The Third Wave of Aeronautics: On-Demand Mobility

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ABSTRACT

Aviation has experienced one hundred years of dynamic growth and change, resulting in the current air transportation system dominated by commercial airliners in a hub and spoke infrastructure. The first fifty years of aviation was a very chaotic, rapid evolutionary process involving disruptive technologies that required frequent adaptation. The second fifty years produced a stable evolutionary optimization of services based on achieving an objective function of decreased costs. In the third wave of aeronautics over the next fifty years, there is the potential for aviation to transform itself into a more robust, scalable, adaptive, secure, safe, affordable, convenient, efficient, and environmentally fare and friendly system. However, such a global optimization requires not only the ability to perform analyses of larger system of system impacts, but also the ability to consider new value propositions that involve different infrastructures and business models than those currently entrenched in the U.S. aerospace industry. While many hurdles exist, including technology, regulation, and perception; the third wave of aeronautics has the potential to mirror other on-demand market revolutions that have taken place over the past thirty years.

INTRODUCTION

This paper provides the system of system vision portion of a trilogy of papers that report out the results of the Personal Air Vehicle (PAV) Sector of the NASA Vehicle Systems Program (VSP). The NASA VSP was cancelled over the past year as part of the Aeronautics Enterprise restructuring, being replaced by the Fundamental Aeronautics Program. Since no further investment is currently planned relating to small aircraft, transitioning this research to industry is imperative to maximize the potential societal benefit. These three papers present the project research, incorporating the overarching system of systems perspective of this vehicle sector (The Third Wave of Aeronautics: On-Demand Mobility - SAE paper 2006-01-2429), the technology portfolio investment required to enable PAV sector capabilities (NASA Personal Air Transportation Technologies – SAE Paper 2006-01-2413), and the integrated vehicle concept development required to achieve a balanced and complementary technology portfolio (Next Generation NASA GA Aircraft Concept – SAE Paper 2006-01-2430). The PAV Sector was the smallest of the six VSP vehicle sectors, with a full cost investment of $10 million dollars over the 3 years.

There has been a long held belief that aviation would one day be capable of reaching an everyday impact in peoples daily lives'. This belief included highly successful innovators such as the Wright brothers and Henry Ford. Yet after many years of rather empty promises, ranging from roadable aircraft to a helicopter in every garage, the aviation community remains transfixed in a highly centralized world of very expensive, and highly productive vehicles. While serving the long distance travel market extremely efficiently, the current entrenched market limits the potential breadth and impact of aviation's daily impact. Pessimists of the personal aircraft vision say that the aviation market evolution has brought us to the logical solution. Optimists of the vision respond that government regulations and the conservatism of the aerospace community have inhibited the market. Both are correct, and as is typically the case, the answer lies somewhere in the middle. However, with a long-term viewpoint of demand and utility, it appears inevitable that someday small aircraft will have a far more significant daily impact in many of our daily activities. The timeline for this to occur is as much a function of the required technologies becoming available, as it is to the development of new regulations, vehicle and airspace concepts, and an aerospace community more willing to take risk due to greater potential rewards. Obviously that time has not yet occurred, however, an enticing question is when will it occur, what causal factors will enable it, and how might this on-demand aviation evolve from the existing market.

MAIN SECTION

The United States has entered the 21st century pioneering a wave of on-demand technology advances in communication, computers, entertainment, and internet-based sales. Though transformational thinking is underway for many military applications, these advances have yet to permeate much of the civil aerospace marketplace. The foundational technologies that drove the first two waves in aeronautics growth in the last century led to today's National Airspace System, hub-and-spoke commercial air carrier industry, as well as innumerable military, public service, and business aviation capabilities helping to create quality of life and prosperity for the nation. In the new century, a third wave of aeronautics offers opportunities for even greater improvements in productivity, resource utilization, market accessibility, economic robustness, and mobility freedom. Today, the needs of the nation have transcended the limited solutions that aviation currently offer, requiring dramatic improvements in capacity, robustness, security, and overall in achieving greater mobility freedom in such an expansive country as the U.S.

In this next century, aviation has the potential to enable expanded air accessibility for more in our society while permitting more equitably distribution to rural, suburban, exurban neighborhoods and communities throughout the nation. Yet the current aviation community struggles with airline bankruptcies, airport congestion, and unprecedented levels of consumer discontent. This topic is relevant today because the legacy infrastructure strategies and business models for commercial air transportation do not adequately scale to meet the future. It is easy to imagine realistic future scenarios where the current aviation system is essentially immobilized, and not only constraining economic growth, but causing a drastic reduction in economic strength. This type of event has already transpired once with the World Trade Center terrorist attack. Imagine the impact on centralized air transportation if a pandemic such as Avian Bird Flu strikes, climate research confirms cruise altitude contrails and airline exhaust are a major source of global warming, populations disperse from central hubs based on quality of life concerns, three times the capacity of air travel occurs with the same existing hubs, one third the air travel occurs because of advances in computer communications and tele-presence, or simple available missile or projectile weapons begin to be used to shoot down airliners. These future scenarios are not unrealistic, and demonstrate the potential that the current aviation system could be in the wrong place[1], not be responsive to needs, and be highly vulnerable to interruption and delay. The future needs of commerce, mobility, safety and security in air transportation will not be met unless strategies, coupled to new technologies, transform the airspace infrastructure and business models with a system of systems perspective, to interface aviation with the entire transportation system and mobility user needs. Just as computer and communication technologies have transformed to equally serve the 'top 40' and 'long tail' markets with on-demand services, aviation could transform to achieve the same robust market breadth.

