

Distributed Aviation Concepts and Technologies

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ABSTRACT

Aviation has experienced one hundred years of evolution, resulting in the current air transportation system dominated by commercial airliners in a hub and spoke infrastructure. While the first fifty years involved disruptive technologies that required frequent vehicle adaptation, the second fifty years produced a stable evolutionary optimization of decreasing costs with increasing safety. This optimization has resulted in traits favoring a centralized service model with high vehicle productivity and cost efficiency. However, it may also have resulted in a system that is not sufficiently robust to withstand significant system disturbances. Aviation is currently facing rapid change from issues such as environmental damage, terrorism threat, congestion and capacity limitations, and cost of energy. Currently, these issues are leading to a loss of service for the weaker spoke markets. These catalysts and the lack of robustness could result in a loss of service for much larger portions of the aviation market. The impact of other competing transportation services may be equally important as casual factors of change. Highway system forecasts indicate a dramatic slow down as congestion reaches a point of non-linearly increasing delay. In the next twenty-five years, there is the potential for aviation to transform itself into a more robust, scalable, adaptive, secure, safe, affordable, convenient, efficient and environmentally friendly system. In order to achieve these new characteristics, the new system will likely be based on a distributed model that enables on-demand services. Short range travel is already demonstrating itself to be inefficient with a centralized model, providing opportunities for the first wave of emergent distributed services through air-taxi models. Technologies from the on-demand revolution in computers and communications are now available as major drivers for the aviation on-demand adaptation. Other technologies such as electric propulsion are currently transforming the automobile industry, and will also significantly alter the functionality of future distributed aviation concepts. Many hurdles exist, including technology, regulation, and perception. There is an inherent governmental role in aviation that was not present in other recent on-demand

transformations, which may pose the greatest risk of curtailing this 'democratization' of aviation.

INTRODUCTION

Distributed Aviation Concepts and Technologies explores the long-term potential of achieving a new distributed aviation system to transcend the current centralized model. The current system is dominated by vehicles and technologies designed for hub and spoke operations. A distributed vision for the future would redefine both the system and the vehicles. System benefits would consist of improved robustness, capacity, security, affordability, and mobility freedom. Vehicle benefits would include improved safety, emissions, noise, performance, and efficiency. Instead of treating aviation as an isolated transportation system, or vehicles as isolated component disciplines, tight synergistic coupling is explored at both the system and vehicle level. Scale is a guiding principle for this topic area, with scale-free networks and technologies being applied to achieve newfound economies of scale. Airspace issues will not be directly addressed in this paper, since this relates to another topic area, however will be mentioned since it is a primary enabler of distributed vehicle systems. Future successful markets depend upon technology enablers in both these key research areas, involving both the vehicle and the airspace.

This paper considers the challenges that exist for the current aviation system in terms of robustness. It also postulates that aviation may be primed for a disruptive innovation cycle based upon the principles of *The Innovators Dilemma: When New Technologies Cause Great Firms to Fail*[®]. An analogy is made between aviation's product cycle and natural selection/evolution, with comparisons to other on-demand revolutions that have recently taken place. The robustness and survivability of the current aviation innovation cycle is questioned, in light of system disturbances that are likely to occur. An alternative aviation system based upon distribution of service is considered, which would utilize peer-to-peer (aircraft to aircraft) information sharing (instead of aircraft to tower). The hurdles and technology enablers of this distributed vision are

discussed, along with concepts of operation that could lead to new desirable societal capabilities. The role of government in this product cycle evolution is also discussed.

MAIN SECTION

SURVIVAL OF THE FITTEST

"A key factor in the equation is our definition of the 'fittest' who are being naturally selected. Ever since the debate began, there has been a bias among both supporters and critics to interpret fittest as strongest, smartest, cleverest, and most aggressive. But if we consider fittest to be the most suited to survival and expansion of the species, then there is no necessity a priori that the required qualities be defined as strongest, smartest, and so on. It could be the reverse, depending on the conditions present".³

The first 50 years of aeronautics was composed of rapid and chaotic technology innovation, with hobbyists and small companies providing dramatic 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 were constantly disrupting and pushing aside the existing technology and market solutions. As with biologic systems that exhibit 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 relates to this analogy is the seaplane, which initially experienced rapid growth and tremendous research funding (for instance through the Schneider prizes), but ultimately led to market irrelevance. 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 made the vehicles less able to compete. While disruptive technology periods are chaotic, with a tendency for duplicated effort and product failures, the genetic material of value still manages to survive, just as the Supermarine seaplane later led to the highly successful Spitfire.

