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A Benefit Analysis of Infusing Wireless into Aircraft and Fleet Operations

Report to Seedling Project Efficient Reconfigurable Cockpit Design and Fleet Operations Using Software Intensive, Network Enabled, Wireless Architecture (ECON)

*Natalia Alexandrov
Langley Research Center, Hampton, Virginia*

*Bruce J. Holmes
NextGen Apps Company, Williamsburg, Virginia*

*Andrew S. Hahn
Langley Research Center, Hampton, Virginia*

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Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Hampton, VA 23681-2199
Fax: 757-864-6500

A Benefit Analysis of Infusing Wireless into Aircraft and Fleet Operations

Report to Seedling Project *Efficient Reconfigurable Cockpit Design and Fleet Operations Using Software Intensive, Network Enabled, Wireless Architecture (ECON)*

Natalia Alexandrov¹, Bruce J. Holmes² and Andrew Hahn¹

We report on an examination of potential benefits of infusing wireless technologies into various areas of aircraft and airspace operations. The analysis is done in support of a NASA seedling project *Efficient Reconfigurable Cockpit Design and Fleet Operations Using Software Intensive, Network Enabled Wireless Architecture (ECON)*. The study has two objectives. First, we investigate one of the main benefit hypotheses of the ECON proposal: that the replacement of wired technologies with wireless would lead to significant weight reductions on an aircraft, among other benefits. Second, we advance a list of wireless technology applications and discuss their system benefits. With regard to the primary hypothesis, we conclude that the promise of weight reduction is premature. Specificity of the system domain and aircraft, criticality of components, reliability of wireless technologies, the weight of replacement or augmentation equipment, and the cost of infusion must all be taken into account among other considerations, to produce a reliable estimate of weight savings or increase. However, we also claim that wireless augmentation may be beneficial even in the face of weight increase, when other system objectives are taken into account. Finally, we recommend areas of applications and technology development and exploration in wireless for aviation connectivity.

I. Introduction

We report on a study of the potential of infusing wireless technologies into various areas of aircraft and airspace systems and operations. This analysis is done in support of a NASA seedling project titled *Efficient Reconfigurable Cockpit Design and Fleet Operations using Software Intensive, Network Enabled, Wireless Architecture (ECON)* [1]. As to broader relevance, this research supports the following three of the six NASA Aeronautics Research Mission Directorate (ARMD) strategic thrusts³:

1. Safe and Efficient Growth in Global Operations. Affordability and increased safety of air travel, supported by wireless technologies, facilitate growth.

¹ NASA Langley Research Center, Mail Stop 442, Hampton VA 23681-2199

² NextGen Apps Co., 205 Skimino Landing Drive, Williamsburg VA 23188-2251

³ <http://www.aeronautics.nasa.gov/programs.htm>

2. Assured Autonomy for Aviation Transformation. By expanding situational awareness of both the operational environment and the physical status of the aircraft, wireless in the cockpit and cloud-based systems contribute to safe (assured) autonomy.
3. Ultra-efficient Commercial Vehicles. Cloud-based services may reduce the total cost of operations of each flight.

We outline considerations within which the benefits of emerging wireless technologies could create new value for aircraft producers and users, as well as airspace managers. While the original ECON project proposal focused on aircraft weight savings, we suggest a broader perspective on benefits, to include facilitation of new operating capabilities, ones not previously feasible in the absence of wireless-enabled bandwidth. We see the benefits from wireless, both on-board and in information transfer to and from the aircraft, as potentially transformative in aviation systems and operations. However, the potential for transformation has to be viewed in the context of infusion cost, capability, security, and reliability of wireless technologies, and system/subsystem criticality. Such detailed analytical effort is beyond the scope of this report.