THE FIRST WAVE

The first 50 years of aeronautics was composed of rapid and chaotic technology innovation, with hobbyists and small companies providing drastic improvements to the State of the Art within a relatively short time span. The aviation market went from non-existence to dominating military strategy and providing valuable civilian services. This was a highly disruptive period of development, that is, new technologies would constantly be disrupting and pushing aside the existing technology and market solutions. As with biologic systems that follow rapid change upon initial introduction to the genetic algorithm, there were many genetic dead-ends that became insignificant compared to the solution best adapted to survival. A portion of the aircraft market that is akin to this is the seaplane, which initially experienced rapid growth and tremendous research funding (for instance through the Schneider prizes), but ultimately led to a market dead-end. This is intuitive with hindsight, since lack of infrastructure supported this ancestry of taking off and landing on almost any waterway, until airports became available and the penalties absorbed by the vehicle for this capability were non-ideal. While chaotic research has a tendency to be duplicative and somewhat wasteful, the genetic material of value still manages to survive, just as the Supermarine seaplane later led to the highly successful Spitfire.

Figure 1 Supermarine Schneider Trophy Winner 1927. (Science Museum London)

Throughout this period from approximately 1900 to 1950, aviation markets constantly re-invented themselves to provide new services as technologies, regulations, and consumer demanded adaptation. Mail services and the military were instrumental in fostering support for this young industry, while recreation and transportation were limited to only the early-adopters. Without legacy regulations or corporations exerting strong influence on the market, a free forming evolution occurred that enabled the genetic (or capitalistic) survival of the fittest.

Personal aviation had been a goal since early in the first wave of aeronautics. Henry Ford is often quoted as saying "Mark my word. A combination airplane and motor car is coming. You may smile. But it will come." But did he literally mean what others later developed as roadable aircraft? The answer to this is best available from Ford's effort into small aircraft with his 'Flying Flivver'. Clearly, he didn't expect us to drive these vehicles down a major roadway, and what would be the point when flying is much faster? Apparently he thought the answer lay in having a vehicle that could get close to where people wanted to go, so that only a short taxi was required to the final destination. "Observers watched it spin down a country road like an automobile, the tail skid having been replaced by a wheel, thus demonstrating how easily the owner of such a machine could drive it from his home to any open place for takeoff."[2] Ford's efforts were more an attempt to achieve an affordable aircraft that would cost little more than an automobile, with a 1926 price of $500.

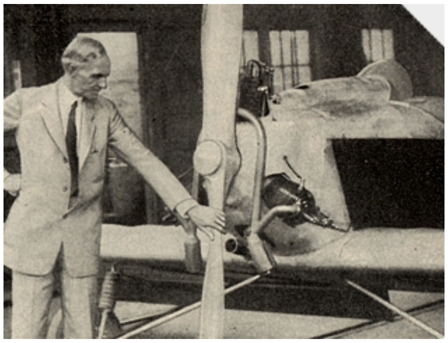

Figure 2 Henry Ford with the Ford Flivver (Ford Museum)

Federal research was an essential element of the first wave of aeronautics, and to a great extent shaped the initial industry and market. It is interesting to note that federal oversight was only instituted until after the request from private companies to provide safety regulations to improve the industry reputation and reliability. Extensive research was conducted into personal aviation, especially through the efforts of the Bureau of Air Commerce and the National Advisory Committee for Aeronautics[3]. In 1933 the U.S. government spent half a million dollars to produce a 'poor man's airplane through the efforts of Eugene Vidal, promising a 2-3 seat, all metal aircraft costing $700 (the approximate price of a nice car and considerably less than any aircraft). While this effort was not embraced by the aircraft manufacturers of the time and portrayed as "an all mental aircraft", the idea was enthusiastically greeted by the public. A direct result of this research was the Erco Ercoupe, which achieved new levels of ease of use, along with a spin-proof, safe stalling, small-field capable, inexpensive aircraft. T.P. Wright, the Administrator of Civil Aeronautics, wrote an extensive review of NACA small aircraft efforts to "meet the needs of the family". "When the market for all other types of planes is grouped it is apparent that what may be termed a really large industry, and one having an important effect on national economy, will not be provided. Of course the market for military aircraft will for a long time represent possibly the most important field in aircraft development and manufacture. However, even considering this with the others it can readily be seen that, developed to an adequate extent, the personal aircraft can easily become the most important factor in the aircraft industry. Used both for business and pleasure it is here only that an almost limitless potential market is available." [4] His analysis of the economics, comparative markets, and technologies relating to this vision of on-demand mobility, point to the technology need of improving the utility to cost of these vehicles.