Throughout this period from approximately 1900 to 1950, aviation markets constantly re-invented themselves to provide new services as technologies, regulations, and the 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 early-adopters. Without legacy regulations or strong corporations exerting influence on the market, a free

forming evolution occurred that enabled the genetic (or capitalistic) survival of the fittest.

The next 50 years of aeronautics belonged to a very different era of commercialization, with consistent evolutionary technology advancement primarily from large (strong) 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 the cost 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, (even above other passenger value propositions).

Deregulation of the airline industry in 1978 further encouraged airlines to apply additional pressure towards this cost optimization, at the expense of many other passenger concerns. Deregulation was also a pivotal point for the hub and spoke system model. Originally Delta Airlines pioneered hub and spoke operations out of Atlanta, with other airliners operating with point to point models. FedEx was next to implement hub and spoke out of Memphis in 1973, with incorporation of the 'SuperHub' concept in 1981. Most other airlines followed to hub and spoke operations after deregulation. Currently the airline closest to using a point to point model is Southwest, which uses a hybrid system of smaller hubs with a higher fraction of direct flight city pairs. The main benefit of the hub and spoke model which caused its widespread use is that the route complexity is of the order of the number of hubs, with only one connection required to connect all nodes. A point to point model has a route complexity of the order nodes squared in order to connect every node, but with no connections required. The hub and spoke routing permits feeder spokes to supply hubs with passengers for high density routing, resulting in high load factors. These high load factors are the critical element to the success of hub and spoke, leading to higher productivity of very expensive aircraft, and centralization of complex operations such as aircraft maintenance, and passenger, baggage, and package routing. One drawback to the hub and spoke model is that direct trips are unlikely (except on major routes), which causes increased travel time and burdening of the passenger with additional centralized time penalties. Centralization by its very nature creates additional travel miles and network bottlenecks, with

disturbances at any hub propagating across the entire system. An additional concern is the 'fortressing' of major airports to discourage competition that is a natural result of centralization. Fortress airline hubs are those with control of more than the monopoly limit of 70% of flights in and out of the hub. "There has been rising concern among some of the smaller airlines that the seven largest passenger carriers in the U.S. are no longer competing against each other. Essentially, the argument goes, the 'Big Seven' have carved up the U.S. aviation market and will not tolerate any competition from small start-ups. Whenever a new airline announces a new service, particularly into a so-called fortress hub, it faces stiff price competition, bracketing of its schedule, and new added service from the dominant carrier."⁴ Fortress hubs currently include Charlotte, Washington Dulles, Dallas-Ft Worth, Detroit Metro, Atlanta, Salt Lake City, Minneapolis-Saint Paul, Newark, and Houston.

Southwest has shown the profitability of utilizing a more distributed model (currently demonstrating itself as the most profitable airline). Boeing also appears to be positioning its products to better support hybrid models, instead of greater hub concentration through even larger aircraft. So it is likely that the near-term future will see additional carriers utilize hybrid models, yet maintain fortress positions in key markets. The hub and spoke model was a natural, important step in the progression to establish initial aviation traffic densities. However, the natural progression from this point is toward greater distribution to better meet traveler needs. The question is not whether greater distribution will occur, but how far vehicle and airspace technologies can push aviation distribution toward the ideal of on-demand, point to point travel. Nature is often a useful indicator in long-term optimization, with an overwhelming selection towards functional and population distribution in order to achieve the maximum capacity and survivability (i.e. robustness).

In the near-term, evolutionary technologies will continue to improve the component, vehicle, and system level characteristics. Certain research 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). These areas include noise, emissions, and efficiency technologies. Acoustic specific technologies 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 offers improvements in efficiency for higher passenger vehicles, while 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. System operational and scheduling optimization continues to be deployed. However, all these efforts are evolutionary increments along the same centralized service path of the past 50 years. As the expense of achieving ever diminishing improvements becomes larger, the current system will become more and more stagnant of technology innovation, until a significant system change occurs that permits new optimization boundaries.