The original NASA ECON Seedling project proposal stated several goals and conjectured a number of benefit mechanisms:

The overall goal of this research is to reduce the cost of cockpit/vehicle design, manufacture, and operations by increasing software- and network-enabled cockpit system applications management. These improvements will reduce the weight and maintenance costs of mechanical interface devices as well as transition many functionalities (e.g., flight management systems machine-to-machine communications) to cloud/network thus reducing costs per cockpit in hardware and software. The objectives of this research are twofold:

1. *Extend the “glass cockpit” further with as many software-enabled controls, interactions, and cockpit devices as possible to be software controlled, and by transitioning to a cloud-controlled digital cockpit, particularly in the context of hybrid or all-electric energy systems.*
2. *Identify those software functions, e.g., flight trajectory optimization/management, to be moved to cloud/networked architecture thereby reducing duplication, enabling faster upgrades, and serving multiple vehicles through the cloud, which provides benefits by increasing efficiency and reducing per vehicle and per fleet costs.*

In this report, we consider these and other benefits, as well as existing technology gaps that can be addressed through wireless-based information and control systems.

The deployment of wireless connectivity for aircraft is forecast to experience more than a 15% cumulative annual growth rate from 2015, reaching a market value approaching ten billion dollars by 2024⁴. While that growth is forecast for inflight entertainment (IFE) products and services, the bandwidth enabled benefits for inflight connectivity (IFC) in the front (cockpit) of the aircraft has even greater economic potential. One of the prospects we highlight here is the evolution of the “Internet of Things – That Fly” and the benefits made possible, beyond weight savings, through new functionalities, leading to improvements in safety, cost, performance, efficiency, and environmental considerations. The drivers for IFC capabilities include advancing antennae technologies, innovations in connected aircraft network and spectrum management systems, and applications of U.S. NextGen⁵ and EU SESAR⁶ operating airspace management operating concepts, through increasing bandwidth to and from aircraft.

In section II, we consider one of the major benefits of wireless – weight reduction – conjectured in the seedling proposal. In Section III, we advance a list of applications of wireless technologies, partitioned by benefit types and our sense of priorities for infusion. Section IV concludes with technology gaps and a suggested order of priorities in addressing the gaps and infusing technologies.

⁴ Grand View Research, 2016 #544

⁵ Next Generation Air Transportation System (NextGen)

⁶ Single European Sky Air Traffic Management Research (SESAR)

Finally we note that, although this report targets near-future systems, with a human pilot in command, technologies described here are also relevant to completely autonomous (self-governing automated) systems.

II. Wireless: The Weight Reduction Hypothesis

Because significant aircraft weight reduction was one of the main conjectured benefits in the original proposal, we start by examining this hypothesis.

The following benefit mechanisms were posed:

- Remove wires; therefore, reduce weight;
- Reduce electrical power required for wired systems, therefore reduce power generation weight;
- Wireless allows us to have more sensor information about the components; therefore, better diagnostics; therefore, better maintenance; therefore, reduced component redundancy.

Replacement of Wires with Wireless

Calculating the effect of replacing wired mechanisms and their wires with wireless and the attendant devices would require assumptions about both the prospective wireless technologies and detailed weight and design information about specific aircraft. Neither was available to the team. However, a rough idea of weight savings from replacing wires with wireless can be estimated. To get such an estimate, we considered a database of weights for a large representative military aircraft and a representative civilian aircraft. The raw weight data are proprietary and are not quoted here. A “back-of-an-envelope” calculation of a wireless system design change is still instructive.

The available data and related subject aircraft analyses came with limitations. First, although the weight data were detailed, they did not call out wire explicitly by function. We made an assumption that wireless would be designed for use for information (signals) only, not for power. This wireless system design definition resulted in removal of “Electrical” weight. Then we considered the Avionics system design, which consumes power and transfers information. This wireless system design definition left in place a number of relevant items that included general instruments, flight instruments, automatic flight control instruments, engine instruments, avionics installation, communication equipment, flight and navigation equipment, and other avionics and systems management controls. In a more detailed future analysis, the definition of a wirelessly connected avionics system should be developed in the requirements, because some of these instruments might change, resulting in reductions in weight (for example, in a more autonomous aircraft with reduced crew requirements).