THE SECOND WAVE

The next 50 years of aeronautics belonged to a very different era of commercialization, with consistent evolutionary technology advancement primarily from large corporations. While you could accurately say that current airliners are far more advanced, the shape and operation are very similar to jet transports from the 1950's. Throughout this period, the aviation market focused on the optimization of productivity and dollars per passenger mile. Fortunately for the current market, reduced fuel consumption was a part of that cost function that pushed engines and vehicles towards improved fuel efficiency. Lower noise aircraft naturally fit into this solution through more efficient high-bypass ratio turbine engines, without requiring the aviation industry to incur significant vehicle penalties to achieve reduced environmental impact. The hub and spoke system was a natural consequence of this optimization process where airlines value the productivity and efficiency of their main asset, over other passenger value propositions. Deregulation of the airline industry in the 1970's further encouraged airlines to apply additional pressure towards this cost optimization, at the expense of most other passenger concerns.

Figure 3 Current Hub and Spoke Aviation System

However, in this second wave that currently defines our aviation system we have reached a point of diminishing returns for the cost sub-optimization. This is called a sub-optimization because the objective function that airlines are working towards doesn't include either the entire system, or other factors of high importance to the consumer. When an industry reaches a point of diminishing returns on their ability to improve service, it is only natural that competition becomes quite severe with prevalent industry consolidation or bankruptcy. This isn't to say that evolutionary improvements won't continue, just that now these cost and performance improvements are harder to come by. Instead of technologists being able to work solely in their small domain of expertise to achieve advances, now technologists must work across multiple technology disciplines to achieve a positive impact on the vehicle. That is, the optimization of the total combined system becomes more important, over sub-optimizations of any particular element, and the reason for increased focus on system integration and analysis. This remark may not be well received by some, because it is a caustic realization by discipline specific technologists that the optimal aircraft system doesn't have one optimal component on it. Each technology area typically compromises another sub-system so that none are optimal within their own domain.

Certainly the hub and spoke system does a great job of meeting consumer needs for long distance travel in terms of block speed and cost compared to alternative travel methods. But for shorter trips, it doesn't serve us nearly as well. Due to the significant time burdens associated with a centralized/scheduled system, airline travel for trip distances of less than 500 miles on average are less than 80 miles per hour. While the current centralized hub and spoke network has evolved into a very efficient system for the airlines, the question remains of whether this is the best system for meeting consumer travel needs, or is there the potential for something better, especially at shorter ranges where centralized air travel suffers most. Figure 4 shows the distribution of the number of trips for all trips taken greater than 100 miles range, from the Department of Transportation American Travel Survey[5]. This shows that over 50% of all travel is at this mid-range travel. The chart also shows the percentage of trips that is associated with each mode of travel, and that airlines capture almost none of these mid range trips.

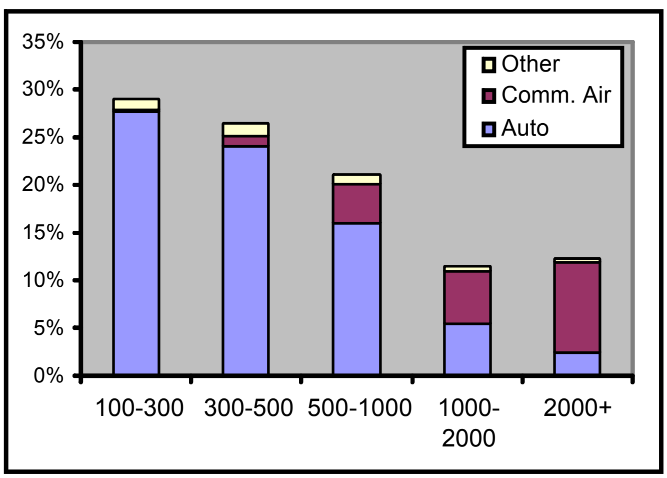

Figure 4 U.S. Travel Trip Distributions by Range (DOT American Travel Survey)