The hub and spoke system is reaching a point of diminishing returns, at least for the current cost sub-optimization. The term sub-optimization is used because the objective function that airlines work towards doesn't include the door-to-door transportation experience, or factors of high value to the consumer. When an industry reaches a point of diminishing returns of their ability to improve service, it is only natural that competition becomes quite severe with industry consolidation and bankruptcies of the weaker participants. This isn't to say that evolutionary improvements won't continue, just that now these cost and performance improvements are more difficult to achieve. 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 difficult realization by discipline specific technologists that the optimal aircraft system doesn't contain any optimal components. Each discipline area typically compromises another sub-system so that none are optimal within their own domain. So, as we reach this point of diminishing returns in our current aviation system in terms of many important metrics, the natural (selection) question becomes, what's next, and who are the fittest to populate the future environment of aviation? Inevitably the 'fittest' in times of feast and famine, or during times of change, are different species. Without robust characteristics to permit a species to adapt in a changing environment, the probability of disruptive change is increased, providing opportunities to other species that; 1) Value robustness, 2) Have continuing, favorable associations with the changing environment that 'feeds' them, and 3) Follow an evolutionary trend of adaption to smaller sizes during times of stress, and larger sizes during plentiful times (i.e. A380's and Sport Utility Vehicles)..

However, the current dominant solution does not value robustness, and have an association with their environment that is continually degrading (i.e. customers are increasingly dissatisfied and looking for

alternative solutions). In a recent University of Michigan American Satisfaction Index⁵, airlines scored near their historical lows with a ranking of 63 out of a 100 point scale (2 points below the satisfaction with the Internal Revenue Service). It's also interesting to note that an alternative transportation solution, automobiles, scored at 82, near their historical highs. These factors suggest that a new market could develop if a feasible alternative is offered for selection, especially in the presence of concurrent environmental disturbances and technology disruption.

CAUSAL FORCES OF DISTURBANCE

"It will be difficult for the air transportation system to change rapidly enough to meet changing requirements related to capacity, environmental effects, consumer satisfaction, safety, and security, while meeting ongoing requirements for the economic viability of service providers." - NRC⁶

The current aviation environment has recently introduced causal factors that create the possibility for various degrees of system disruption. Several key factors include terrorism threat, environmental concerns, pandemic contagion dispersion, congestion and capacity limitations, dwindling rural community accessibility incentives, the emergent UAV market, and cost of energy. While many in-depth research papers are available on these topics, a summary of impacting issues is presented below. These system disturbances have already caused the weaker spokes of the aviation network to suffer loss in service. However, there is the potential for significantly greater service disruptions in the future due to the highly centralized nature of the current aviation system. While these factors will affect any air transportation system, the degree which they effect a centralized system is pronounced enough to create risk of disruption for the entire system, instead of merely localized disruptions.

Terrorism

One of the largest disruption threats for the centralized aviation system is terrorism. Currently the government has primarily taken reactive measures that deal with previously demonstrated vulnerabilities in aviation. This reactive approach is due to the expense associated with system changes. While many potential areas of attack exist, such as through cargo explosives which currently receive very little screening, these concerns can be addressed through new government security programs. However, one of the most significant threats simply doesn't have a solution due to centralized vulnerability. This threat relates to shooting down airliners from ground (i.e. Figure 1).

"The potential payoff of such an attack is incredible, with returns greatly exceeding 1,000 to 1. For example,

the downing of a single passenger aircraft carrying approximately 300 passengers approaches \$1 billion in expenses after hull loss and insurance claims are assessed, not to mention the tremendous emotional loss of life. Contrast this with the cost of an infrared guided MANPADS (Man-Portable Air-Defense Systems) available on the black market for \$5,000 to \$250,000. Clearly in light of the aftermath of 9/11 in which the stock market declined \$1.7 trillion in value within one week, the immeasurable carnage, economic impact, and psycho-social repercussions that would follow a simultaneous MANPADS attack is motivation for Al Qaeda to attempt a strike and for the United States to aggressively seek solutions."⁷

"Worldwide, there have already been over twenty successful missile attacks on a variety of commercial airlines resulting in over 500 deaths over the past 30 years, but none have been against a U.S. commercial passenger airliner. At a recent briefing of the Israeli Parliament's Security and Foreign Affairs Committee, the head of the Israeli Security Agency labeled shoulder launched missile attacks against civilian aircraft as the top security risk today. With an estimated 500,000 operable MANPAD units in the world, simplicity of use and a reported price tag of as little as \$1000 on the international arms black market, it is clear to see why this particular threat to aviation is imminent."⁸



Figure 1. DHL cargo aircraft in Iraq after impact from a single missile.

