints due to human factors** cognitive workload limitations reduces capacity in a limited number of high density /high workload sectors. The FAA is conducting most of the research in this area. If the NASA SATS program is successful, this problem will change dramatically. One of the advantages of the Hub and Spoke system is that it is economical in aircraft movements. One needs only  $2(N-1)$  movements to connect  $N$  cities (i.e. for  $N=100$  cities, 198 flights). The bad news is that all of these flights go through the hub and the hub eventually gets congested. Direct flights between  $N$  cities does not concentrate flights at any one hub but can potentially generate  $N(N-1)$  flights (i.e. for  $N=100$ , 9,900 flights). This will pose the enroute air traffic control system with a very complex traffic management problem. This problem should be addressed in the SATS research program.

#### **Reduce Cost of Air Travel by 50%**

As I stated in my opening remarks, the price of commercial air travel is dominated more by the economics of the market place and by yield management software and not by technology. On the other hand, technology is the critical factor for small general aviation aircraft. The AGATE program has made progress in introducing modern mass production technology into the aircraft manufacturing business. Much more progress is required, however, before the economic hurdle rates can be adequately reduced to make the SATS initiative a viable mass transportation system. The growing supply/demand mismatch for major airlines should be adequate to ensure an ample profit margin in the future. Some of the technology funded under this initiative is to increase engine fuel efficiency, which has a collateral benefit of reducing noise and engine emissions. This technology is important for the next goal.

#### **Reduce Noise, 4X and Reduce Emissions, 5X**

This is an area where NASA has virtually a monopoly on research and it is becoming one of the critical limitations on capacity. Ronald Reagan National Airport is a good example of a noise-limited airport. Neither runway, aircraft separation nor wake vortex limitations limit it. It is slot controlled for environmental reasons [6]. The addition of the fifth runway in Atlanta, San Francisco and Los Angeles or the second runway in San Diego is a further example of this capacity restriction. NASA needs to increase their research on noise and emissions and needs additional funding in this area. The FAA is a regulator of noise but relies almost totally on NASA to conduct research on ways to reduce noise and emissions. As you are aware, this is becoming an increasingly sensitive issue in the

international community and could put our aircraft at a technical disadvantage in the future world market place. *Increased research efforts toward this goal are necessary.*

### **Invigorate GA, 20K units Annually**

NASA has done a superb job in helping to reinvigorate general aviation with its AGATE program. It is now proposing to begin a follow-on program (SATS) to establish private aviation as a serious means of public transportation. General aviation innovations provide a plausible way for the national air transportation capacity to grow beyond the hub constrained air carrier system. Much of the technology to allow this now exists but significant barriers remain. Autonomous flight vehicles that have been demonstrated by both NASA and the DOD illustrate that we have the flight control systems that can make flying an airplane as easy as driving a car. These autonomous aircraft are not currently allowed in controlled civil airspace, however. The air traffic control paradigm for allowing over 100,000 aircraft in the air, with auto-collision avoidance, is technically possible. Credible demonstrations of this technology will be required, however, before this transportation system becomes a practical option. *One of the major technical challenges remaining is the wireless Internet system that can allow flight data information to be shared seamlessly.*

### **Conclusions**

In the short time that I have been allotted in this testimony, I have tried to provide the committee my views on an extremely complicated research agenda. Overall, I believe that NASA is a competent Agency and is doing high quality research in the interest of the nation's air transportation system. Both safety and capacity are intertwined in this research agenda, as they are in actual operations. NASA and the FAA are working hard at coordinating their research agendas, even though they have very different missions and cultures.

I believe that NASA has set some very ambitious goals that may not be technically achievable without a fundamental rethinking of the air transportation mode. Specifically, the increase in system throughput by a factor of three is not achievable using large aircraft at hub airports. A reduction in accident rates by an order of magnitude is an equally daunting goal. Pending the availability of funds, NASA could do more in the operational demonstrations of automatic collision avoidance and noise/emissions reduction research. Automatic collision avoidance is routinely discussed in the context of the FHWA ITS program, where it is extremely difficult to implement, and seldom discussed for aviation where the technology is much more mature and the problem is much more tractable. I believe that this technology will be required in the future to increase both the safety and the capacity of the air transportation system. Substantial funding to NASA and the FAA will be required if these stated goals are to be achieved.

Thank you for inviting me here today and I will be happy to answer any questions.

4/5/00 5:13 PM

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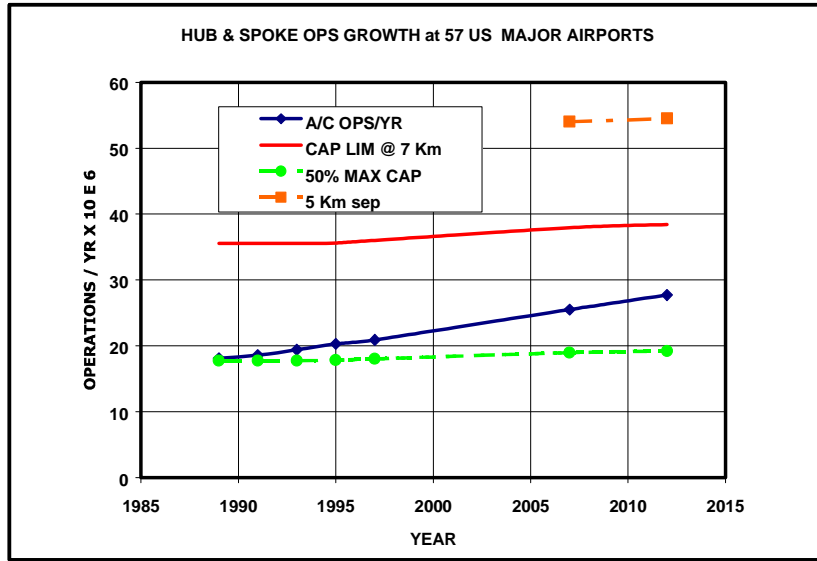


Figure 1. Current US Hub and Spoke operational capacity using the GMU Macro Capacity Model. Dashed line represents 50% capacity threshold above which noticeable delays increase Hyperbolically [3]. Capacity fraction was 58% (1997) and predicted to be over 70% (2010).