A natural perturbation from the some of the centralization delay problems of the current hub and spoke system is the direct route that low cost carriers such as Southwest and JetBlue currently offer. While these airlines attempt to remove the layover of hub carriers such as United, Delta, American, and USAir, they still suffer equal amount of flight delay and only serve the major, high density routes. Recent flight delay research by Rupp6, Mayer and Sinai7 indicates that it is the very nature of the centralized system, due to deliberate over scheduling during peak periods by the carrier themselves to increase the amount of connecting traffic at their hub airports. Deregulation and the removal of most federal incentives to serve lower density routes and smaller population center airports, applies additional pressure to the centralized system; where carriers vigorously compete to serve large markets, while forgetting the smaller markets. These rural and regional areas suffer from an transportation mobility solutions, which in turn limit their opportunities for economic growth. A recent GAO report[2] found that these communities are burdened with an incomplete transportation system that can severely limit the economic prospects of future development. These communities are already dependent on General Aviation (GA), and are therefore likely first adopters of a PAV transportation system. "Small communities face a range of fundamental economic challenges in obtaining and retaining commercial passenger air service. The smallest of these communities typically lack the population base and level of economic activity that would generate sufficient passenger demand to make them profitable to air carriers." This propensity for centralization to only serve larger markets creates the spiral development of growth feeding growth. A recent example of this is the new Denver airport which as built relatively far out to avoid noise and congestion environmental concerns, only to have the commerce, housing and industry rapidly grow up around the new airport. Adding transportation mobility obviously increases the opportunity for economic development to occur, the question is whether it is best to centralize this development, or find more balanced approaches which better utilize resources, without inducing environmental and land use problems. One particular example of this is that an unfair environment burden is placed upon localities as a centralized strategy is followed, with drastically more noise and emissions being applied to a community than its proportional amount relating to its own mobility needs. It is no wonder that NIMBY (Not In My Back Yard) is a typical community response to airports, even though they provide significant economic and quality of life benefits. If a person lives in Chicago, why should he pay (through noise and emissions) for someone who wants to fly from Norfolk, Virginia to Purdue University in Indiana? The hub and spoke system creates unnecessary travel miles (especially for regional shorter trips) as part of its natural inefficiency for the consumer, because it is more cost effective for the airline. Until the penalties of aviation are minimized to those required for actually serving the local community, it is only natural that these complaints will continue. No one would tolerate a neighbor mowing his yard unless he was receiving some peripheral benefit, in this case, the yard looks nicer and makes the neighborhood a better place to live; even though it makes more noise than an aircraft, for a much longer period of time. This is especially true for GA airports because 99% of the community does not currently have a direct benefit from GA flight activity, and until they do, it is only natural that noise battles will continue with the local communities.

There are excellent evolutionary technologies that NASA is working to continue improvements in noise, emissions, and efficiency in this second wave, at both the component and vehicle level. These areas are still fertile for significant improvements since the objective function of cost is now actively constrained with environmental considerations (with cost penalties for non compliance impacting the objective function). Acoustic specific technology such as chevrons, water injection, and synthetic jets accomplish localized noise improvements, while technologies such as quick mixing rich-burn low NOx combustors and multi-point lean direct injection offer emissions improvements. The Blended Wing Body concept achieves a 25% improvement in efficiency and over-wing nacelle concepts accomplish significant reductions in community noise through wing shielding and accommodation of higher bypass engines without penalizing other aspects of the vehicle.

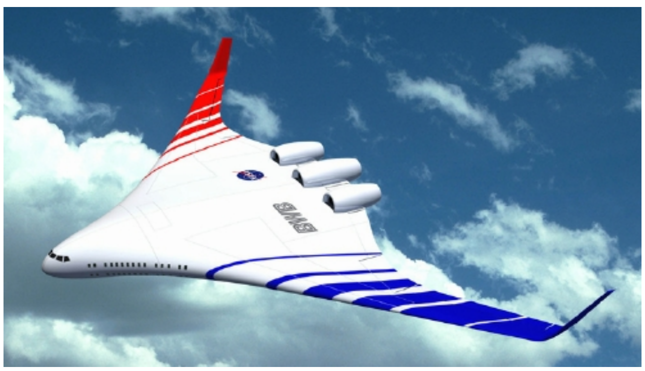

Figure 5 Blended Wing Body Concept (NASA)

If alternate on-demand aviation transportation vehicles were available, and provided safe, affordable, accessible, and comfortable travel, they could offer a block speed benefit for mid-range travel. These alternate choices in transportation from auto or airline could also more easily provide other attributes which are highly valued by the consumer, such as flexibility, control, and freedom – which have never been involved in the airlines cost optimization. The interesting point here is that there is a significant market need for mid-range travel, even though the current travel modes poorly serve this market sector. Imagine how many more trips would be taken in mid-range travel if there were actually a travel mode that was optimized for it. An analysis that paralleled T.P. White's was presented by E.F. Kraus[6] of Cessna 40 years later indicating that it is not performance technologies that would save General Aviation manufacturers from the decline in sales that they were experiencing, but improvements in the cost to utility while meeting the expectations of the larger market for personally operated aircraft. An even more detailed research paper that included the development of a mode choice comparative analysis was performed[9] which highlights the cost to utility barriers present in the GA market. Figure 6 shows an example of the comparative auto, airline, and on-demand air market shares based on value of time and range. So even within the second wave of aeronautics technological and market advancement, the required personal air vehicle characteristics were not able to be demonstrated, even in light of increasing need and dissatisfaction with the available transportation options.