Unfortunately, there was no indication in the database as to what was an individual item, what was a subtotal, or might have been double-book kept. We have broken the data into straightforward Instruments and Other. The latter contain duplicate information.

Fortunately, the Cost Estimating Relations (CERs)⁷ are sensitive to the amount of weight that is electronics (high \$/lb.) and the installation (low \$/lb.), and this amount is explicitly broken out in our data source. Installation includes racks, bolts, all wires (power and information), and connecting plugs. Examination of the data yields approximately the standard 30% installation penalty, often used in conceptual design estimation. Assuming that signal wiring plus connectors is only, say, 33% of that penalty, then signal wiring accounts for approximately 10% of all of the electronics weight, which in the case of the military aircraft examined in the subject analysis is approximately 480 lb.

The weight is roughly equivalent to that of two people. Given that this is a very large aircraft, two people account for less than 1% of its payload. Also, in this case, the wires represent only approximately 0.0007 of the aircraft’s gross weight.

In the case of a representative civilian aircraft examined in the subject analysis, the signal wires plus connector weight was approximately 390 lb., which is once again approximately the weight of two persons,

⁷ NASA Cost Estimating Handbook, Version 4.0

out of a total passenger capacity of 480 in one class or 412 in two-class seating; or 266 in three-class seating. It is also only about 0.00048 of the gross weight. Assuming that the wireless technology weighs nothing, this is maximum savings. For comparison, this number is on the order of the weight of the magazines on a commercial flight.

There have been instructive historical efforts in reducing the weight of wires. For instance, the Lockheed L1011 replaced copper power cables with aluminum. This substitution turned out to be problematic due to the tendency of the terminals to oxidize. There has been significant effort in putting copper terminals on the aluminum wire, so this solution may return. While this approach is currently used for power wire, if it is reliable, then it could be applied to signal wire as well. The weight penalty would be cut down by 40%. This substitution would be a cheaper, more reliable way to lower the weight, and it could be applied to power cables as well, thereby being even more effective at saving weight. If technology moves away from centralized hydraulics to electro-hydraulic actuators, aluminum wire would be very beneficial to carry the power. The signal would still be on copper, but would not have to be. Research into the costs and benefits of wireless for primary flight controls would be required to achieve the requisite levels of trust, reliability, and assurance of security before applications could be pursued.

In an interesting example from another domain, China is using enterprise 4G cellular for locomotive control synchronization on trains. This wireless system replaces the wired system that previously had connectors and flexible cables between each car. The wireless system works over train lengths of up to 1.5 miles and is for safety critical primary control.

In another example, the first step that the airframe companies took in the subject analysis when attempting to reduce the wire in the aircraft was to multiplex the passenger switches. This switching system explains a delay a passenger experiences in turning on the reading lamp. These multiplexed wires are long runs, and there are many seats, leading to a large payoff for a wireless substitution. Thus wireless could be of benefit for the entertainment systems. Unfortunately, these wires are buried in the furnishings weight, and it is difficult to estimate how much weight can be saved.

Another consideration is that if the airlines had WiFi and USB power at each seat, they could remove the magazines and in-seat monitors and allow the passengers to use the devices they already have to access their content. Arguably, this removal would be the biggest weight saver. Also, only having to connect USB to each seat row would greatly simplify the labor for setting up the cabin.

In summary, a rough analysis indicates that removing the wires in the cockpit may not yield significant weight savings, even assuming zero weight for wireless equipment. However, other, simpler alternatives in the aircraft cabin may be fruitful.

Redundancy Reduction

Current efforts to explore the potential for wireless systems to achieve weight reduction objectives include developing an industry standard. The RTCA recently announced the establishment of a new committee at the request of the FAA, for this purpose. The committee is SC-236, Standards for Wireless Avionics Intra-Communications System (WAIC). According to the RTCA website announcement⁸:

“The use of wireless links for communication services provides new opportunities for the development of functions which are currently not possible using wired communications. It has the potential to enable improvements in safety and a reduction in weight, thereby enhancing efficiency.”