Equipping all 7000 U.S. airliners with a single laser system countermeasure would cost approximately \$11 billion⁷, and has been discussed by government regulators. However, this program would probably only be initiated after a successful missile attack to re-instill confidence in the aviation system, because these devices would not solve the problem of shoot-down risk. Single laser systems would be unable to handle several incoming missiles or direct targeting weapons. For this reason, the current government action is to conduct research on more effective protection systems, and repurchase as many MANPADS on the open market as possible. If single laser counter-measure systems were installed in the U.S. fleet, it would also

add significant operating costs. "Annual operating costs would represent nearly 50 percent of what the federal government currently spends for all transportation security in the United States. Well-financed terrorists will likely always be able to devise a MANPADS attack scenario that will defeat whatever countermeasures have been installed, although countermeasures can make such attacks considerably more difficult and less frequent. Installing countermeasures to MANPADS attacks may simply divert terrorist efforts to less protected opportunities for attack. To put it another way, how many avenues for terrorist attack are there, and can the United States afford to block them all?"⁹



Figure 2. GA aircraft after deliberately hitting building in Florida.

While MANPADS risk can be reduced, there is no effective solution to protecting large airliners that have exposure to vast areas surrounding airports. These aircraft fly at low glide slopes on prescribed approach paths, with little impact damage tolerance. Even if protection is developed for active missile systems, direct projectile weapons can perform equivalent damage with effective ranges of one mile from highly portable 50 caliber rifles, automatic weapons, or RPGs (one reason why any reported laser sighting on airliners is aggressively investigated). These direct projectile weapons could be used effectively within a 5 km area surrounding airports, permitting an open rooftop truck or warehouse roof location with several people to have easy accessibility to areas that could not possibly be protected. Therefore, large transports provide a highly vulnerable target that can result in large damage. While this risk will always be present for long distance aircraft, development of the air transportation system with a more highly distributed model would permit less impact from such an attack. Smaller vehicles simply don't offer the same target appeal in terms of risk to reward. So the question becomes whether almost all passenger travel should continue to have this risk exposure, or should the air transportation system adapt to a state of greater robustness, where alternate

choices of air travel would still be available given such an attack.

Arguments could be raised against a distributed system in terms of increased accessibility for use of aircraft as weapons. However, the effective damage energy of small General Aviation aircraft is a very small fraction of that for large transports. "The World Trade Center towers and the Pentagon were large, conspicuous landmarks and, as such, were more easily targeted in an aerial attack than would be a nuclear power plant. The success of these attacks was predicated on the use of large, turbine-powered commercial aircraft with immense fuel carrying capacity. A general aviation aircraft, at only a fraction of the weight, speed and fuel load, would be unable to inflict damage on the scale witnessed on that tragic day."¹⁰ An attempt was made to use such a small aircraft as a weapon against a skyscraper in Florida (Figure 2); however, the resulting damage was inconsequential to the building with the only fatality being the pilot.

Environmental Concerns

Fundamental differences exist between the proportioning of environmental damage for centralized and distributed aviation services. The three most important areas of concern include aviation impact on climate change, local air quality, and community noise. An additional environmental factor relates to weather disruptions, and the potential for increasingly extreme weather as climate changes occur. Centralized models are susceptible to weather delays in one hub propagating to delays across the entire system. "According to some studies, 40–65 percent of delays that U.S. domestic airlines experience are attributable to adverse weather, at annual costs estimated to range from \$4–5B per year."¹¹ Since a distributed network does not rely on a hub feeding system, weather delays result in only localized effects.

Communities surrounding centralized hub airports experience a concentrated environmental burden, that is, more noise and emissions are applied to the surrounding community than the amount relating to their specific mobility needs. This disproportionate allocation of environmental penalties fosters a NIMBY (Not In My Back Yard) perspective as a typical community response to airports, even though they provide significant economic benefits. As an example, if a person lives in Chicago, why should he pay (through noise and emission exposure) 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 traveler, in order to increase the efficiency of the airline (burden the individual for the benefit of the whole). 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. A distributed aviation system applies these locality-based environmental issues more proportionally. While it can be argued that a distributed system will increase aircraft operations to closer proximities for communities, the operations are of a very different type. Distributed operations only make sense with smaller vehicles that can maintain high load factors, at lower passenger travel densities. However, noise is primarily a function of the vehicle size, along with the jet velocity and type of the propulsion system. With small vehicles that operate at lower speeds, there is the opportunity to be significantly quieter than large vehicles. Currently the GA fleet has an average age of over 30 years, with those products not designed for low noise. However, as will be discussed in the Disruptive Technologies section of this paper, there is the potential to drastically reduce small aircraft noise and emissions. These technologies do not translate to higher performance large aircraft, providing an opportunity for distributed operations to excel in these locality-based environmental issues.