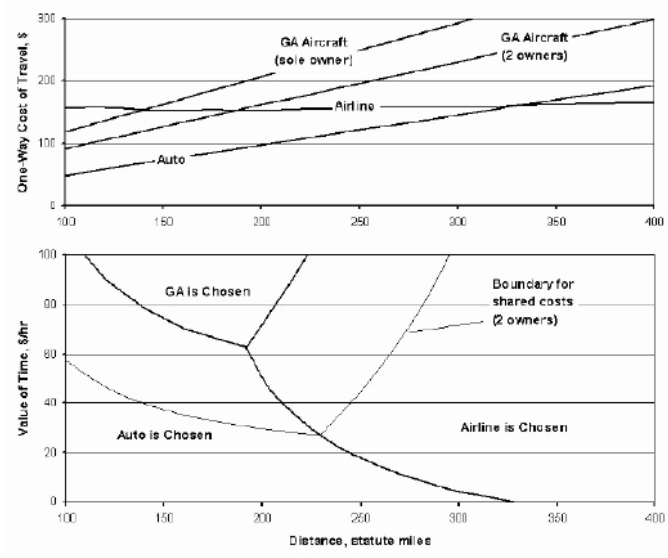

Figure 6 Mode Choice Criteria Study for the Determine of Cost to Utility Barriers to GA

THE THIRD WAVE

The third wave of aeronautics is much more than the idea of on-demand, distributed air transportation meeting mid-range travel needs. It is an airspace and vehicle technology empowerment of completely new missions and markets that could impact all stratas of society in a more daily way. These emergent markets are based on critical national needs that could be accomplished by all sorts of new vehicle types, from large numbers of small sensor aircraft to monitor the atmosphere, borders, or traffic congestion, to pseudo-satellites aircraft that provide low cost communication platforms, from faster response of EMS services that protect life in the golden hour, to regional extremely short takeoff air travel that opens up rural parts of the country directly connect to downtown metropolis locations. In an age of global competition, this 3^{rd} wave of aeronautics would become digital air superiority for the US marketplace, to provide on-demand information and accessibility for goods and services. We cannot possibly predict what new markets this capability set would produce, and that is why it's so critical that instead of predicting the future, the most robust aviation solution space is achieved so markets can expand in each of these directions without growth constraints.

The third wave is not merely an extrapolation of the existing aviation services that provide a critical role to our country, but a radical technology shift, built on fundamental aeronautics capabilities, that empowers dramatic new markets that will daily impact ever citizen of our country. The resulting integrated airspace and aircraft technologies will provide the equivalent of an internet PC ubiquity, to an air transportation system that now exists as a centralized hub and spoke mainframe.

The emergent markets of the third wave of aeronautics are based on critical national needs that can only be achieved by capitalizing on the future potential of our airspace. The most convincing evidence of this change in civil aeronautics stems from the U.S. military future net-centric battlefield, and their requirements to institute on-demand, distributed operations across foreign and domestic airspace. These operations will permit peer-to-peer query and intent that essentially permit the equivalence of free flight, the ability to fully use the airspace across drastically different platforms with high density operations, across constantly changing conditions with maximum robustness and versatility. However, it is not merely the development of a dynamic, digital airspace that empowers this third wave of aviation; it is the integration with enabling sensors, sentient and adaptive controls, powered-lift aerodynamics, low noise propulsion, lightweight and resilient structures, and many other technologies into complex, highly integrated vehicles and networks that yield critical societal capabilities. These capabilities will be accomplished through collaborative government policy, regulations, technology research, and infrastructure solutions across the FAA, the Department of Defense, academia, industry, and NASA.

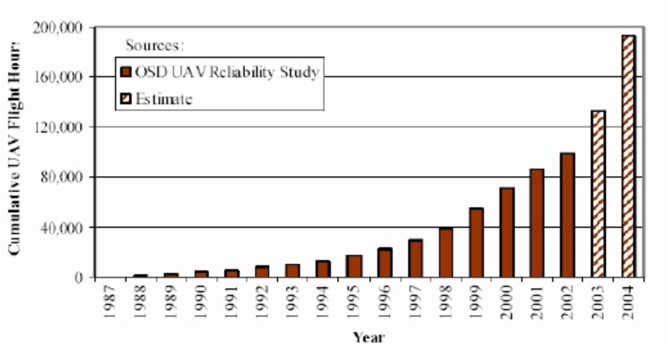

Figure 7. UAV Flight Hours.

The growing demand for societal mobility is already driving a continually increasing demand for air travel. The third wave of aviation will be enabled by a transformation in the way limited airspace resources are managed. Our National Airspace System must accommodate multiples of today's levels of flights while ensuring safety for the air traveler. Based on a 2004 FAA forecast, demand for air travel is expected to increase by 70% by 2015. Passenger and cargo fleet growth is expected to increase by 48%, with a 40% growth in air carriers and a 144% growth in regional jets. Air traffic controller workload is expected to grow by 40%. Actual future demand is likely to be dynamic and unpredictable, based on economic growth, emerging fleet usage, and unpredicted events. Unmanned Aerial Vehicles (UAVs) are currently experiencing exponential growth[10] (figure 7) in operation hours in the NAS, even with current FAA regulations requiring significant planning and approval processes. The Department of Homeland Security alone forecast that it would require a fleet of 5000 UAVs in a 20 year period to meet its surveillance needs. Studies of the emerging Very Light Jet (VLJ) and Air-Taxi markets[11] indicate that with relatively conservative estimates, approximately 4600 VLJs would be in service within 8 years, with many of those conducting Ait-Taxi operations. This is a conservative estimate because this analysis assumed a cost for service of $1.75 per passenger mile, while current breakeven Air-Taxi estimates from actual operators are below $1.50.