In a related recent media article⁹, an industry analysis mentions only 229 lb. weight savings – a tiny portion of the aircraft gross weight. While the background behind this figure is not available, we surmise that the full weight reduction benefits from wireless adoption are perhaps being offset by complementing airborne systems with wireless, rather than substitution.

⁸http://www.rtca.org/article_content.asp?adminkey=9286ee151d581ab3b042cd3e2c292283&article=231
(Accessed on July 23, 2016)

⁹ FAA Joins Push to Use Wireless Signals for Aircraft-Safety Systems, <http://www.wsj.com/articles/faa-joins-push-to-use-wireless-signals-for-aircraft-safety-systems-1466591478#livefyre-comment>

Triple-redundant systems include actuators on control surfaces, some of the wires for which might be candidates for elimination, producing weight reduction. The challenge, of course, will lie in completing failure modes and effects analyses (FMEAs), comparing wired to wireless system reliability. Certification authorities will have to ensure that no loss in system reliability accompanies the substitution of wireless for wired systems.

Other Mechanisms for Weight Reduction

Other mechanisms for reducing weight through wireless systems may include the following:

- Reduction of crew from two to one and the subsequent savings directly and indirectly, through providing co-crew operations through air-to-ground, orbit-to-air, and air-to-air wireless. However, the savings cannot be estimated without assessing the new equipment that would ensure a single pilot's safety in off-nominal conditions.
- Substitution of lighter-weight electrical components for heavier weight hydraulic, electro-hydraulic, mechanical, and electro-mechanical components.
- Secondary and tertiary effects, such as structural and fuel system weight reductions derived from the primary effects of electrical system component weight savings.

Studies on “More Electric Aircraft” have explored these kinds of weight savings opportunities and methods for quantifying the effects during aircraft design, for example, in Chakraborty et al. [2].

Summary

Current predictions of weight reduction due to wireless infusion are necessarily of low fidelity. To improve the fidelity of predictions, a critical component analysis is necessary to understand what wires are eligible for replacement, in principle, and which systems can only be augmented. What redundancy in other components can be eliminated or reduced? The analysis must be performed, subject to limitations in wireless reliability, currently and, in principle, given the state of technology in the future.

In addition, while a portion of wires is removed, the weight of new, wireless equipment must be taken into consideration. To achieve a reasonable degree of accuracy in predictions, re-design must be considered in the context of specific aircraft.

Similar considerations apply to a broader range of wireless technologies, such as connectivity through optical communications and the effects of 5G – 5th generation mobile networks or 5th generation wireless systems¹⁰, beginning deployment in about 2020, according to industry reporting. Either 5G or optical communications promise significant performance and cost advancements over current wireless technologies.

In summary, while straightforward replacement of wires with various wireless technologies appears to be a promising area of investigation, specificity of the system domain and aircraft, criticality of components, reliability and security of wireless technologies, the weight of replacement or augmentation equipment, and the cost of infusion must all be taken into account, among other considerations, to produce a reliable estimate of weight savings or increases vs. other system objectives. It is conceivable that even an increase in weight due to wireless augmentation may still be beneficial when other system design objectives are taken into account.

III. Potential Applications of Wireless Technologies

In this section, we discuss potential uses and benefits of wireless technologies from the system perspective. To that end, it is useful to consider that the overarching use of wireless technologies is to transmit information. The question then becomes: What are the benefits of adding information or using a different form of information delivery, i.e., via wireless?

¹⁰ https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

A. Fact Finding and the Benefit Categories

To get an idea of the benefit pool, we started the analysis from conversations with a number of stakeholders in aircraft operations, including pilots and a technology development lead of a major passenger airline. The following comments summarize benefit priorities for these representative stakeholders:

- ***Passenger airlines.*** Customer/passenger loyalty is the main driver in airline operations. Passengers assume that commercial aircraft are equipped with state-of-the-art technologies for flying the aircraft safely. Thus the factors that determine passenger loyalty are usually related to service and only implicitly related to, say, cockpit technology. For instance, the size and quality of the video screen available at a seat on an airplane, as well as the airline's ability to recover delayed luggage, and schedule reliability play large roles in passenger loyalty. A better cockpit design does not. Therefore, airlines tend to have relatively smaller budgets for funding new cockpit technologies; therefore, it is important to show how a prospective technology will impact passenger loyalty. Airlines do care about cost; and reducing weight and thereby fuel expenditure is also viewed as an important benefit. These opinions were shared with us prior to the emergence of IFC aircraft connectivity that offers new paths to flight efficiencies and cost savings in the future.
- ***Pilots.*** Reliability and safety are the main drivers affecting airline technology investment decisions for pilots. Because pilots are trained in existing systems, pilots are comfortable during nominal operations. Moreover, the contemporary multifunctional displays can be customized to the preferences and convenience of a specific pilot. When asked what a pilot would want in a perfect cockpit, a respondent replied that, given current training, *during normal operations*, the cockpit was already well designed. However, pilots can use a great deal of help – unavailable previously – for off-nominal conditions, especially in safety-critical emergencies. Such off-nominal conditions include icing, loss of control due to disorientation, weather, and deteriorating aircraft, among others. Thus, sensors combined with wireless data communications can be of great benefits to pilots.

Based on these discussions, we will consider the benefits of a potential technology application to fall into three interrelated benefit categories:

- Flying the aircraft, i.e., maintaining lift, thrust, and control;
- Economics;
- Public good, such as the environment, safety, accessibility of transportation.

The use of these categories reminds us that the value proposition from employing wireless technology may actually increase aircraft weight; however a benefit or benefits in any of the three main categories may have value that outweighs the simple weight saving argument. Aircraft design history is replete with examples. For instance, retractable landing gear increases aircraft weight, but results in significant net benefits in speed and energy efficiency. Wireless is likely to have similar counterbalancing effects.

B. A Sample of Notional Functions Enabled via Wireless

In this section we propose a list of functions that can be introduced through wireless-enabled bandwidth and the ability to add functions not previously possible in the absence of bandwidth; and briefly discuss their benefits.

Weather: Filling the NEXRAD weather graphics latency gap by producing high-fidelity atmospheric forecasts and up linking the information to the cockpit

Bad weather continues to be a major cause of aircraft accidents and incidents for all categories of aircraft operations. Real-time weather tracking and prediction of local conditions would improve safety and, through safety, impact all three benefit categories.

NEXRAD (Next-Generation Radar) is a network of high-resolution S-band Doppler weather radars operated by the National Weather Service (NWS), an agency of the National Oceanic and Atmospheric Administration (NOAA) within the United States Department of Commerce, the Federal Aviation Administration (FAA) within the Department of Transportation, and the U.S. Air Force within the Department of Defense. Its technical name is WSR-88D, which stands for Weather Surveillance Radar, 1988, Doppler¹¹. NEXRAD allows for accurate detection, tracking and prediction of precipitation and wind, as well as tracking and anticipation of severe weather and tornadoes. The data are available freely and would greatly improve the situational awareness in the cockpit. However, the bandwidth requirements and the need for frequent updates currently prevent data feed into the cockpit. Developments in wireless technologies are required to address this gap.

NEXRAD data graphics transmitted over satellite or ground-to-air links have known latencies ranging between a few seconds and several minutes. These latencies pose safety issues for pilots making flight path decisions in the presence of fast-moving weather systems. The National Center for Atmospheric Research (NCAR) has conducted research into the implementation of high fidelity local forecasting tools that fill in these latency-induced weather gaps with probabilistic solutions that have the potential to enhance safety.

Flight Path Guidance: Delivering Out-the-Window graphical flight path diagnostics by generating computational imagery on the ground that can be delivered to the cockpit, on safe flight path advisory knowledge

Spatial disorientation (somatogravic illusion) in the cockpit has continued to be a cause of fatal accidents from the inception of powered flight to present times. The FAA Airplane Flying Handbook (FAA-H-8083-3) describes this hazard associated with flying when visual references, such as the ground or horizon, are obscured:

“The vestibular sense in particular tends to confuse the pilot. Because of inertia, the sensory areas of the inner ear cannot detect slight changes in the attitude of the airplane, nor can they accurately sense attitude changes that occur at a uniform rate over a period of time. On the other hand, false sensations are often generated; leading the pilot to believe the attitude of the airplane has changed when in fact, it has not. These false sensations result in the pilot experiencing spatial disorientation.”