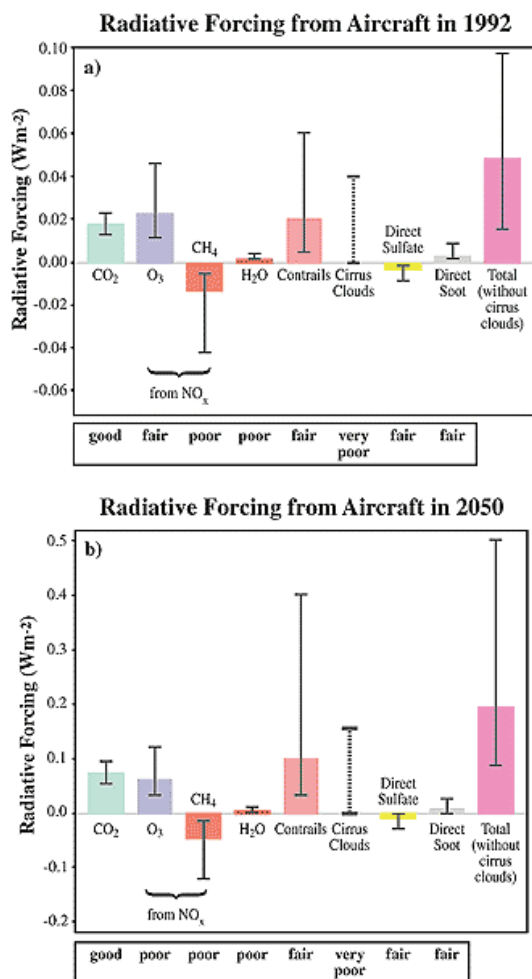


Figure 3. Radiative Forcing from Aircraft in 1992 and projection for 2050.¹²

While aviation only accounts for 2% of the total CO₂ emissions relating to climate change, it accounts for 13% from all transportation sources.¹² Airlines accounted for approximately 860.6 billion available passenger seat miles¹³, compared with automobiles 10,860 billion¹⁴. Therefore aviation provided 7.3% of the travel capacity, while accounting for 13% of the CO₂ emissions. But commercial aviation achieves a much higher passenger load factor than automobiles (70% average compared to automobiles 34%). So from an actual passenger mile traveled basis, the CO₂ emissions are in line when comparing the vehicle type and miles traveled. However, climate change is also impacted by other factors where commercial aviation doesn't compare as well. Figure 3 shows the IPCC estimates of aviations impact on radiative forcing (global warming) for 1992 and 2050. Not only is a five times increase predicted over this time period, but also it can be seen that this impact is primarily a function of contrails and cirrus cloud formation, which are a direct result of commercial aircraft flying at high altitudes (in order to decrease drag and fly above weather concerns). Flying at lower altitudes will adversely impact commercial aviation performance and efficiency, but may be required in the future as aviation environmental regulation increases. A distributed system off-loads shorter trips to vehicles that fly at lower altitudes, with these vehicles completely avoiding the primary usual effects of aviations contribution to global warming. Distribution also decreases the total number of trip miles through direct routing, and elimination of unnecessary miles travelled to hubs. It would also be important for distributed vehicles to achieve high load factors, and implement CO₂ friendly propulsion technologies (again that are unavailable to large transports), in order for aviation to have the least possible contribution to global warming.

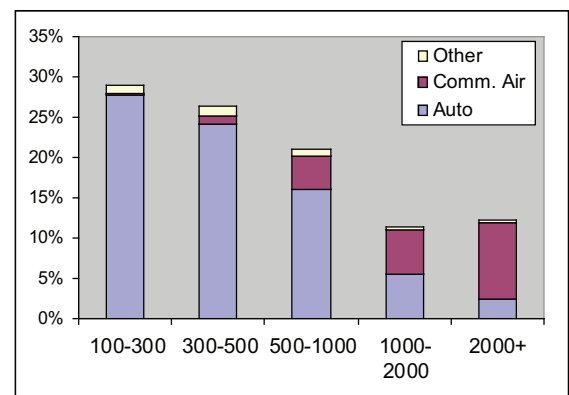


Figure 4 U.S. Travel Trip Distributions by Range¹⁶

Pandemic

Aviation has not yet been required to deal with major contagion issues relating to pandemic outbreaks of disease. However, a centralized system derives its