THIRD WAVE - NGATS

Even without new market operation growth, the current air traffic control system is already saturating frequently. This is primarily a result of bottlenecks caused by air traffic controller workload that limits the number of aircraft in a region of airspace. A recent study by the FAA indicates that in as early as 2010, even with Air-Taxi operations being conducted primarily out of small regional airports, these aircraft will "still have a major negative impact on the En-Route Air Traffic Control System in terms of increased congestion and delay for all aircraft".[12] Other factors in saturation and inefficiency are rigid strategic flow management practices that rely on unrealistically precise weather prediction, and by airlines simultaneously arriving at major airport hubs. Studies conducted by the National Research Council and the Commission on the Future of the United States Aerospace Industry have concluded that the current system cannot scale to meet future demand. As a result, the United States Congress has established a multi-agency organization known as the Joint Planning and Development Office (JPDO), which is chartered to develop a national plan to transform the National Airspace System by 2025. In Europe, similar activities are underway. Single European Sky (SESAME) is a 15 year European air transport community program that supports the European ATM 2020 Master Plan. SESAME's goals are globally harmonized air traffic management, increased traffic handling capacity, and increased safety and efficiency to support economic growth.

Figure 8. The Next Generation Air Transportation System (NGATS) JPDO partnership

The JPDO efforts are collected into the Next Generation Air Transportation System (NGATS)[13], which is a collaborative assembly of government agencies developing architecture and working groups to facilitate the 25 vision for U.S. aviation. Many of the NGATS goals align with those already discussed for the 3rd wave of aeronautics. However, there are good reasons to suspect that NGATS will be an agent of evolutionary extrapolation of the current hub and spoke system, and that longer-term, scalable strategies will not be exercised. One problem is that the JPDO is an unfunded organization, so that it can only recommend and advise the participating agencies on what work to do to enable NGATS. Another problem is that even within NASA there is still an ongoing debate of whether centralized or distributed airspace control is the future solution. Certainly both should be researched, while within NASA the centralized solutions from NASA Ames are the dominant voice compared to the distributed solutions from NASA Langley. Another problem is that NGATS is not addressing the entire aviation system, or travel experience – it is strictly defined as airport curb to airport curb. Therefore true consumer block speed is not even a consideration in its metrics. Other consumer values are also not even considered as the new optimization objective function is being established. Another problem is that the problems NGATS is facing are so significant, and the resources to fix these problems so limited, that they will have huge pressures to address near-term issues, instead of taking a step back to see the big, long-term picture. But the largest concern with NGATS is the Innovators Dilemma[14].

THE THIRD WAVE – THE INNOVATORS DILEMMA

The word innovators dilemma is taken from a popular business book by Clayton Christensen that does an excellent job of analyzing innovation in the marketplace. This review across industries shows how large companies are often pummeled by small companies as new, disruptive technologies come about. One of the key points is that the large companies are smart, powerful, and rich – so why do they lose out to the little guy in emerging markets involving disruptive technologies? For example, why didn't IBM rule the PC market, or ATT rule the wireless phone market? Christensen's answer is that large corporations are hostage to the current customers, New customers are not taken into account as much as existing customers, and the initial customers may have very different concerns that a following larger customer base.. A common theme is that companies focus on improving the performance of their product because that is what the current customer desires. Why would the current IBM customer in the 1970's want a slower computer that is much less capable than their mainframe products? This innovators dilemma addresses how current products can identify new value propositions with a broader customer base, identify the disruptive technologies that enable these new markets, and transition to these new value networks.

In aviation, and with NGATS, we are facing an innovators dilemma. The current customers to NGATS are not the average traveler. they are the airlines; the current system users that make up the vast majority of revenue passenger miles. An important realization is to whom NGATS is going to listen? The current customers are facing large financial pressures, congestion and environmental problems that require immediate near-term fixes. The future 3rd wave customers have no voice and aren't paying into the current system yet could make the aviation system much more relevant and profitable in the long-term. It seems likely that NGATS will make the same decision that IBM and ATT did, of meeting the current customer needs, while missing out on a future opportunity that would have provided substantial economic growth.