One of somatogravic illusions is the “head-up illusion”: when an aircraft undergoes a forward linear acceleration, the pilot may perceive that the nose of the aircraft is pitching up and responds to the illusion by pushing the control yoke forward to pitch the nose of the aircraft down, which could result in a crash. The illusion is so strong that pilots tend to ignore correct information supplied by instruments.

The situation can be further exacerbated through a phenomenon described in the FAA Advisory Circular AC 60-22, Aeronautical Decision Making and known as “get-there-itis”: *“Pilots, particularly those with considerable experience, as a rule always try to complete a flight as planned, please passengers, meet schedules and generally demonstrate that they have ‘the right stuff.’... Common among pilots, [get-there-itis] clouds the vision and impairs judgment by causing a fixation on the original goal or destination combined with a total disregard for any alternative course of action.”*

In situations with obscured visual references, these effects combine to deprive the pilot of situational awareness and lead to accidents. Continuously updated Out-the-Window graphically intuitive images of safe flight path information would counteract somatogravic illusions and other visual deficiencies,

¹¹ <https://en.wikipedia.org/wiki/NEXRAD>

improving the safety of flight. Such information could be generated on the ground and transmitted to the cockpit via wireless, for example.

This function impacts all three benefit categories, through safety.

Aircraft State: Delivering sensor information about the flight-envelope state of the aircraft and autopilot actions to pilot

This function addresses a fundamental gap in situational awareness of pilots during contemporary aircraft operation within the performance and control flight envelope. Icing provides a good example of this phenomenon. Experienced pilots understand that icing results in sluggish controls. However, in normal autopilot-flown operations, automation compensates for this sluggishness and the pilot may be unaware that icing has taken place. The automation is also “unaware” that airframe icing has taken place and cannot impart this information to the pilot. Instead, automation compensates for sluggish controls in the way a human would. The problem is that if automation breaks down, the pilot can be faced with a marginally or un-controllable aircraft. In general, pilots may not be able to control a situation competently unless they are aware of the reason for failure and attendant control and performance limitations.

This example points to the need for not only more intelligent automation (e.g., autopilot), but also for continual sensor-based assessment of the state of the aircraft and relaying this information when a deviation from nominal conditions has occurred. In our example, when automation starts compensating for icing, the pilot has to be alerted in case a need arises to take over from automation. Wireless transmission of sensor information would serve to improve safety, and impact all three benefit categories through safety.

Remote Support: Creating Virtual Flight Operations centers (VOC) to enable a kind of “On-Star™” for pilots

Single pilot operations would benefit from remote assistance of the type provided by the On-Star™ system for automobiles today. For example, in General Aviation today, most 14CFR Part 91 operations are performed by a single pilot. In future fleets of air taxis flown under Part 135, single pilot operations may increasingly become the norm. As autonomy technologies mature, increasing interest in reduced crew operations under Part 121 will likely grow. Examples of remote support services could include: detailed navigation instructions in high-complexity areas; assistance with meeting and picking up passengers and their luggage, in normal operating conditions; and real-time alternative airport advisories during IFR flying. In off-nominal operations, automated response would mitigate emergency conditions. The remote support concept includes the prospect that the pilot-flying and pilot-not-flying could be either in the cockpit or on the ground.

The main benefits of this function are economic and public good: it improves access to airspace and facilitates the infusion of on-demand air transportation. In addition, emergency services would benefit from enhanced safety.