TABLE 1 Regional Air Transportation Capacity Fraction For (57) Major Airports

REGION	NUMBER HUB R/W	Estimated # A/C TURN POINTS	Number Ops/Hr		% Cap97/ CapMAX	Avg 8 yr Growth Rate %	TAF 1997 ENP X10E6	OPERATIONS	
			MODEL	1997				2012	1997
NORTH EAST	14	420	348	294	84	9	54	1,950,000	1,645,786
PACIFIC SOUTHWEST	9	262	403	298	74	10	43	2,205,000	1,670,280
PACIFIC NORTHWEST	22	353	693	455	66	8	62	3,364,000	2,549,603
NORTHERN MIDWEST	42	773	1090	684	63	32	99	5,522,000	4,040,088
ATLANTIC COAST	13	269	438	241	55	8	31	1,701,000	1,347,458
CENTRAL MIDWEST	12	205	237	131	55	3	19	1,496,000	1,114,207
WEST	22	415	758	405	53	9	62	3,180,000	2,270,307
SOUTHEAST	21	424	776	391	50	-2	54	2,704,000	2,190,557
FLORIDA & LATIN AM	14	322	602	287	48	18	48	2,114,000	1,608,673
SOUTH SOUTHWEST	27	380	892	433	48	16	59	3,468,000	2,424,105
<b>TOTAL</b>	<b>196</b>	<b>3823</b>	<b>6239</b>	<b>3620</b>	<b>58</b>	<b>11</b>	<b>532</b>	<b>27,704,000</b>	<b>20,861,064</b>
<b>% NATIONAL TOTAL</b>								<b>78</b>	<b>77</b>

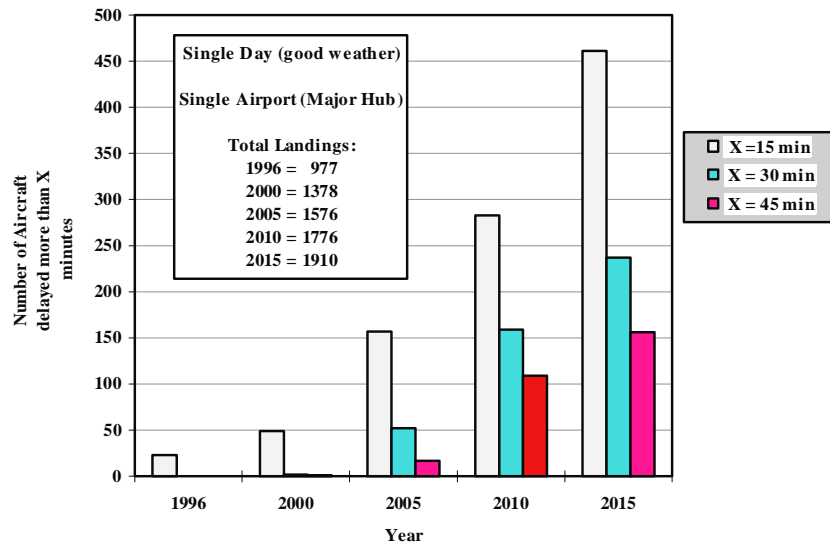


Figure 2. Predicted delay increase at a major hub airport using the MITRE DPAT model [4].

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**<sup>i</sup> Dr. Donohue was formerly the Associate Administrator of Research and Acquisitions at the Federal Aviation Administration from 1994 to 1998. Prior to this appointment he was a vice president of The RAND Corp. in Santa Monica, Calif. From 1989 to 1994 and Director of the Aerospace and Strategic Technology Office at DARPA from 1988 to 1989. He is a Fellow of the AIAA , a member of the NRC TRB and a member of the Goals subcommittee of the NASA R&D Advisory Committee. Donohue holds a Ph.D. in Mechanical and Aerospace Engineering from Oklahoma State University and is a licensed private pilot.**

**The views expressed in this testimony are his alone and do not represent the official views of George Mason University or the Logistics Management Institute, for which Dr. Donohue consults on the development of a new SATS transportation model.**

**<sup>ii</sup> Operating a hub is expensive. But this expense is more than compensated by the high load factors and the revenues that are generated by hubbing.**

**<sup>iii</sup> If the growth in passenger demand exceeds the growth in seats available, then the airlines will be able to fill their aircraft with a higher fraction of business travelers who, on the average, are willing to pay much higher prices for the available seat. Whether the average increase in revenue that results is greater or less than the added cost from congestion is not known.**

**<sup>iv</sup> This leaves aside the complementary question of just how the FAA, the airports, and even the airlines actually are financed. For the purposes of this testimony I am assuming no fundamental change in the pricing structure or in FAA financing.**