Figure 9. On-Demand Aviation Transportation Market Analogy to the Computer Industry

Figure 9 shows an analogy of the aviation innovators dilemma to the computer market timeline of the past (and future) 30 years. The commercial airlines are the equivalent of mainframe computers in the 1970's – which made up almost the entire computer market at that time. However, disruptive technologies enabled the workstation market of the 1980's, where a new value proposition was presented to consumers of lower performing products, that had other intrinsic benefits. In this analogy, the workstation market is correlated to that of the emerging Air-taxi market because system administrators, or professional pilots, are still required in this new transition, and because it is a market niche that the average public could not afford to use. The next step in the workstation market in the 1990's involved the continued development of disruptive technologies, permitting an even lower performance product that again offered a new value propositions. But this time the value was to a much larger market base. Because of the breadth of this new Personal Computer (PC) market, technology investment acceleration and production economies of scale were very high. Soon workstations offered little over a high end PC, but cost a great deal more, and the market virtually disappeared (along with companies such as Digital Equipment and Silicon Graphics). This isn't to say that the mainframe market was invalidated, because it still excelled at the services that its products were best adapted. It's interesting to note that the disruptive technology that really enabled the PC was the developed of an ease of use system, so that professional system administrators were no longer required; Windows and the Mac operating systems. This is precisely the innovation that is the prime enabler of self-operated on-demand aviation. The Air-taxi market currently appears to have very high risk associated with it for this very reason. All announced Air-taxi operations will be flown with two pilots for insurance and passenger acceptance reasons, placing an enormous burden on economics when the average load is only forecast to be 1.3 passengers. It's not only the pilots salary that impacts the economics, with essentially nearly two-thirds the average payload consumed by these system administrators. The average consumer certainly couldn't afford to operate a PC with this overhead.

THE THIRD WAVE – GOALS

If a new air transportation network were to be developed, what goals would be established for this system? It appears that it would be a quite different set of objective functions than what the airlines used to shape the 2nd wave of aeronautics. The 3rd wave goals that appear to offer the most value are the following.

- Since all scenario studies and predictions are prone to large magnitudes of error, the most critical descriptor would be adaptive, so that almost any potential future could yield a highly useful system. The transformed system should be demand adaptive: infrastructure is available when needed, but not sitting idle when and where it is not needed.

- While many system are point designed and optimized about a given assumed state, this will not be the case for an enormous system of systems such as the air transportation network. Robustness and the ability yto tolerate conditions far from nominal is essential in order to maintain service across the broadest solution space. Diverse threats and weather are currently large factors in delay that propagate from one hub across the entire system. To likewise achieve safety and security, the new system must accommodate disturbances and contain no single points of failure. Another element of safety is the distribution of assets to minimize loss from a failure. Biologic systems clearly demonstrate that nature prefers distributed systems over centralization to achieve both robustness and the ability to survive in off-nominal conditions.

- Scalability is another prime concern, permitting the transformed system to grow with demand without placing an economic burden on the nation. To accomplish this, it needs to be designed to minimize the computing, networking, communications, navigation, surveillance, and human support infrastructure that can't scale appropriately with demand. Scale free computer networks also tend to exhibit a preference for distributed systems over centralization.

- Fairness requires that the noise and emissions that are exposed to the local community are at levels proportional to the community use, or that these environmental contaminants are withheld within the airport boundaries.

- Throughput capacity is the overarching goal of the current NGATS plan, and an appropriate requirement or monitoring metric. However, difficult 'soft' metrics are as important in order to satisfy the traveling public; taking into account their affordability, value of time, comfort, flexibility, freedom, and accessibility.

- In the current information age, an important capability would be the ability to utilize all available information in each element of the system. JPDO has also identified the need for the transformed system to take advantage of network-enabled high-bandwidth information access, services such as access to airports during busy periods based on the performance capability of the aircraft, and operations based on accurate 4-dimensional aircraft trajectory predictions rather than predictions of traffic levels in a region of airspace.

Based on these characteristics it appears that adaptive, scalable, robust, high capacity, safe, environmentally compatible, and consumer-focused aircraft operations would be more aptly suited to decentralization. At a minimum it appears that the NGATS should entertain parallel research efforts in centralized and distributed architectures. Rather than expecting air traffic controllers to provide guidance to blind aircraft using ground radar, advances in technology now enable a new paradigm: the airspace service provides a limited fixed infrastructure, and airspace users equip aircraft to achieve a needed operations improvement. Each aircraft provides its own surveillance and computer-based guidance and crew decision-support capability to fly safely in the presence of other aircraft and weather, while still complying with any constraints that ensure efficient traffic flow. Aircraft with flight crews use the on-board machine intelligence to make decisions best suited to their needs, and future unpiloted aircraft will utilize the capabilities to fly autonomously. Network enabled information access allows a system that puts the decision into hands of the participant with the best information and the best capability to carry out a specific task. Flight crews have the best information about their immediate weather environment and their airborne resources, and are most capable of precise flying. Dispatchers are best suited to optimize fleet resources and balance business objectives. Decentralization retains the advantages of a human-centered air traffic control system while minimizing workload bottlenecks, simplifying complex tasks, and increasing performance for each task. Decentralized traffic management systems are extremely robust to failures because of their highly redundant and distributed capabilities. The future decentralized system would be demand-adaptive because its capabilities are airborne: increased traffic within a region brings along an increased communications and surveillance infrastructure and decision-making capability. Decentralization also enables a direct relationship between airspace user's capital and recurring investments and received benefits, thereby facilitating a system that is largely self-modernizing based on demand.