Maintenance Prognostics: Enabling streaming critical Maintenance Repair and Overhaul (MRO) data as well as on-board analytics from the aircraft to the ground for prognostic analysis and “just-in-time” maintenance management

A modern aircraft such as the Boeing 787 produces as much as 500 Gb of data per flight. Much of these data are from sensor signals that can be analyzed post-flight. Some of the data are valuable to both the flight crew and the maintenance crews during a flight. The ability to stream flight-critical and maintenance-critical analytics from the airplane is enabled through wireless connectivity. The outcomes of these functions fall under the economics and safety benefits categories.

PIREPS: Supporting automated, networked PIREPS (pilot reports)

The idea of this service is akin to Waze™ for surface traffic. The service would supply pilots with detailed route information and user-submitted flight times and route details, as well as weather information.

This service supplements GPS navigation software by gathering up-to-date real-time traffic information for the system users.

The benefit goes to improved safety via increased situational awareness of aircraft operators, and thus fits under all three general benefit categories.

Tele-Medicine: Creating remote cabin tele-medicine connectivity between passenger/patients and ground-based medical personnel

Most in-flight medical emergencies are not life threatening and can be handled by a team of trained professionals. However, life-threatening or complicated emergencies require ground support. Airlines use MedLink, a tool for direct communication between the flight crew and MedAire. MedAire is an organization of physicians who have been educated about in-flight emergencies and offer advice to the air crew and a physician onboard, if one is available. MedLink relies on the quality of communications. Improved audio-visual transmission of information and real-time display capabilities would advance the life-saving efforts onboard.

The primary benefit of this function is public good. Considerations of potential legal liabilities enter into the economic benefits. Because pilots may have to make a decision to divert and land an aircraft in adverse conditions (e.g., with high fuel levels), appropriate response to medical emergencies may impact the overall safety of the aircraft and, therefore, the fly-the-aircraft benefit category.

Airspace Management: Integrating ANSP – AOC – Flight deck decision support

Today's airspace architectures and procedures are designed to be managed by humans. While increasing use of automation tools for air traffic controllers and managers continues to evolve, the airspace is reaching saturation in terms of controllability by humans alone. The need to reconcile disparate decisions made at various locations and at different time scales and with varying degrees of situational awareness adds to the complexity of decision making and, in general, to system complexity and human workloads in the air and on the ground. Increased complexity, in turn, reduces predictability and, hence, controllability of the system. Automation tools, based on wireless connectivity, for multi-scale (temporal and spatial) integration of ANSP, AOC, and flight deck decision making would reduce decision making complexity. Such tools would facilitate both strategic and tactical decision coordination among these three participants, through connectivity-enabled information integration for flight path and airspace performance optimization [3]. Such tools would impact all three benefit categories.

Remote Pilots: Implementing remote emergency flight control

This function is required not only in case of medical emergencies (pilot incapacitation), but also in the cases where pilot actions are evaluated as dangerous to the aircraft, the lives of passengers, or the public on the ground. The safety benefit propagates to all three benefits categories.

IV. Concluding Remarks: Technology Barriers and Suggested Priorities

There are a number of barriers that stand in the way of enabling many of the proposed wireless-enabled functions, summarized as follows:

1. *Bandwidth.* Intelligent and more autonomous systems place great demands on bandwidth. The architectures for autonomous systems such as self-driving cars are still in development, but expected to make rapid progress over the next decade or even sooner, in the minds of some. In the cases of closed circuit television (CCTV) and dynamic message signs (DMS), the sheer number of video surveillance cameras alone, as well as demand for visual fidelity, place great demands on bandwidth for existing 4G

LTE wireless networks. It appears likely that these current networks will not be able to carry the loads necessary to gather and deliver information required for management of dense air traffic of the future.

Emerging wireless technologies affecting bandwidth are relevant to strategies for connectivity in aviation. The advancements of importance include optical means for connectivity between aircraft and ground, as well as 5G LTE, for example. In particular, the 5G technology offers a multitude of advancements in connectivity that will matter for aviation connectivity applications and performance¹². In aviation connectivity applications, the 5G standards will support “...*much greater throughput, much lower latency, ultra-high reliability, much higher connectivity density, and higher mobility range. This enhanced performance is expected to be provided along with the capability to control a highly heterogeneous environment, and capability to, among others, ensure security and trust, identity, and privacy*” [4]. It appears clear that 5G LTE networks hold significant potential for aviation benefits in safety, economics, and public good.