Decentralized and vehicle-centric air traffic operations have been shown in nationwide system assessments to provide the critical attributes of the transformed system. A 2004 analysis of two NASA-developed decentralized concepts estimated benefit/cost ratios ranging from 2.4 to 8.9, with payback periods of only one year. Prototypes of airborne decision support systems developed at NASA Langley have been used in large-scale simulations of several hundred aircraft to validate feasibility of autonomous airborne operations. In simulation, traffic capacities greater than twice current-day levels were easily achieved. Airborne surveillance technologies, referred to collectively as Automatic Dependent Surveillance – Broadcast (ADS-B) are available today. International working groups are defining ADS-B broadcast message standards and future flight deck avionics architectures that will support them. However, in light of all these possibilities, distributed and de-centralized architectures do not appear to be in consideration, nearly to the extent of extrapolations of the existing centralized solution.

THE THIRD WAVE – CAUSAL FORCES

There appears to be very strong causal forces that could enable this 3rd wave of aeronautics. Key among them are the DoDs investment of billions of dollars to achieve a battlefield airspace that permits high density operations of highly different aircraft types. In addition there are market pressures from manufacturers to enable remotely piloted and autonomous UAVs in the airpace. The emergent Air-taxi market, while perhaps not being successful in its initial form because of a lack of fundamental technology or cost changes, will at a minimum be a catalyst for sector airspace control change. Congestion and delay projections of not only hub airports but also the centralized ground highway system indicate that the U.S. will likely experience a mobility epiphany over the next 25 years. That is, that the transportation choices are not meeting the basic service needs that the customers insist upon receiving. It also appears inevitable that another terrorist or pandemic attack will occur which could create such a loss in airline revenues, that market forces may pressure regulatory and technological change. The past 30 years have provided some powerful technology enablers to also facilitate this 3rd wave, with dramatic advances in communications, navigation, control, network theory, computers, and other digital electronics. A number of aircraft and airspace specific technologies have also been developed by NASA and industry to enable the next wave of aviation. Programs such as the Advanced General Aviation Technologies Experiment (AGATE), the Small Aircraft Transportation System (SATS), the General Aviation Propulsion (GAP) program, High Altitude Long Endurance Remote Operated Aircraft (HALE-ROA) sector, and the Personal Air Vehicle (PAV) sector each developed technologies that specifically enable the concept of distributed vehicle-centric airspace control and operation.

CONCLUSION

A 3rd wave of aeronautics could bring about great new capabilities for society that would bring aviation into a new age of being relevant in most people's daily lives. This new age requires significant technology advancement, a new air transportation system that would probably be distributed and vehicle-centric. Inherent to both the airspace and vehicle roles in the system, there are disruptive technologies and an innovators dilemma that would be at play in this new aviation paradigm that would likely be brought about by non-aerospace companies. .There is a significant government role, both in terms of long-term, fundamental technology and regulatory development. The JPDO NGATS research effort is a critical step towards the 3rd wave, but could easily become entrenched in near-term problems and solutions of the current airline operators. It is unlikely that fundamental technology work based in discipline specific approaches would contribute significantly to this system of system vision, unless system analysis provides guidance on collaboration and synergies across the research efforts. Many technology and society enablers are present, and will continue to get stronger, to facilitate a mobility epiphany over the next 25 years.

ACKNOWLEDGMENTS

A number of associates assisted in developing the 3rd wave concept, and have accomplished significantly more than myself in terms of assisting in the progression towards this end state. I would specifically like to thank my NASA associates Bruce Holmes, Dennis Bushnell, Rich Antcliff, Andy Hahn, Ken Goodrich, and Mark Ballin for their important contributions to this paper, and the pleasure of working with them on this endeavor.

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Mark D. Moore was the Personal Air Vehicle Sector manager in the NASA Vehicle Systems Program until the the recent redirection of NASA Aeronautics into the Fundamental Aeronautics Program. Most research activities relating to both SATS and the PAV sector have been concluded and no new research into these topic areas is currently planned by NASA. After the conclusion of the final contracts next year, NASA will continue to encourage small aircraft related research through the NASA PAV Centennial Challenge yearly competitions. This research effort has in many ways mirrored the research path of other disruptive technologies as discussed in 'The Innovator's Dilemma' by Clayton Christensen and has once again shown that "disruptive projects stalled when it came to allocating scarce resources among competing product and technology development proposals". While large institutions such as IBM and Bell Labs often initiate disruptive research that has major societal impact, it appears that "firms that lead the industry in every instance of adopting disruptive technologies are entrants to the industry, not its incumbent leaders". The author remains committed to NASA's important role in disruptive technology development and continues to work on independent research in this topic area through his current PhD studies and may be contacted at mark.d.moore@nasa.gov.