2. *Reliability*. Some of the functions on an aircraft can tolerate communication delays and interruptions and some cannot. Given the relatively low reliability of the wireless (RF), a critical component analysis on aircraft wires and systems is necessary to determine what wired systems can be replaced, in principle, and what systems must remain wired, regardless of the materials used in the wires. Wireless reliability implies that wireless can serve as augmentation but not replacement of critical wired systems.

3. *Cybersecurity*. Security of wirelessly connected systems is a serious and unresolved problem. Current systems exemplify the problem. For instance, it is possible for such systems as On-Star to be remotely activated by third parties. In March 2014, a group of students succeeded in faking a traffic jam using Waze¹³.

4. *Sensors*. On-board sensor systems that could be designed for wireless signal transmission to data servers would directly reduce costs for engineering, manufacturing and maintenance of those systems. Such systems could also enable more widely distributed sensing on aircraft surfaces, for example, of real-time aerodynamic properties associated with lift and drag, yielding higher-fidelity information about aircraft performance than can be achieved with the fewer existing pitot-static, total-air-temperature, and angle-of-attack sensors on aircraft today.

5. *Autonomy*. While wireless technologies are required to enable autonomy, truly autonomous systems (self-governing systems) must be capable of surviving in case of wireless system failure. This requirement points to the need of developing survivable autonomous systems that, perhaps, are architected for optimal reliability based on independent (not connected) as well as interdependent (connected) vehicle management systems.

It stands to reason that in making decisions on wireless research investments, technologies that target existing safety and public good problems should have the highest priority. The first three technologies outlined on the notional list are of the highest priority, in the authors’ opinion. Moreover, safety-related functions should be actively pursued by government research institutions.

We suggest that the development of technologies of economic value will unfold as a result of market demand. Such developments are already taking place. For instance, Lufthansa is now using a wireless inflight entertainment solutions (IFE) BoardConnect. The system weight savings for the Airbus A340-600

¹² https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

¹³ <http://www.popsci.com/article/gadgets/israeli-students-spoof-waze-app-fake-traffic-jam>

with 380 seats is about 900 kg, resulting in yearly fuel savings of 47 tons per aircraft¹⁴. In another example, Rolls-Royce is developing a new ship bridge design with functions similar to an aircraft cockpit of the future, with reliance on wireless, among other new technologies¹⁵.

In summary, changes in aircraft weight (reduction or gain) due to the infusion of wireless technologies and tradeoffs with other benefits require further study. It is already clear that wireless technologies have a great potential to improve safety, economics, and public good aspects of aviation. Detailed system studies are indicated to qualify and quantify specific wireless systems technologies that would maximize benefits in aviation operations.

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¹⁴ Lufthansa Group, http://www.lufthansagroup.com/_leadadmin/downloads/en/lh-fuel-e_ciency-0612.pdf

¹⁵ <http://gizmodo.com/the-futuristic-bridge-rolls-royce-designed-for-its-new-1736707806>

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14. ABSTRACT We report on an examination of potential benefits of infusing wireless technologies into various areas of aircraft and airspace operations. The analysis is done in support of a NASA seedling project Efficient Reconfigurable Cockpit Design and Fleet Operations Using Software Intensive, Network Enabled Wireless Architecture (ECON). The study has two objectives. First, we investigate one of the main benefit hypotheses of the ECON proposal: that the replacement of wired technologies with wireless would lead to significant weight reductions on an aircraft, among other benefits. Second, we advance a list of wireless technology applications and discuss their system benefits. With regard to the primary hypothesis, we conclude that the promise of weight reduction is premature. Specificity of the system domain and aircraft, criticality of components, reliability of wireless technologies, the weight of replacement or augmentation equipment, and the cost of infusion must all be taken into account among other considerations, to produce a reliable estimate of weight savings or increase.					
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